Research Article

Effect of Audiometric Configuration on Binaural Temporal Fine Structure Sensitivity in Adults with Sensorineural Hearing Loss

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Short running title: Effect of Audiometric Configuration on…

Highlights:
- Binaural TFS sensitivity is not different between sloping and rising/flat audiograms
- Binaural TFS sensitivity is not solely determined by hearing thresholds
- TFS-LF and TFS-AF 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 audiogram configuration remains unclear. Therefore, this study aimed to compare binaural TFS sensitivity in adults with Sensorineural Hearing Loss (SNHL) having different audiogram configurations.

Methods: This comparative cross-sectional study included 47 adults (32 with sloping audiograms, 15 with rising/flat audiograms) 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 lower in the sloping group at all frequencies, but the difference between the two groups was not significant (p>0.05). For the TFS-AF test, thresholds at IPD 135° were significantly higher than at IPD 45° (p<0.001), but the difference between the two groups was not significant. Significant correlations were observed between the TFS-LF and the TFS-AF thresholds (r=–0.783, p<0.001).
Conclusion: There is no significant difference in TFS sensitivity between adults with sloping and rising/flat audiograms. Absolute hearing thresholds at various frequencies do not solely influence TFS sensitivity; factors such as cochlear health, neural timing, and individual variability may also affect the outcome.
Keywords: Temporal fine structure; sensorineural hearing loss; configuration; interaural phase difference

Introduction

The auditory system encodes sound through two primary temporal components: Envelope (ENV) and 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 in the timing of neural discharges, TFS conveys the rapid oscillations of a sound waveform through the phase locking of auditory nerve fibers. These fine temporal cues are essential for binaural unmasking, pitch perception, and spatial hearing. 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 have indicated 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, including degraded phase locking, broadened auditory filters, and central compensatory changes. Interestingly, even when low-frequency hearing thresholds are within normal range, 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 [14].
Several tests have been developed to assess TFS sensitivity. Among them, the TFS-Low Frequency (TFS-LF) test evaluates binaural sensitivity to Interaural Phase Difference (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 test, the stimulus frequency changes adaptively while IPD is manipulated, enabling estimation of the highest frequency at which reliable phase locking can occur. Thus, although 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 significantly poorer performance compared to the normal-hearing group in speech perception, 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 three groups. Senior adults with hearing loss demonstrated poorer TFS sensitivity than younger and older adults with normal hearing. This suggests that TFS sensitivity decreases with age and hearing impairment [20]. King et al. examined the impact of age and hearing impairment on TFS sensitivity in 46 subjects with mild to moderate

SNHL utilizing the TFS-IPD test. A positive correlation was identified between the absolute threshold and TFS-IPD; however, it had no relationship with ENV-IPD. The findings indicated that hearing loss independently affects TFS sensitivity, regardless of age [21]. Moore and Sek evaluated TFS sensitivity in 22 participants using the TFS-AF test. The results indicated that TFS sensitivity declines with ageing and decreased hearing ability [22]. Matthew et al. conducted a study to evaluate the TFS sensitivity in 30 individuals with normal hearing and 30 individuals with various configurations of hearing loss (sloping, rising, and flat), aged 19–53 years. The TFS-AF test was conducted at IPD 30°, 60°, and 90°. The results showed that those with normal hearing had a greater TFS sensitivity than individuals with hearing loss [23].

Previous studies have mainly focused on comparing individuals with hearing loss and normal hearing, often without considering the audiogram configuration or matching for age. Lorenzi et al. reported that individuals with mild to moderate high-frequency SNHL had significantly poorer performance in speech tasks relying on TFS cues [4]. Few studies have examined how specific audiogram shapes (e.g., sloping, flat, 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 audiogram configurations, while controlling for age (18–50 years). The goal was to investigate the effect of audiogram shape on binaural TFS encoding, regardless of the old age factor.

