Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Effect of Nonlinear Frequency Compression on Frequency-Following Responses in Individuals with Sensorineural Hearing Loss

Sharda Sarda

sharda.sarda@bharatividyapeeth.edu

Bharati Vidyapeeth (Deemed to be University)

Saurabh Soni

Bharati Vidyapeeth (Deemed to be University)

Kalyani Ghate

Bharati Vidyapeeth Deemed University

Research Article

Keywords: Nonlinear frequency compression, frequency-following response, sensorineural hearing loss, neural encoding, hearing aids, speech processing

Posted Date: November 6th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10160012/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Abstract

Objective

The present study investigated the effect of nonlinear frequency compression (NLFC) feature of hearing aid on Frequency-Following Response (FFR) in individuals with sensorineural hearing loss (SNHL). *Design*: FFR responses were recorded with and without activation of NLFC of a hearing aid in individuals with Sensorineural hearing loss (SNHL). Additionally, FFR measures were compared between normal hearing individuals and individuals with sensorineural hearing loss using NLFC features. *Study sample*: Thirty-five adults aged 40–70 years with moderately severe to severe sensorineural hearing loss and 10 normal-hearing individuals were included in the study .

Results

No significant differences were observed in the latency & amplitude parameter of FFR measures in two test conditions, FFR recording with and without activation of NLFC feature in individuals with SNHL ($p > 0.05$). Further, comparison between normal-hearing individuals and individuals with SNHL revealed no significant differences in latency measures of FFR. However, amplitudes of F1 and F2 formants of FFR were found to be significantly reduced in participants with SNHL as compared to normal hearing individuals ($p < 0.05$) .

Conclusion

NLFC did not significantly influence FFR characteristics in individuals with SNHL. However, reduced harmonic encoding in the SNHL group suggests degraded neural representation of spectral speech cues at the brainstem level despite amplification.

Introduction

Sensorineural hearing loss (SNHL) is associated with reduced audibility of high-frequency speech cues and impaired speech perception, particularly in challenging listening environments. Although conventional hearing aids improve overall audibility, amplification of high-frequency speech sounds often remains limited because of dead region & feedback constraints (Moore, 2007; Wilson et al., 2017). Consequently, individuals with SNHL frequently experience distorted perception of high-frequency consonants that contribute significantly to speech intelligibility.

To improve access to high-frequency speech information, frequency-lowering technologies have been introduced in hearing aids. Among these approaches, nonlinear frequency compression (NLFC) selectively compresses high-frequency acoustic information into lower-frequency regions where hearing is relatively preserved (Alexander, 2013). Previous studies have shown that NLFC may improve detection

and recognition of fricatives & affricates, particularly in individuals with steeply sloping high-frequency hearing loss (Glista et al., 2009; Wolfe et al., 2011). However, outcomes remain variable across literature could be due to altered spectral characteristic of sound that may negatively affects speech perception and sound quality (Souza et al., 2013; Alexander, 2016).

Most previous investigations examining the effects of NLFC have relied primarily on behavioral speech perception measures. While behavioral outcomes provide clinically relevant information, they do not fully explain how acoustically modified speech signals are encoded within the auditory system. Electrophysiological measures provide an objective approach for evaluating neural processing of speech and may offer additional insight into the physiological effects of hearing-aid signal-processing strategies.

The Frequency-Following Response (FFR) is an electrophysiological response that reflects sustained phase-locked neural activity within the auditory brainstem and provides objective information regarding neural encoding of speech signals (Skoe & Kraus, 2010). FFR represents temporal and spectral features of speech, through the fundamental frequency (F0) and harmonic components, making it particularly useful for investigating subcortical speech processing in individuals with hearing loss (Krishnan et al., 2005). Previous studies have reported degraded FFR characteristics in individuals with SNHL, including reduced response amplitudes of F0 and harmonics with delayed neural timing suggesting impaired spectral & temporal encoding of speech at the brainstem level (Ananthakrishnan et al., 2016; Jacxsens et al., 2024).

Although the effects of NLFC on speech perception has been widely investigated speech perception tests, limited research has examined its influence on subcortical neural encoding of speech using FFR measures. Because NLFC changes the spectral characteristics of speech, it may influence temporal and spectral encoding within the auditory brainstem. Understanding these neural effects may provide important information regarding the physiological consequences of frequency compression. Therefore, the present study aimed to investigate the effect of nonlinear frequency compression on Frequency-Following Response characteristics in individuals with sensorineural hearing loss. Specifically, the study compared FFR responses between NLFC-activated and NLFC-deactivated conditions and also compared responses between individuals with SNHL and normal-hearing adults.

