Auditory and Vestibular Research

The Early Aging Temporal Processing: Evidence from Temporal Modulation Transfer Function with Background Noise

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Highlights:
Temporal processing begins to decline after mid-30s, specifically in noisy condition
Evaluating temporal processing in background noise reveals early age-related changes
A stronger correlation is obtained between TMTF measures in noise and SNR50

Abstract
Background and Aim: Temporal processing deficits are reported to contribute to speech perception difficulties in noise. However, traditional temporal resolution tasks, which are often conducted in quiet conditions, may not always reflect a noticeable decline in temporal resolution abilities until individuals reach their late 40s or 50s. By examining temporal processing under background noise, this study aimed to provide new insights into the early manifestations of age-related auditory decline and its impact on speech perception in noise among early adulthood.
Methods: A Cross-Sectional 4 x 2 mixed Comparative Research Design was implemented, with four levels of between-group variables (age groups) and two levels of testing conditions (quiet vs noise). Eighty participants with normal hearing were recruited across four groups within the age range of 20-40 years. Temporal modulation transfer function (TMTF)was measured under a quiet and noisy background for broadband stimuli for nine modulation frequencies (2Hz - 512Hz). Signal-to-Noise Ratio-50% (SNR50) was measured using an adaptive procedure for nonsense words.
Results: One-way Analysis of Variance revealed a significant age-related decline in TMTF after 35 years, with a more pronounced deterioration in noisy conditions, particularly at higher modulation frequencies. Paired t-test revealed a significant impact of background noise became more evident after this age. Additionally, correlation analysis showed a stronger relationship between peak sensitivity, bandwidth, and SNR50 in noisy conditions.
Conclusions: The study concludes that assessing temporal processing in background noise can effectively detect early changes and better explain speech perception difficulties in noisy environments.
Keywords: Early changes, aging, temporal processing, temporal modulation transfer function, modulation detection

Introduction
Speech perception is a complex phenomenon that involves both language and auditory processing. It is influenced by various factors such as rate of speech , background noise , signal-to-noise ratio , age , knowledge of the language , cognitive abilities , and temporal and spectral context (1). As age progresses, the auditory system undergoes several structural and functional changes at both peripheral and central levels. One of the adverse effects of these age-related changes is speech perception difficulty, especially in adverse listening situations. The perceived difficulty can be attributed to age-related hearing loss, primarily affecting high-frequency sounds, resulting in the loss of phonetic information crucial for speech perception in noisy environments (2). However,

digital hearing aids that can restore sufficient frequency-specific audibility have been shown to fail in improving speech perception in noise up to the expectation (3)suggesting that age-related changes beyond audibility may be contributing to the speech perception difficulty (4).

Literature reports evidence that temporal processing abilities play a vital role in perceiving speech, especially in noisy situations, and are also found to deteriorate with aging (5). Normal temporal processing abilities are crucial for various auditory processing capabilities such as perception of pitch and identification of voice (6). Additionally, temporal fine structure processing is crucial for the extraction of speech from fluctuating noise (7). The age-related decline in temporal resolution is one of the factors contributing to poor speech perception in noise seen with aging, despite normal audiograms (8). Disturbances in neural synchrony due to aging could be the causative factor for the deficit in temporal processing and speech recognition abilities (9). Available literature states that this decline in temporal processing abilities initiates after the 4th or 5th decade of age (10,11).

Often, some background noise will be present in everyday listening situations, which can mask or distort the available temporal cues by reducing the modulation depth in the temporal envelope of the target signal (12). These obscured temporal cues can significantly impact speech recognition, even in individuals with normal hearing sensitivity (13,14). Thus, the ability to follow these amplitude variations is highly critical to recognizing speech in noisy conditions. Recent studies have shown that individuals might have damage in the cochlea without any effect on their hearing sensitivity but their temporal processing and speech perception abilities in background noise situations deteriorated and may show poor performance in tests such as gap detection tests and modulation detection tests (5,14). This underscores the importance of temporal processing in daily listening environments, including the perception of speech in background competing noise.