Methods

This is a comparative cross-sectional study. The study was conducted at the audiology clinic of shahid beheshti university of medical sciences, Tehran, Iran, in 2024, and included patients with bilateral hearing loss (mean age: 37.47±7.94 years). The inclusion criteria were age 18–50 years, having mild to moderate bilateral hearing loss (26–55 dB) at the frequency range of 250–8000 Hz for both air and bone conduction thresholds, having a normal outer ear (as determined by otoscopic examination), having normal middle ear status (Type A tympanogram), right-handedness, and no signs of cognitive impairment based on the Montreal cognitive assessment score (≥26). We included 47 individuals (35 males, 12 females), 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 of 250–8000 Hz. For classification, we used the better-ear audiogram (i.e., the ear with a lower pure-tone average), calculated as the mean threshold across the mentioned frequencies. The audiograms were categorized as follows: sloping shape: Mean high-frequency threshold (average of thresholds at 2000, 4000, and 8000 Hz) was ≥20 dB HL lower than the mean low-frequency threshold (average of thresholds at 250 and 500 Hz). Rising shape: mean low-frequency threshold (average of thresholds at 250 and 500 Hz) was ≥20 dB HL lower than the mean high-frequency threshold (average of thresholds at 2000, 4000, and 8000 Hz). Flat shape: 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 TFS-LF and TFS-AF tests, employing psychoacoustic software on an HP EliteBook 840 G5 laptop and BY-HP2 headphones.

In the TFS-LF test, 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 a 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 (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 towards the left or right ear, or both (Figure 1). For this reason, the subject is asked to recognize the distance over which the tones appear to change (e.g., moving 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 structure is similar to that of 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 the 2-up/1-down rule, which helps facilitate

convergence in estimating the threshold. This threshold corresponds to achieving 71% of correct responses. The final threshold is calculated as the geometric mean of the frequencies encountered during the last six turn points [16].
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-test, repeated measures ANOVA, and the Bonferroni correction were utilized for group comparisons. Pearson's correlation test was utilized to assess the relationship between TFS-LF and TFS-AF test results. $p<0.05$ was considered statistically significant. All statistical analyses were performed in SPSS v.17 software.

Results
The results of Fisher's Exact Test for the gender factor and the results of the independent t-test for the age factor showed no significant differences between the two groups of sloping and rising/flat audiogram configurations ($p>0.05$), indicating that these two factors were not confounding. Table 1 presents the mean TFS-LF thresholds (mean±SD) at 250, 500, and 750 Hz for both groups. Because TFS-LF thresholds in the sloping group were not normally distributed, a logarithmic transformation was applied and normality was subsequently confirmed by the Shapiro-Wilk test. A two-way repeated-measures ANOVA showed a significant main effect of frequency on TFS-LF thresholds ($F_{(2,90)}=43.74$, $p<0.001$), indicating differences across frequencies. The interaction between frequency and configuration was not significant ($F_{(2,90)}=0.93$, $p=0.398$). The between-subjects effect of configuration was also non-significant ($F_{(1,45)}=0.57$, $p=0.453$, $\eta^2=0.013$), indicating that the overall pattern across frequencies did not differ between the sloping and rising/flat groups. Therefore, pairwise comparisons (Bonferroni-adjusted) were performed on the total sample, and TFS-LF thresholds differed between 250 and 500 Hz ($p=0.020$), between 250 and 750 Hz ($p<0.001$), and between 500 and 750 Hz ($p<0.001$) (Table 2). Although the mean TFS-LF thresholds were higher in the sloping group at three frequencies, this difference was not statistically significant (Figure 2).
Table 3 presents the mean TFS-AF thresholds at two different IPDs (45° and 135°) for both groups. A two-way repeated-measures ANOVA revealed a significant main effect of IPD on TFS-AF thresholds, $F_{(1,45)}=152.943$, $p<0.001$), indicating that thresholds differed between 45° and 135°. The interaction between IPD and configuration was not significant ($F_{(1,45)}=0.001$, $p=0.970$), and the between-subjects effect of configuration was also non-significant ($F_{(1,45)}=0.414$, $p=0.523$, $\eta^2=0.009$). Although the mean TFS-AF thresholds in the sloping group were slightly lower than those in the rising/flat group, this difference was not statistically significant.
Based on Pearson's correlation test results, although both groups demonstrated a significant negative correlation between the TFS-AF and TFS-LF test results ($r=-0.783$, $p<0.001$) (Figure 3), the difference in correlation degree between the sloping and rising/flat groups was not statistically significant ($p>0.05$). Specifically, higher TFS-AF thresholds at different IPDs (45° and 135°) were associated with lower TFS-LF thresholds across the three 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 SNHL. The 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 showed that the TFS-LF threshold in the sloping group was lower than that in the rising/flat group, although this difference was not statistically significant. The results are consistent with those of Lorenzi et al., who compared TFS sensitivity between two groups of normal hearing and high-frequency SNHL. They found that normal hearing thresholds at low frequencies do not necessarily mean that TFS processing works normally, as other factors, such as neural damage, may also contribute to this issue [4]. Li et al. also conducted a study evaluating the impact of steep high-frequency 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) can indirectly affect the neural function of the apical regions (associated with low-frequency sounds) [25].
Our study also compared the TFS thresholds using the TFS-AF test at two different IPDs (45° and 135°) between sloping and rising/flat groups. The results indicated that the TFS thresholds in the group with a sloping audiogram configuration were lower than in the group with a rising/flat configuration, but this difference was not statistically