Methods

Study design

A cross-sectional prospective study was conducted at the School of Audiology and Speech Language Pathology, Bharati Vidyapeeth (Deemed to be University), Pune.

Sample size: Purposive sampling was used.

Participants

Thirty-five adults aged between 40 and 70 years participated in the study. Group I consisted of 10 normal-hearing individuals, while Group II included 25 individuals with bilateral sensorineural hearing loss. Individuals in the SNHL group had hearing thresholds greater than 56 dB HL at 2, 4, and 8 kHz. Participants in the normal-hearing group had pure-tone thresholds within normal limits, type A tympanograms, and no history of retro cochlear pathology. Participants in the SNHL group had bilateral sensorineural hearing loss, type A tympanograms, and no evidence of retro cochlear involvement. Individuals with cognitive, neurological, psychiatric, or uncontrolled systemic disorders were excluded from the study. Participants with tinnitus or hyperacusis were also excluded. Ethical approval for the study was obtained from the Institutional Ethics Committee of Bharati Vidyapeeth (Deemed to be University), Pune (BVDUMC/IEC/348/25–26 dated 24/07/25). Written informed consent was obtained from all participants prior to data collection.

Hearing aid programming

Participants in the SNHL group were fitted with Phonak Terra+ receiver-in-canal hearing aids programmed using Phonak Target software (version 10.1). Two hearing-aid programs were created: NLFC ON and NLFC OFF. Real-ear measurements were performed to verify amplification characteristics and ensure appropriate fitting. To minimize order effects, testing order was counterbalanced. For 50% of the participants, FFR recording was initially performed using the NLFC ON condition followed by NLFC OFF, whereas the order was reversed for the remaining participants.

Frequency-Following Response recording

FFR recordings were obtained using Intelligent Hearing Systems SmartEP (version 5). A speech stimulus (/da/) from the BioMAP protocol was presented in free field through calibrated loudspeakers at 80 dB nHL using alternating polarity and a repetition rate of 4.35 stimuli/s. Responses were recorded with a sampling rate of 40 kHz, analysis window of 200 ms, and 1024 sweeps.

Electrode placement consisted of the non-inverting electrode at Fpz, inverting electrode at the ipsilateral earlobe (A1/A2), and ground electrode at the nape of the neck. Electrode impedance was maintained below 5 kΩ with an inter-electrode difference below 2 kΩ. Recording filters were set between 30 and 3000 Hz.

Response analysis

Temporal FFR measures included latency values of Waves V, A, C, D, E, F, and O. Spectral analysis included amplitudes of the fundamental frequency (F0) and harmonic components (F1 and F2).

Statistical analysis

Statistical analysis was performed using Statistical Package for the Social Sciences (SPSS). Descriptive statistics including median and interquartile range were calculated for all variables. The Shapiro–Wilk test revealed non-normal distribution for several variables; therefore, non-parametric statistical analyses were performed. Wilcoxon signed-rank test was used for within-group comparisons between NLFC ON and NLFC OFF conditions, while Mann–Whitney U test was used for comparisons between normal-hearing individuals and individuals with SNHL. Statistical significance was set at $p < 0.05$.

Results

The Shapiro–Wilk test revealed non-normal distribution for several latency and amplitude variables; therefore, non-parametric statistical analyses were performed. Wilcoxon signed-rank test was used to compare Frequency-Following Response (FFR) measures between NLFC ON and NLFC OFF conditions in individuals with sensorineural hearing loss (SNHL), while Mann–Whitney U test was used to compare FFR measures between normal-hearing individuals and individuals with SNHL.

[Insert Fig. 1 here]

Figure 1. Representative Frequency-Following Response (FFR) waveforms recorded under nonlinear frequency compression (NLFC) ON and NLFC OFF conditions in individuals with sensorineural hearing loss.

Comparison of FFR measures between NLFC ON and NLFC OFF conditions

Representative Frequency-Following Response (FFR) waveforms recorded under the NLFC ON and NLFC OFF conditions are shown in Fig. 1. No statistically significant differences were observed in FFR latency measures between NLFC ON and NLFC OFF conditions for Waves V, A, C, D, E, F, and O ($p > 0.05$).Similarly, spectral amplitude measures including fundamental frequency (F0), first formant (F1), and second formant (F2) amplitudes did not differ significantly between the two conditions ($p > 0.05$).

Median latency values were comparable across conditions, with Wave V latency measuring 9.07 ms in the NLFC ON condition and 8.98 ms in the NLFC OFF condition. Similarly, median F0 amplitudes were 0.0239 and 0.0252 in the NLFC ON and OFF conditions, respectively.

