Effect of Audiometric Configuration on Binaural Temporal Fine Strucure Sensitivity in Adults with Sensorneural Hearing Loss

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Highlights

No significant TFS difference between sloping and rising/flat audiograms
Binaural TFS sensitivity is not solely determined by hearing thresholds
TFS tests offer insights beyond audiograms for hearing rehabilitation

Abstract

Background and Aim: Temporal fine structure (TFS) cues are crucial for pitch perception, sound localization, and speech understanding in noise. Hearing loss can impair TFS sensitivity, but the role of audiometric configuration remains unclear. This study compared binaural TFS sensitivity between adults with sloping and rising/flat sensorineural hearing loss (SNHL).

Methods: This cross-sectional study included 47 adults (32 sloping, 15 rising/flat) aged 18–50 with bilateral mild to moderate SNHL (26–55 dB HL). All participants had normal outer and middle ear status, were right-handed, and had no cognitive impairment. TFS sensitivity was measured using the TFS- Low Frequency (TFS-LF) test at 250, 500, and 750 Hz, and the TFS- Adaptive Frequency (TFS-AF) test at interaural phase differences (IPDs) of 45° and 135°.

Results: For the TFS-LF test, average thresholds were poorer in the sloping group at all frequencies, but differences were insignificant ($p > 0.05$). For the TFS-AF test, thresholds at IPD 135° were significantly higher than at IPD 45° ($p < 0.001$), with no significant group effect. Significant correlations were observed between the thresholds of the TFS-LF and the TFS-AF test.

Conclusion: Based on the results of the TFS-LF and TFS-AF tests, there is no significant difference in TFS sensitivity between the two groups. Furthermore, TFS sensitivity is not determined solely by absolute hearing thresholds across different frequencies, and factors like age, cochlear health, neural timing, and individual variability may also affect outcomes.

Keywords: Temporal fine structure, sensorineural hearing loss, configuration, interaural phase difference

Introduction

The auditory system encodes sound through two primary temporal components: the envelope (ENV) and the temporal fine structure (TFS) [1]. Several studies have investigated the role of TFS cues in speech perception. Reduced TFS processing in individuals with mild to moderate hearing loss, or at frequencies where absolute thresholds remain normal, has been shown to impair their ability to understand speech [2-4]. Impaired TFS processing significantly affects speech perception in noisy environments, particularly when ENV cues are minimal [5]. While ENV cues represent slow fluctuations and contribute to features such as manner of articulation and prosody (2–50 Hz), TFS cues capture rapid variations (600–10000 Hz) essential for pitch perception, sound localization, and speech understanding in noise [6-8]. Although both ENV and TFS information are conveyed through the timing of neural discharges. TFS conveys the rapid oscillations of a sound waveform through phase locking of auditory nerve fibers. These fine temporal cues are essential for binaural unmasking, pitch perception, and spatial hearing. However, TFS information relies heavily on neural phase locking, especially in low-frequency regions [9]. The precise upper-frequency threshold for encoding TFS information in humans is still ambiguous. Current research indicates that the upper-frequency limit for phase locking in binaural processing is approximately 1500 Hz. There is disagreement regarding the upper limit for monaural processing. However, it is estimated to be 8000 Hz to 10000 Hz [10].

The fidelity of TFS encoding is influenced by multiple factors, including age, hearing loss, and cognitive abilities like attention and working memory [11]. Age and sensorineural hearing loss (SNHL) have been shown to degrade TFS sensitivity significantly. Studies indicate that while binaural TFS sensitivity remains stable until age 40, it declines thereafter, particularly in individuals with hearing impairment [12]. Hearing loss, affecting over 1.5 billion people globally [13], can disrupt TFS processing through various mechanisms: degraded phase locking, broadened auditory filters, and central compensatory changes. Interestingly, even when low-frequency hearing thresholds are within normal limits, individuals with high-frequency SNHL may exhibit poor TFS sensitivity [7]. TFS information primarily consists of low frequencies, and it is anticipated that the most significant challenges will arise from low-frequency hearing loss. for a sinusoidal tone, an interaural time difference (ITD) is equivalent to a phase difference between the two ears, which is referred to as the interaural phase difference (IPD) and is typically indicated in degrees [14]. Several tests have been developed to assess TFS sensitivity. Among them, the TFS-low frequency (TFS-LF) test evaluates binaural sensitivity to IPD at fixed low frequencies, this method provides a precise threshold at selected low-frequency regions but is limited because it cannot reflect the full extent of TFS sensitivity across frequencies. To overcome this limitation, the TFS-adaptive frequency (TFS-AF) test was introduced. In this paradigm, the stimulus frequency changes adaptively while IPD is manipulated, enabling estimation of the highest frequency at which reliable phase locking can occur. Thus, while the TFS-LF test provides valuable information about sensitivity at specific low frequencies [15], the TFS-AF test offers a broader and more flexible assessment, and together they provide a more comprehensive evaluation of binaural TFS processing [16]. However, multiple studies suggest that high-frequency hearing loss also affects the processing of TFS information [17-19].