significant. This finding aligns with the findings of Fullgrabe and Moore, who compared the TFS sensitivity between individuals with hearing loss and those with normal hearing. Their findings suggested 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]. Mathew et al. also used the TFS-AF test to evaluate the TFS sensitivity among individuals with normal hearing and those with different configurations of hearing loss (aged 19–53 years). Their results indicated that TFS sensitivity was lower in individuals with hearing loss compared to those with normal hearing and that an increase in IPD was correlated 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., who demonstrated a moderate to strong correlation between the TFS-LF and TFS-AF test scores; i.e., a good TFS sensitivity, reflected by high-frequency thresholds in the TFS-AF test, is associated with low thresholds in the TFS-LF test. [16]. Additionally, in our study, age did not significantly affect the results, suggesting that age-related decline in TFS sensitivity typically begins after middle age [23, 27]. TFS processing is a complex characteristic that is not determined solely by hearing thresholds. Other factors, such as health of cochlear structures, the precision of neuronal timing, and individual differences, can significantly influence the outcome. In this study, the sample size of the two groups was small. A study with a larger sample size can 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. A study needed to assess whether these differences are due to individual processing efficiency, a specific feature of phase locking, or the binaural system.

Conclusion

There is no statistically significant difference in Temporal Fine Structure (TFS) sensitivity (measured by TFS-low frequency and TFS-adaptive frequency tests) between adults with sloping audiogram configuration and those with a rising/flat pattern. 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 solely on audiograms. Instead, employing more precise performance assessments, such as TFS sensitivity, can enhance the accuracy of diagnosing hearing issues and help 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).

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Authors' 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.

Conflict of interest

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

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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

	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 thresholds for temporal fine structure-low frequency test

					95% confidence interval for difference*	
TFS-LF	**TFS-LF**	**Mean difference**	**Std. error**	**p**	**Lower bound**	**Upper bound**
250 Hz	**500 Hz**	–0.047	0.016	0.020	–0.088	–0.006
	750 Hz	–0.153	0.017	<0.001	–0.195	–0.111
500 Hz	**750 Hz**	–0.106	0.017	<0.001	–0.148	–0.064

TFS-LF; temporal fine structure-low frequency
* Bonferroni (adjustment for multiple comparisons)

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

	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

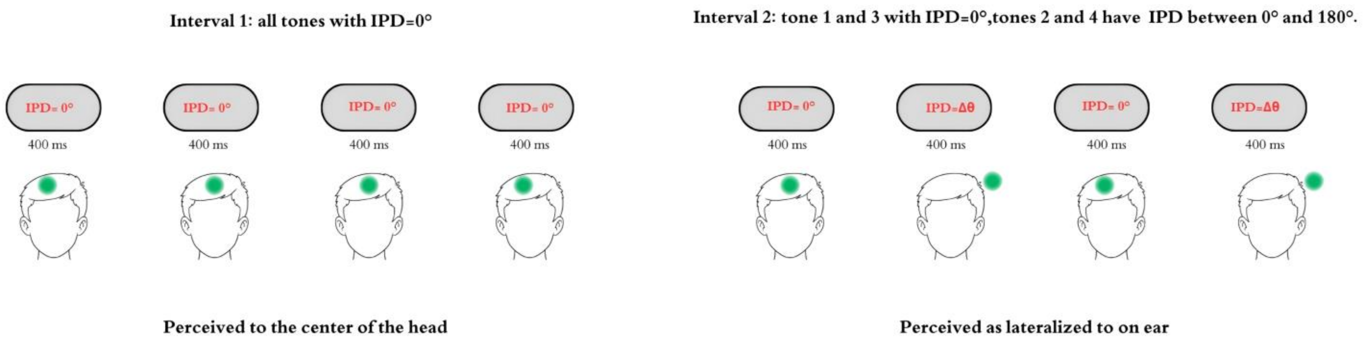

Figure 1. Schematic illustration of the temporal fine structure-low frequency and temporal fine structure-adaptive frequency task. IPD; interaural phase difference