The comparison of FFR latency measures between the NLFC ON and NLFC OFF conditions is presented in Table 1.

Table 1
Comparison of FFR Latencies Between NLFC ON and NLFC OFF Conditions in the SNHL Group

Wave	Condition	Median (ms)	Q1-Q3 (ms)	Min	Max	Z	p
V	ON	9.07	7.76–10.59	6.90	12.75	0.06	0.94
	OFF	8.98	8.10-10.42	6.44	14.40		
A	ON	11.28	9.91–12.66	7.59	14.63	1.60	0.11
	OFF	11.02	9.80-12.25	7.41	15.90		
C	ON	18.96	18.23–19.68	15.30	25.50	0.43	0.66
	OFF	18.90	17.58–20.23	15.00	23.33		
D	ON	24.89	23.90-25.87	21.00	32.40	0.02	0.97
	OFF	25.05	23.35–26.76	20.03	29.85		
E	ON	35.17	32.40-35.94	28.43	37.57	1.58	0.11
	OFF	34.41	31.87–36.42	28.12	38.55		
F	ON	40.90	39.61–42.19	39.45	46.80	0.34	0.73
	OFF	41.18	39.60-42.77	39.15	47.48		
O	ON	171.21	169.64-172.66	167.48	181.05	0.84	0.39
	OFF	170.48	169.02-171.95	168.00	177.00		

Note. Z = Wilcoxon signed-rank test statistic; p = probability value. No corrections for multiple comparisons were applied given the exploratory nature of the analysis.

The comparison of FFR spectral amplitudes between the NLFC ON and NLFC OFF conditions is presented in Table 2.

Table 2

Comparison of FFR Spectral Amplitudes Between NLFC ON and NLFC OFF Conditions in the SNHL Group

Parameter	Condition	Median	Q1–Q3	Min	Max	Z value	p value
F0	**ON**	0.0239	0.016–0.032	0.011	0.079	0.33	0.73
	OFF	0.0252	0.0159–0.0351	0.0096	0.105		
F1	**ON**	0.000043	0.000018–0.000069	0.000015	0.000305	1.76	0.07
	OFF	0.000066	0.000034–0.000103	0.000016	0.000219		
F2	**ON**	0.000015	0.000009–0.000026	0.0000038	0.000128	1.76	0.07
	OFF	0.000026	0.000013–0.000043	0.0000055	0.000094		

Note. Z = Wilcoxon signed-rank test statistic; p = probability value. All amplitude values in microvolts.

Comparison of FFR measures between normal-hearing individuals and individuals with SNHL

Comparison between normal-hearing individuals and individuals with SNHL in the NLFC ON condition revealed no statistically significant differences in latency measures for Waves V, A, C, D, E, F, and O ($p > 0.05$).

For spectral measures, no statistically significant difference was observed for F0 amplitude between the two groups ($p = 0.65$). However, significant differences were observed for F1 amplitude ($Z = 2.38$, $p = 0.01$) and F2 amplitude ($Z = 2.26$, $p = 0.02$), with lower amplitudes observed in the SNHL group compared to normal-hearing individuals.

The comparison of FFR latency measures between the normal-hearing group and the SNHL group in the NLFC ON condition is presented in Table 3.

Table 3

Comparison of FFR Latencies Between Typical Hearing and SNHL Groups in the NLFC ON Condition

Wave	Group	Median (ms)	Q1-Q3 (ms)	Min	Max	Z	p
V	**Typical Hearing**	8.52	7.91–9.18	7.05	10.20	1.23	0.21
	SNHL (NLFC ON)	9.07	7.76–10.59	6.90	12.75		
A	**Typical Hearing**	10.81	10.00-11.23	9.75	12.38	0.02	0.98
	SNHL (NLFC ON)	11.28	9.91–12.66	7.59	14.63		
C	**Typical Hearing**	18.56	17.79–19.29	15.75	21.75	0.37	0.71
	SNHL (NLFC ON)	18.96	18.23–19.68	15.30	25.50		
D	**Typical Hearing**	25.36	23.91–26.36	20.25	31.12	0.35	0.72
	SNHL (NLFC ON)	24.89	23.90-25.87	21.00	32.40		
E	**Typical Hearing**	32.52	31.67–34.87	27.22	40.88	1.48	0.14
	SNHL (NLFC ON)	35.17	32.40-35.94	28.43	37.57		
F	**Typical Hearing**	42.64	40.09–44.04	27.82	50.33	0.41	0.68
	SNHL (NLFC ON)	40.90	39.61–42.19	39.45	46.80		
O	**Typical Hearing**	171.67	170.79-174.15	164.40	181.20	1.04	0.29
	SNHL (NLFC ON)	171.21	169.64-172.66	167.48	181.05		

Note. Z = Mann-Whitney U test statistic; p = probability value.