Lorenzi et al. conducted a study to assess TFS sensitivity in individuals with normal hearing versus those with mild to moderate high-frequency hearing loss, utilizing speech stimuli. The findings demonstrated that the hearing-impaired group had markedly poorer performance compared to the normal hearing group in understanding speech, including TFS. This suggests that individuals with mild to moderate high-frequency hearing loss encounter difficulties with TFS information, even at frequencies where their absolute thresholds are within the normal range [4]. Hopkins and Moore examined the TFS sensitivity across the three groups of people. Their findings revealed that senior adults with hearing loss demonstrated poorer TFS sensitivity than younger and older individuals with normal hearing. This suggests that TFS sensitivity decreases with age and increasing hearing impairment [20]. King et al. examined the impact of age and hearing impairment on TFS sensitivity in 46 subjects with mild to moderate sensorineural hearing loss utilizing the TFS-Interaural Phase Difference (IPD) test. A positive correlation was identified between the absolute threshold and TFS-IPD; however, no link was detected with ENV-IPD. The findings indicated that hearing loss independently affects TFS sensitivity, regardless of age factors [21]. Moore and Sek evaluated TFS sensitivity in 22 participants using the TFS-AF test. The results indicated that TFS sensitivity declines with age and decreased hearing ability [22]. Matthew et al. conducted a study to evaluate the sensitivity of TFS in 30 individuals with normal hearing and 30 individuals with various configurations of hearing loss (sloping, rising, and flat), aged 19 to 53 years. The TFS-AF test was conducted at IPD 30°, 60°, and 90°. The results showed that those with normal hearing had a larger TFS threshold than individuals with hearing loss [23].

Prior research has largely focused on comparing individuals with hearing loss to those with normal hearing, often without considering the configuration of hearing loss or matching for age. For instance, Lorenzi et al. showed that individuals with mild to moderate high-frequency SNHL performed significantly worse on speech tasks relying on TFS cues [4]. However, few studies have examined how specific audiogram shapes (e.g., sloping vs. flat or rising) influence TFS sensitivity, especially in non-elderly populations. Therefore, this study aimed to address this gap by comparing TFS sensitivity across individuals with different audiometric configurations, while controlling for age (18–50 years). By doing so, we aimed to isolate the effect of audiogram shape on binaural TFS encoding, independent of aging factors.