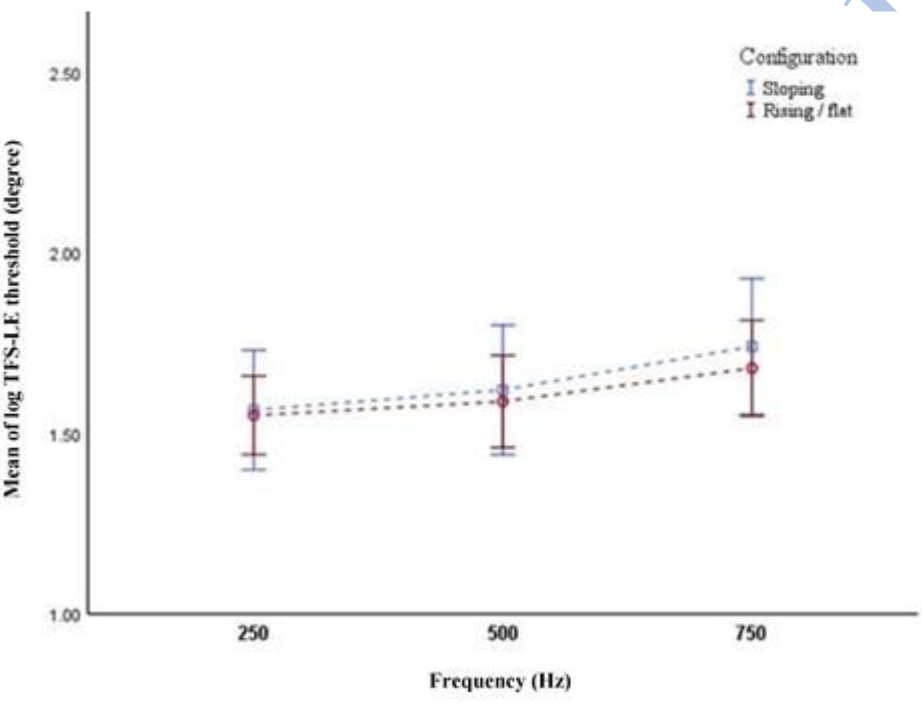

Figure 2. The mean of Log10-transformed temporal fine structure-low frequency thresholds (in degrees) at 250, 500, and 750 Hz for participants with sloping and rising or flat audiometric configurations. TFS-LF; temporal fine structure-low frequency

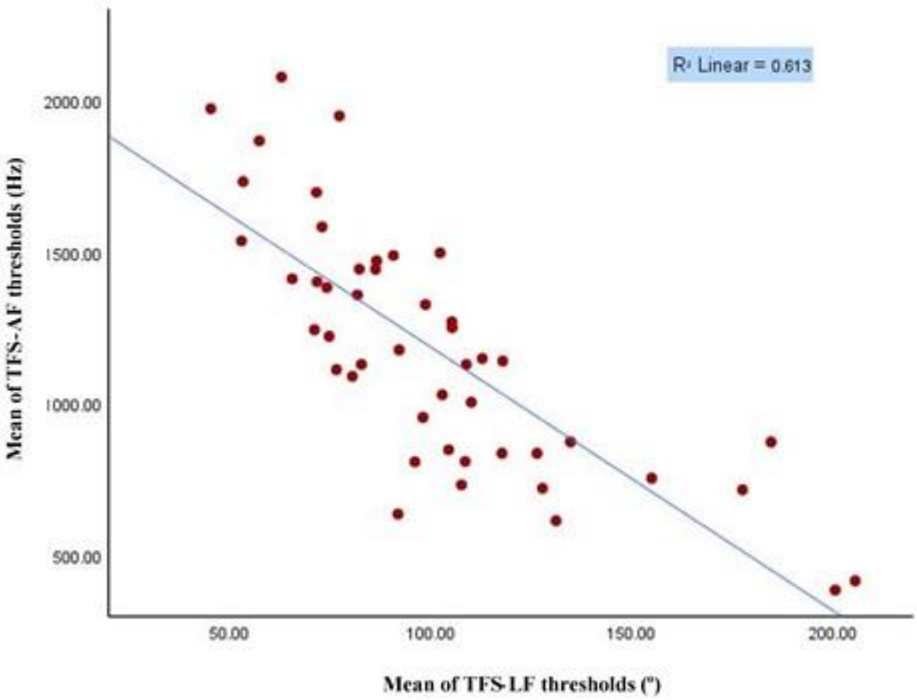

Figure 3. Pearson correlation between the average thresholds of the temporal fine structure-low frequency and the temporal fine structure-adaptive frequency test. TFS-AF; temporal fine structure-adaptive frequency, TFS-LF; temporal fine structure-low frequency