The comparison of FFR spectral amplitudes between the normal-hearing group and the SNHL group in the NLFC ON condition is presented in Table 4.

Table 4

Comparison of FFR Spectral Amplitudes Between Typical Hearing and SNHL Groups in the NLFC ON Condition

Parameter	Condition	Median	Q1–Q3	Min	Max	Z value	p value
F0	**Typical hearing**	0.02682	0.0211–0.0375	0.0089	0.0794	0.45	0.65
	NLFC ON	0.02391	0.016–0.032	0.0110	0.0798		
F1	**Typical hearing**	0.000099	0.0000579–0.0002079	0.0000145	0.001230	2.38	**0.01***
	NLFC ON	0.000043	0.000018–0.000069	0.0000153	0.000305		
F2	**Typical hearing**	0.0000376	0.0000261–0.0000619	0.0000030	0.000185	2.26	**0.02***
	NLFC ON	0.0000157	0.000009–0.000026	0.0000038	0.000128		

*Note. Z = Mann-Whitney U test statistic; p = probability value. *p < 0.05. SNHL group values are from the NLFC ON condition.*

The comparison of F1 amplitudes between the normal-hearing group and the SNHL group is illustrated in Fig. 2.

[Insert Fig. 2 here]

Figure 2. Box plots showing F1 amplitude (μV) of the Frequency-Following Response for the normal-hearing group and the sensorineural hearing loss (SNHL) group in the NLFC ON condition. The horizontal line represents the median, the box indicates the interquartile range, and the whiskers represent the minimum and maximum values.

The comparison of F2 amplitudes between the normal-hearing group and the SNHL group is illustrated in Fig. 3.

[Insert Fig. 3 here]

Figure 3. Box plots showing F2 amplitude (μV) of the Frequency-Following Response for the normal-hearing group and the sensorineural hearing loss (SNHL) group in the NLFC ON condition. The horizontal line represents the median, the box indicates the interquartile range, and the whiskers represent the minimum and maximum values.

Summary of findings

The results demonstrated that activation of nonlinear frequency compression did not significantly alter temporal or spectral FFR characteristics in individuals with SNHL. However, individuals with SNHL

exhibited significantly reduced harmonic encoding for F1 and F2 components compared to normal-hearing individuals, despite hearing-aid amplification.

Discussion

The present study investigated the effect of nonlinear frequency compression (NLFC) on Frequency-Following Response (FFR) characteristics in individuals with sensorineural hearing loss (SNHL). Comparisons were made between NLFC ON and NLFC OFF conditions in individuals with SNHL and between normal-hearing individuals and individuals with SNHL using hearing aids with NLFC processing.

The results revealed no significant differences in FFR latency measures between NLFC ON and NLFC OFF conditions. Temporal peaks including Waves V, A, C, D, E, F, and O remained comparable across both processing conditions, suggesting that activation of NLFC did not substantially alter neural timing or temporal encoding of speech at the brainstem level. These findings indicate that the spectral modifications introduced by NLFC were not sufficient to produce measurable changes in the temporal characteristics of the FFR. Similar findings have been reported in studies demonstrating limited electrophysiological and perceptual effects of NLFC in adults with mild-to-moderate hearing loss when conservative compression settings are used (Picou et al., 2015; Souza et al., 2013).

Similarly, no significant differences were observed in spectral amplitude measures between NLFC ON and NLFC OFF conditions. Although slight reductions in F1 and F2 amplitudes were observed in the NLFC ON condition, these differences were not statistically significant. The findings suggest that the degree of frequency compression used in the present study may have preserved the overall neural representation of speech cues without introducing substantial spectral distortion. Previous studies have suggested that less aggressive NLFC settings are less likely to produce distortions affecting speech perception and sound quality (Alexander, 2013; Parsa et al., 2013).

Comparison between normal-hearing individuals and individuals with SNHL revealed no significant differences in FFR latency measures, suggesting relatively preserved neural timing in aided individuals with hearing loss. However, significant reductions were observed for F1 and F2 amplitudes in the SNHL group compared to normal-hearing individuals. These findings indicate degraded neural encoding of harmonic and spectral speech information despite amplification. Reduced harmonic representation in individuals with hearing loss has previously been associated with impaired neural synchrony, reduced phase-locking ability, and cochlear pathology affecting temporal fine-structure processing (Ananthakrishnan et al., 2016; Krishnan et al., 2005).