Methods

The present study is cross-sectional comparative research investigating the impact of hearing loss on binaural TFS sensitivity. Participants were selected from patients who visited routine audiology clinics and reported bilateral hearing loss. The inclusion criteria required participants to be between the ages of 18 and 50 years old (mean age: 37.47 ± 7.94), have bilateral mild to moderate hearing loss (26–55 dB) across the frequency range of 250–8000 Hz for both air and bone conduction thresholds, have a normal outer ear (as determined by otoscopic examination), have normal middle ear status (Type A tympanogram indicates normal compliance and normal middle ear pressure), be right-handed, and show no signs of cognitive impairment (Montreal Cognitive Assessment (MoCA) questionnaire score ≥ 26). The study included 47 individuals, 32 with sloping hearing loss and 15 with rising or flat hearing loss. Audiometric configurations were determined from air-conduction thresholds measured at octave and inter-octave frequencies between 250 and 8000 Hz. For classification, we used the better-ear audiogram (i.e., the ear with the lower pure-tone average), calculated as the mean threshold across tested frequencies. The audiograms were categorized as follows: Sloping: mean high-frequency threshold (average of thresholds at 2000, 4000, and 8000 Hz) was ≥20 dB HL poorer than the mean low-frequency threshold (average of thresholds at 250 and 500 Hz). Rising: mean low-frequency threshold (average of thresholds at 250 and 500 Hz) was ≥20 dB HL poorer than the mean high-frequency threshold (average of thresholds at 2000, 4000, and 8000 Hz). Flat: difference between the mean low- and high-frequency thresholds was ≤10 dB HL (i.e., thresholds were approximately equal across frequencies). TFS sensitivity was evaluated using two tests, TFS-LF and TFS-AF, employing psychoacoustic software on an HP EliteBook 840 G5 laptop and BY-HP2 headphones. The TFS-LF test is used to assess the sensitivity of the binaural TFS. It was developed from a test described by Hopkins and Moore [24] and modified by Sęk and Moore [15]. The listener's task is to identify the lateral position of the tone burst based on its IPD, where the ENV of the tones is simultaneous between the two ears; therefore, this test is applicable if the listener is sensitive to IPD. The tones are presented in both ears at 30 dB sensation level (SL). It is a forced choice between two intervals and two alternatives, each with four successive tones in each interval. One interval randomly selects four tones, each with the same IPD of 0°. In the next interval, the IPD of the tones changes between 0° and Φ (Here, Φ represents a phase angle of 180 degrees). A listener with normal hearing and sensitivity to binaural TFS perceives a pure tone with IPD=0° as close to the center of the head, while a tone with a large IPD is perceived as oriented toward the left or right ear, or both, or may be confused (*Figure 1*). For this reason, the subject is asked to recognize the distance over which the tones appear to change, for example, move inward, and to indicate the correct response after each presentation. The initial value of Φ is usually set to 180°, and Φ varies adaptively according to the 2-down 1-up rule. To converge on the estimate, the threshold corresponds to 71% of correct responses. The threshold is calculated geometrically based on the average value of Φ at the last six turn points [15]. The TFS-AF test, which stands for Adaptive Frequency, was developed to overcome a limitation of the TFS-LF test. Its structure is similar to the TFS-LF test, involving a forced choice between two intervals, each containing four successive tones at the same frequency. In one randomly selected interval, all four tones have the same IPD of 0°, while in the following interval, the IPD varies between 0° and Φ (180°) in the subsequent tones. The frequency is initially set to 200 Hz, as the setting is typically suitable for most individuals sensitive to IPD changes. The frequency then changes adaptively according to a 2-up 1-down rule, which helps facilitate convergence in estimating the threshold. This threshold corresponds to achieving 71% correct responses. The final threshold is calculated as the geometric mean of the frequencies encountered during the last six turn point [16].

Statistical analysis
The Shapiro-Wilk test was conducted to evaluate the normality of the data distribution. Considering the existence of two groups and multiple variables, and given the normal distribution, independent t-tests, repeated measures ANOVA, and the Bonferroni correction were utilized for intergroup and intragroup comparisons. Finally, Pearson's correlation coefficient was utilized to assess the relationship between TFS-LF and TFS-AF test results. The P-value less than 0.05 was considered statistically significant, and all statistical analyses were performed using IBM SPSS Statistics Version 17.

Results
Data analysis using Fisher's Exact Test (for gender distribution) and the Independent Samples Test (for the age factor) did not reveal any statistically significant differences between the two groups ($P > 0.05$), indicating that these two factors are not confounding. *Table 1* presents the descriptive statistics of TFS thresholds using TFS-LF

at three different frequencies (250, 500, and 750 Hz) for both participant groups. A logarithmic transformation was applied since the TFS-LF thresholds data in the sloping group were not normally distributed. After transformation, normality was confirmed using the Shapiro–Wilk test. As shown in *table 2*, Bonferroni-adjusted comparisons show significant differences in TFS-LF thresholds between frequencies (250, 500, and 750 Hz), with 95% confidence intervals reported ($p < 0.001$). A two-way repeated measures ANOVA was conducted to compare the mean of TFS-LF thresholds (250, 500, and 750 Hz) between two groups (sloping and rising or flat). Although the mean of TFS-LF thresholds at all three frequencies was higher in the sloping group than in the rising/flat group (*Figure 2*), this difference was not statistically significant , $F(1, 45) = 0.572$, $p = 0.453$, with a small effect size ($\eta^2 = 0.013$).