Interestingly, F0 amplitude did not differ significantly between groups, suggesting relatively preserved neural representation of the fundamental frequency. Preservation of F0 encoding may reflect the robustness of low-frequency temporal envelope cues within the auditory brainstem even in the presence of hearing impairment. Similar observations have been reported in previous FFR studies demonstrating relatively stable encoding of low-frequency components compared to higher-frequency harmonic cues in individuals with hearing loss (Skoe & Kraus, 2010; Anderson & Kraus, 2013).

Overall, the findings of the present study suggest that NLFC had limited influence on subcortical neural encoding of speech as measured using FFR. While NLFC may improve behavioral access to high-frequency speech cues, the present findings indicate that it may not substantially modify temporal or spectral neural encoding at the brainstem level under the tested conditions. However, the reduced harmonic encoding observed in individuals with SNHL highlights persistent deficits in spectral speech processing despite amplification. These findings support previous evidence suggesting that hearing-aid amplification alone may not completely restore neural representation of complex speech cues in individuals with SNHL (Souza et al., 2013; Picou et al., 2015).

The present study has certain limitations. The sample size was relatively small, and acclimatization to NLFC processing was limited to the testing period. In addition, only one hearing-aid manufacturer and processing strategy were evaluated. Future studies involving larger samples, extended acclimatization periods, and different frequency-lowering parameters may provide further insight into the neurophysiological effects of NLFC on speech encoding. Furthermore, inclusion of behavioural speech perception measures alongside electrophysiological recordings may help clarify the relationship between neural encoding and functional listening outcomes.

Conclusion

The present study investigated the effect of nonlinear frequency compression (NLFC) on Frequency-Following Response (FFR) characteristics in individuals with sensorineural hearing loss (SNHL). The findings revealed no significant differences in temporal or spectral FFR measures between NLFC ON and NLFC OFF conditions, suggesting that activation of NLFC did not substantially alter subcortical neural encoding of speech under the tested conditions.

Comparison between normal-hearing individuals and individuals with SNHL demonstrated significantly reduced F1 and F2 amplitudes in the SNHL group, indicating poorer neural representation of harmonic speech cues despite amplification. However, temporal encoding and F0 representation remained relatively preserved.

Overall, the findings suggest that NLFC may have limited influence on brainstem-level speech encoding as measured using FFR, while individuals with SNHL continue to exhibit deficits in spectral neural processing. The study highlights the potential utility of FFR as an objective measure for evaluating neural encoding of amplified speech in hearing-aid users.

Declarations

Funding

No external funding was received for the present study.

Ethical approval

The study was approved by the Institutional Ethics Committee. Written informed consent was obtained from all participants prior to participation in the study.

Author Contribution

S.S. (Saurabh Soni) conceptualized and designed the study, collected data, performed data analysis and interpretation, prepared the figures and tables, and drafted the manuscript. **S.S. (Sharda Sarda)** supervised the study, contributed to the study design, interpreted the data, and critically revised the manuscript for important intellectual content. **K.G. (Kalyani Ghate)** contributed to the study methodology, data interpretation, and critically reviewed and revised the manuscript. All authors read and approved the final manuscript.

References

1. Moore BCJ (2007) Cochlear hearing loss: Physiological, psychological, and technical issues, 2nd edn. Wiley, Chichester
2. Wilson BS, Tucci DL, Merson MH, O'Donoghue GM (2017) Global hearing health care: new findings and perspectives. Lancet 390(10111):2503–2515
3. Alexander JM (2016) Nonlinear frequency compression: Influence of start frequency and input bandwidth on consonant and vowel recognition. J Acoust Soc Am 139(2):938–957
4. Glista D, Scollie S, Bagatto M, Seewald R, Parsa V, Johnson A (2009) Evaluation of nonlinear frequency compression: Clinical outcomes. Int J Audiol 48(9):632–644
5. Wolfe J, John A, Schafer E, Nyffeler M, Boretzki M, Caraway T (2010) Evaluation of nonlinear frequency compression for school-age children with moderate to moderately severe hearing loss. J Am Acad Audiol 21(10):618–628
6. Souza PE, Arehart KH, Shen J, Anderson M, Kates JM (2015) Working memory and intelligibility of hearing-aid processed speech. Front Psychol 6:526
7. Skoe E, Kraus N (2010) Auditory brain stem response to complex sounds: A tutorial. Ear Hear 31(3):302–324
8. Krishnan A, Xu Y, Gandour J, Cariani P (2005) Encoding of pitch in the human brainstem is sensitive to language experience. Cogn Brain Res 25(1):161–168
9. Ananthakrishnan S, Krishnan A, Bartlett E (2016) Human frequency following response: Neural representation of envelope and temporal fine structure in listeners with normal hearing and sensorineural hearing loss. Ear Hear 37(2):e91–e103
10. Jacxsens L, Biot L, Escera C, Gilles A, Cardon E, Van Rompaey V et al (2024) Frequency-following responses in sensorineural hearing loss: A systematic review. J Assoc Res Otolaryngol 25(2):131–147