Table 3 presents the descriptive statistics of TFS thresholds using TFS-AF at two different IPDs (45° and 135°) for both participant groups. After confirming the normality of the data distribution, as shown in *Table 2*, Bonferroni-adjusted comparisons show significant differences in TFS-AF thresholds at 45° and 135°, with 95% confidence intervals reported ($p < 0.001$). A two-way repeated measures ANOVA was used to compare the mean of TFS-AF thresholds (45° and 135°) between the two groups. As illustrated in *Figure 3*, the average TFS thresholds in the sloping group were poorer than those in the rising or flat groups; nevertheless, the difference was not statistically significant $F(1, 45) = 0.414$, $p = 0.523$, with a very small effect size ($\eta^2 = 0.009$).

To explore the relationship between the TFS-AF and TFS-LF test results, we applied Pearson's correlation coefficient, considering the normal distribution of the TFS-AF test variables and the logarithmic transformation of the TFS-LF test values. The results showed that although both groups demonstrated a moderate negative correlationbetween the two tests ($r = 0.613$), the difference in correlation strength between the sloping and rising/flat groups was not statistically significant ($p > 0.05$) (*Figure 4*). Specifically, higher TFS-AF thresholds at different IPDs (45° and 135°) were associated with lower TFS-LF thresholds across the three tested frequencies (250, 500, and 750 Hz).

Discussion

This study investigated the impact of audiogram configuration on TFS sensitivity in young-to-middle-aged participants with mild to moderate sensorineural hearing loss. TFS thresholds were measured in degrees using the TFS-LF test at three frequencies (250, 500, and 750 Hz) and the TFS-AF test at two IPDs (45° and 135°). The results of the present study showed that the TFS-LF test threshold in the sloping group was poorer than that of the rising or flat group, although this difference was not statistically significant. Similar results have been reported in research evaluating the TFS sensitivity in different configurations of hearing loss. The results of the current study align with those of Lorenzi et al., who compared TFS sensitivity between two groups: individuals with normal hearing and those with high-frequency hearing loss. They found that normal hearing thresholds at low frequencies do not mean that TFS processing will work normally and that other factors, such as neural damage, may contribute to this issue [4]. Li et al. also conducted a study evaluating the impact of steep high-frequency SNHL (SHF-SNHL) on speech perception that uses TFS cues in the low-frequency region. Their research indicated that reduced TFS performance in low-frequency regions was correlated with decreased hearing abilities in high-frequency regions [19]. This could be related to disrupted auditory function, suggesting that damage to the basal regions (associated with high-frequency sounds) could indirectly affect the neural function of the apical regions (associated with low-frequency sounds) [25].

This study also evaluated the TFS threshold using the TFS-AF test at two different IPDs (45° and 135°) for both participant groups. The results indicated that the TFS threshold in the group with sloping hearing loss was poorer than in the group with rising or flat hearing loss, but this difference was not statistically significant. This finding aligns with the research conducted by Fullgrabe and Moore, which compared the TFS sensitivity between individuals with hearing loss and those with normal hearing. Their findings indicated that performance on the TFS-AF test does not necessarily correlate with hearing thresholds but may indicate a decline in the accuracy of neural timing processing rather than just a change in an individual's hearing threshold [26]. Additionally, an increase in the threshold for TFS-AF was also observed with increasing IPD. Mathew et al. also used the TFS-AF test to evaluate the TFS sensitivity among individuals with normal hearing and different configurations of hearing loss (ages 19 to 53 years). Their results indicated that TFS sensitivity is poorer in individuals with hearing loss compared to those with normal hearing and that an increase in IPD correlates with a rise in the TFS threshold [23].

The results of this study indicated a correlation between the TFS-LF and TFS-AF test thresholds, which aligns with the findings of Fullgrabe et al., their research demonstrated a moderate to strong correlation between scores on the TFS-LF and TFS-AF tests and, in fact, good TFS sensitivity, reflected by high-frequency thresholds in the TFS-AF test, is associated with low threshold values in degrees in the TFS-LF test. [16]. Additionally, this study found that age did not impact the results. Consequently, the decline in TFS sensitivity starts after middle age [23, 27].

TFS processing is a complex characteristic not determined solely by hearing thresholds. Other factors, such as age, the health of cochlear structures, the precision of neuronal timing, and individual differences, can significantly influence the outcome.