11. Picou EM, Ricketts TA (2015) Hearing aid benefit and subjective ratings are not always positively associated. Ear Hear
12. Parsa V, Scollie S (2013) Frequency lowering technologies for hearing aids: Current evidence and clinical applications
13. Anderson S, Kraus N (2013) Auditory training: Evidence for neural plasticity in older adults. Perspect Hear Hear Disord Res Diagn 17(1):37–57

Figures

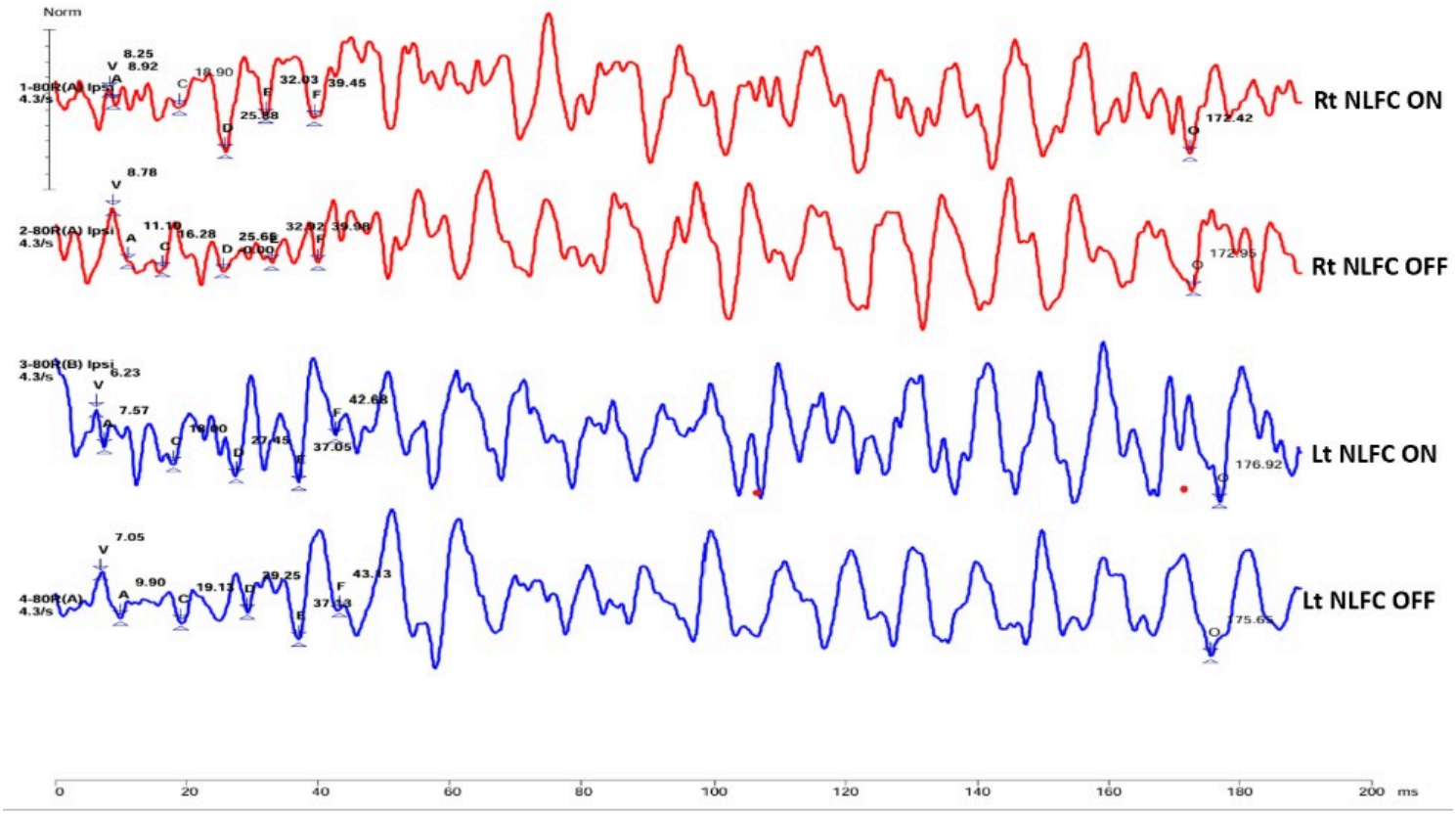


Figure 1

Representative Frequency-Following Response (FFR) waveforms recorded under nonlinear frequency compression (NLFC) ON and NLFC OFF conditions in individuals with sensorineural hearing loss.

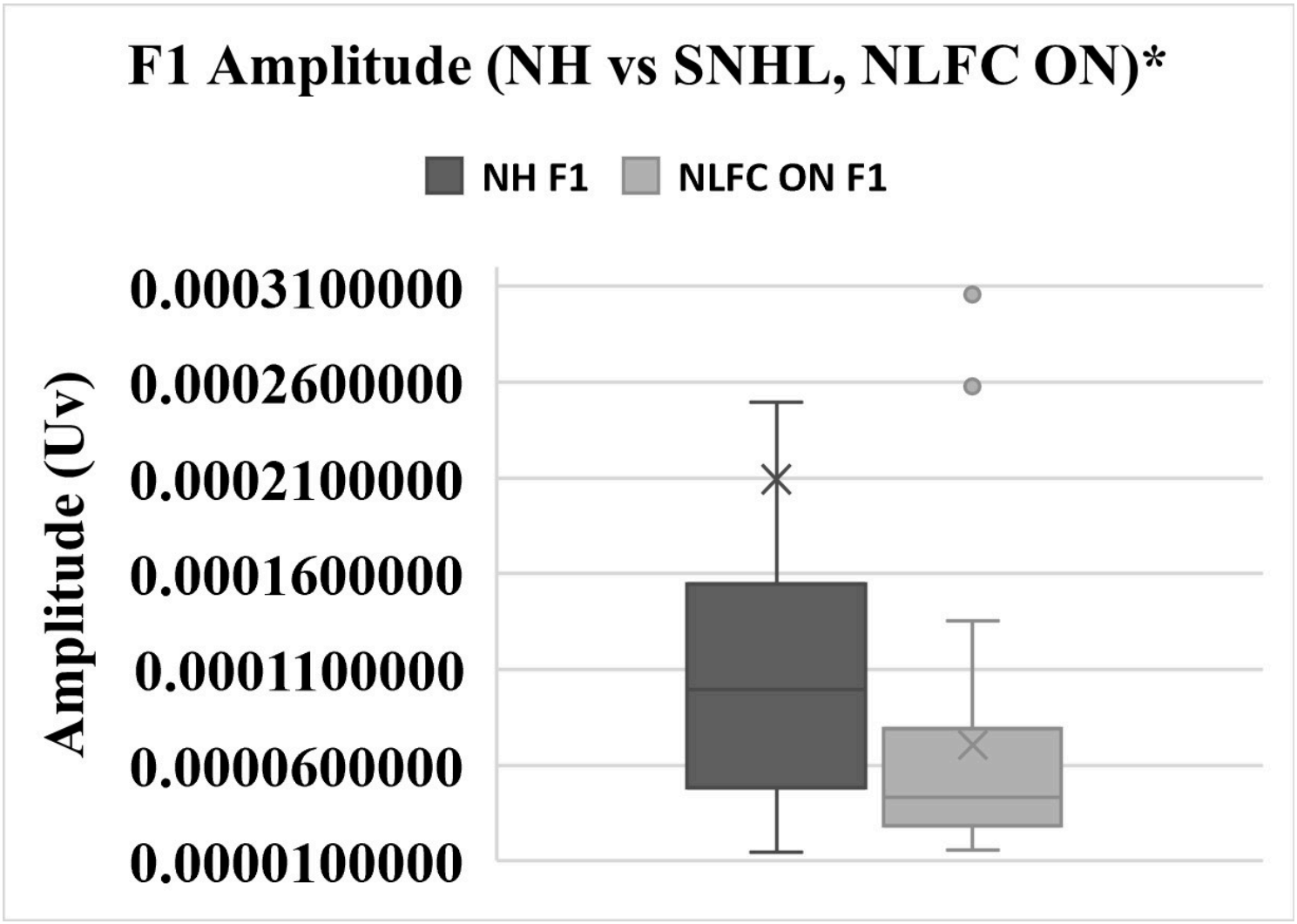


Figure 2

Box plots showing F1 amplitude (μV) of the Frequency-Following Response for the normal-hearing group and the sensorineural hearing loss (SNHL) group in the NLFC ON condition. The horizontal line represents the median, the box indicates the interquartile range, and the whiskers represent the minimum and maximum values.