In this study, the sample sizes between the two groups differed. A study with a larger sample size could provide a more accurate picture of how TFS sensitivity changes with hearing loss at different frequencies. There are apparent individual differences in binaural TFS sensitivity. It is unclear whether these differences are due to individual processing efficiency, a specific feature of phase locking, or the binaural system.

Conclusion

This study's results indicate no statistically significant difference in sensitivity to temporal fine structure (TFS) between individuals with a sloping hearing loss pattern and those with a rising or flat pattern, as measured by TFS-LF and TFS-AF binaural tests. Moreover, absolute hearing thresholds at various frequencies do not solely influence TFS sensitivity. Since lower TFS sensitivity can reduce speech perception in noisy environments, hearing assessments and rehabilitation should not rely exclusively on audiograms. Instead, employing more precise performance assessments, such as TFS, can enhance the accuracy of diagnosing hearing issues and aid in designing effective interventions.

Ethical Considerations

Compliance with ethical guidelines

This study was approved by the Research Ethics Committee of Shahid Beheshti University of Medical Sciences (IR.SBMU.RETECH.REC.1403.150).

Funding Statement

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Acknowledgements

The authors would like to thank all participants for their cooperation in this study.

Author Contributions

SB: Study design, data collection, data analysis, interpretation of results, and drafting the manuscript. PRF: Study design, supervision, interpretation of results, and critical revision of the manuscript. AAB: Statistical analysis, interpretation of results, and critical revision of the manuscript.

All authors read and approved the final version of the manuscript.

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Table 1. Descriptive statistics of Temporal Fine Structure-Low Frequency thresholds (in degree) at different frequencies for Sloping and rising /flat groups.

TFS-LF	**Sloping (n= 32)**		**Rising / flat (n=15)**	
Frequency (Hz)	Mean (SD)	Min-Max	Mean (SD)	Min-Max
250	39.37(15.87)	16.00-83.50	36.44(8.82)	21.70-54.50
500	45.08(18.14)	13.30-82.70	40.13(10.39)	19.20-54.50
750	60.42(28.86)	25.70-137.20	49.90(14.96)	27.40-76.40

TFS-LF: Temporal fine structure-low frequency

Table 2. Pairwise comparisons of temporal fine structure (TFS) thresholds for both temporal fine structure-low frequency and temporal fine structure-adaptive frequency tests.

(I) TFS_LF	**(J) TFS_LF**	**Mean Difference (I-J)**	**Std. Error**	**Sig.[b]**	**95% Confidence Interval for Difference[b]**	
					Lower Bound	**Upper Bound**
Pairwise Comparisons (TFS-LF)						
250 Hz	**500 Hz**	-.047*	.016	.020	-.088	-.006
	750 Hz	-.153*	.017	.000	-.195	-.111
500 Hz	**750 Hz**	-.106*	.017	.000	-.148	-.064
Pairwise Comparisons (TFS-AF)						
45˚	135˚	-275.177*	20.541	.000	-316.523	-233.830

TFS-LF: temporal fine structure-low frequency, TFSA-AF: temporal fine structure-adaptive frequency

Table 3. Descriptive statistics of temporal fine structure-adaptive frequency thresholds (in Hz) at interaural phase differences (IPDs) of 45° and 135° for sloping and rising/flat groups.

TFS-AF	**Sloping (n=32)**		**Rising / flat (n=15)**	
IPD (°)	Mean (SD)	Min-Max	Mean (SD)	Min-Max
45	677.61(325.85)	66.90-1316.20	729.76(206.48)	399.60-1036.40
135	952.25(275.72)	476.30-1518.70	1006.10(178.19)	734.20-1390.20

TFS-AF: Temporal fine structure-adaptive frequency, IPD: Interaural phase difference