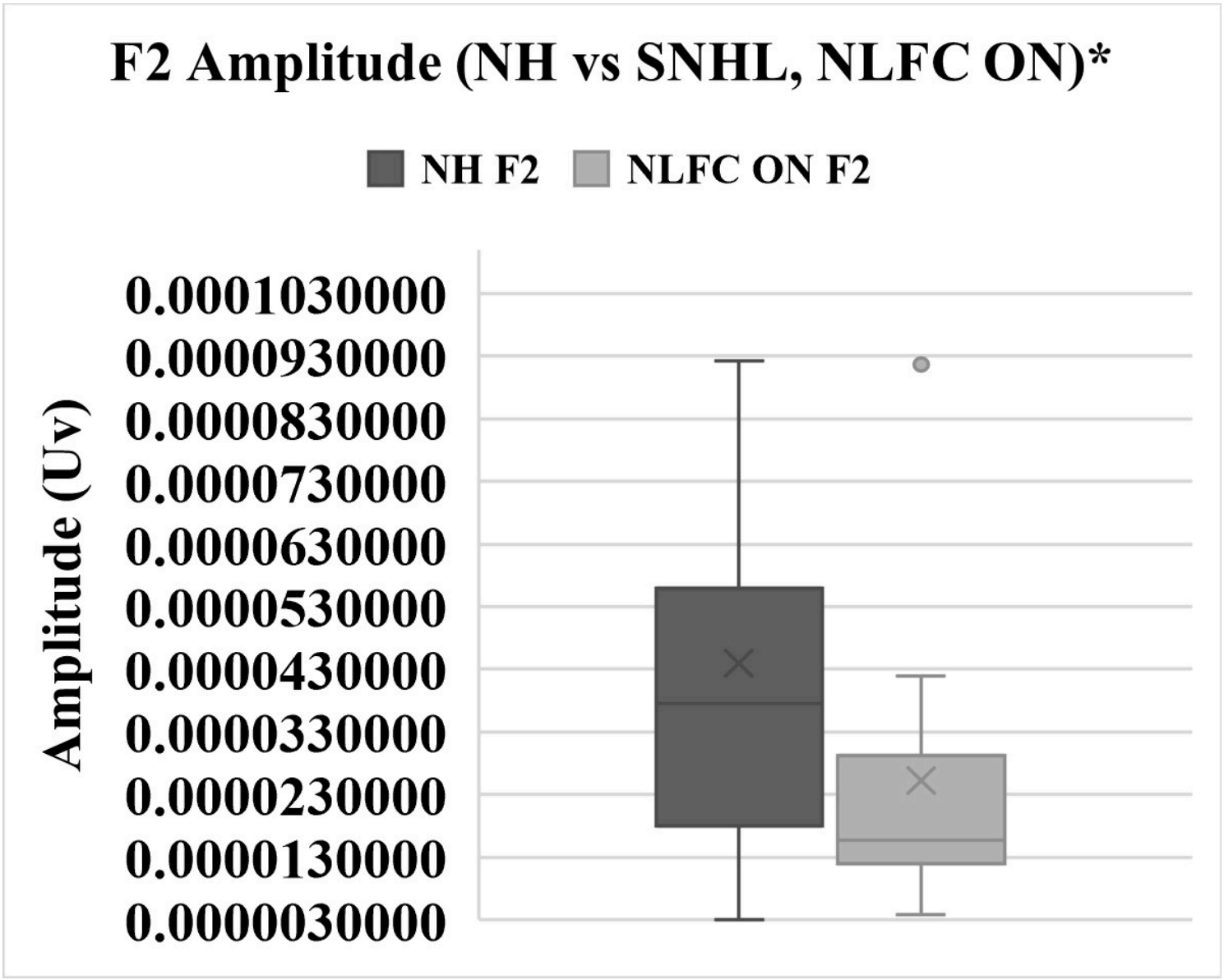


Figure 3

Box plots showing F2 amplitude (μV) of the Frequency-Following Response for the normal-hearing group and the sensorineural hearing loss (SNHL) group in the NLFC ON condition. The horizontal line represents the median, the box indicates the interquartile range, and the whiskers represent the minimum and maximum values.