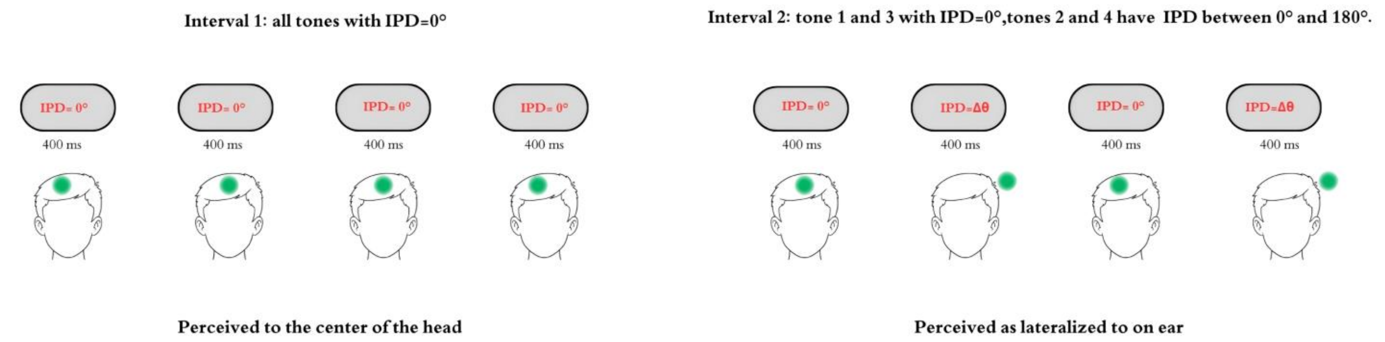

Figure 1 Schematic illustration of the temporal fine structure-low frequency and temporal fine structure-adaptive frequency task.

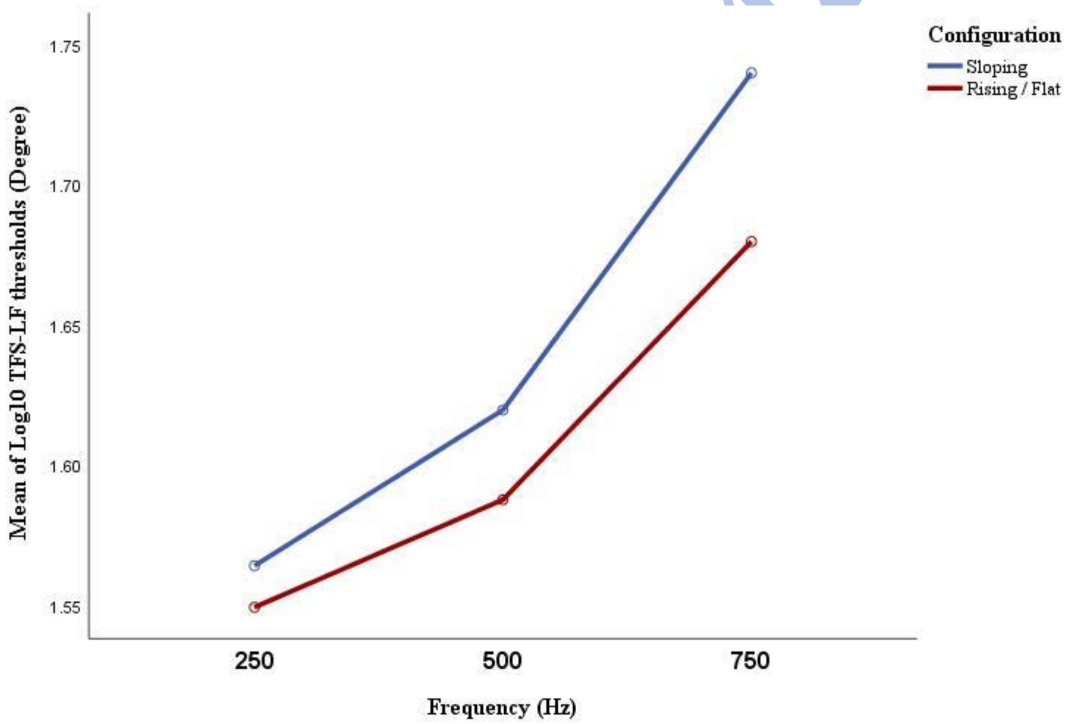

Figure 2. The mean of Log10-transformed TFS-LF thresholds (in degrees) at 250, 500, and 750 Hz for participants with sloping and rising or flat audiometric configurations.

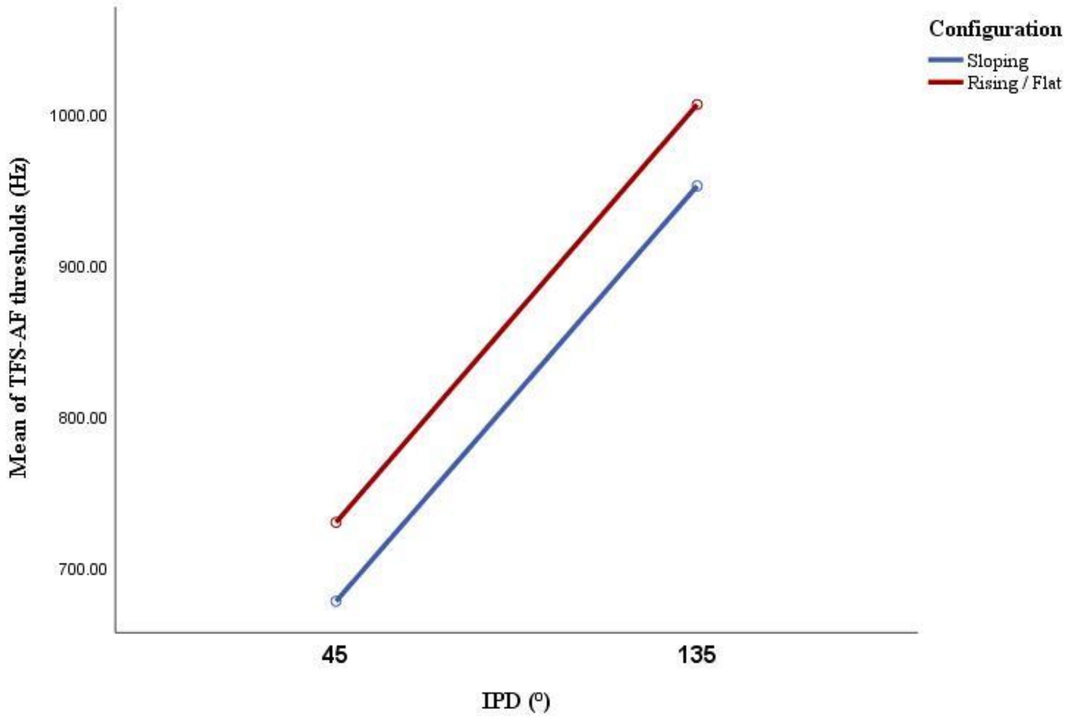

Figure 3. The mean of TFS-AF thresholds (in Hz) at interaural phase differences (IPDs) of 45° and 135° Hz for participants with sloping and rising or flat audiometric configurations.

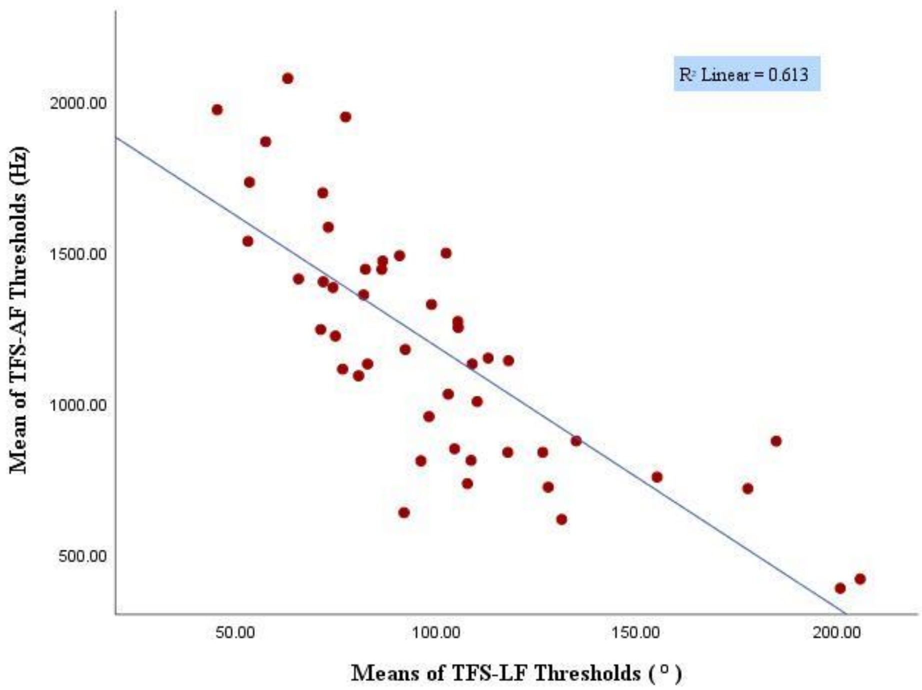

Figure 4. Pearson correlation between the average thresholds of the TFS-LF and the TFS-AF test.