Temporal processing is widely assessed using temporal resolution tasks. Among the different techniques to assess temporal acuity, the TMTF is widely implemented in clinical research. It estimates the minimum modulation depth needed to detect the presence of amplitude modulation in the carrier frequency signal across different modulation rates, yielding a Temporal Modulation Transfer Function- TMTF (15), and it results in representative measures such as peak sensitivity and bandwidth (15). There is a well-established correlation between the measures obtained from TMTF (Peak sensitivity, bandwidth, MDT) and speech perception in noise (2,11).

However, traditional temporal resolution tasks, which are often conducted in quiet listening conditions, may not always reflect a noticeable decline in temporal resolution abilities until individuals reach their late 40s or 50s. This finding is inconsistent with real-world experiences, as many younger adults also report difficulties understanding speech in adverse listening environments. If temporal processing abilities were truly preserved until late adulthood, this would not explain why younger individuals struggle in adverse listening conditions.

One possible explanation for this discrepancy is that standard temporal resolution tasks are performed in a quiet background, whereas real-world listening challenges occur in the presence of competing noise. In noisy situations, listeners must extract and process temporal cues despite the presence of masking sounds, which likely requires more refined temporal resolution skills. As a result, traditional assessment methods may underestimate temporal processing deficits in some younger individuals who might experience difficulty understanding speech in adverse listening environments despite normal hearing sensitivity.

Therefore, assessing temporal processing abilities in the presence of background noise, rather than in quiet conditions, may provide a more accurate representation of age-related changes in auditory processing. Such an approach could help determine whether these changes contribute to the speech perception difficulties experienced by individuals below the age of 50 in noisy environments. Temporal processing in adverse conditions could be an early indicator of aging and a decline in speech perception abilities (5). Based on this premise, the present study was designed to evaluate temporal processing in both quiet and noisy conditions among four groups of young adults in the age range of 20-40 years and to correlate these findings with speech perception in noise (SPIN) performance. By examining temporal processing under ecologically relevant conditions, this study aimed to provide new insights into the early manifestations of age-related auditory decline and its impact on speech perception.

Methods

A cross-sectional 4 × 2 mixed comparative research design was implemented, incorporating four levels of age groups as the between-group variable and two levels of testing conditions (quiet vs. noise) as the within-group variable. The study was conducted in the audiology laboratory of a multidisciplinary university located in southern India, within an acoustically treated, soundproof room that maintained ambient noise levels in accordance with ANSI standards (ANSI/ASA S3.1-1999 (R2018)).

Participants: A total of 80 participants were recruited under four cross-sectional age groups ranging from 20 to 40 years. The groups were defined as: Group A (20–25.11 years), Group B (26–30.11 years), Group C (31–35.11 years), and Group D (36–40 years). Each group comprised 20 participants. The mean ages and standard deviations for each group were: Group A (M = 22.2, SD = ±1.23), Group B (M = 26.1, SD = ±0.78), Group C (M = 32.65, SD = ±1.26), and Group D (M = 38, SD = ±1.48). An equal male-to-female ratio was maintained across all groups. All participants were literate. Group A participants were enrolled in undergraduate programs, while Group B included individuals pursuing postgraduate or doctoral studies. Participants in Groups C and D were full-time faculty members at the university. A purposive recruitment strategy was employed. Prior to participant recruitment, permission was obtained from departmental heads and faculty coordinators for outreach. An internal advertisement was circulated within the university, inviting volunteers. Those who expressed interest were subsequently screened for eligibility based on inclusion and exclusion criteria. All participants had a pure-tone average (PTA) of ≤15 dB HL across 500 Hz, 1 kHz, 2 kHz, and 4 kHz. Immittance evaluations confirmed normal middle-ear function and auditory nerve integrity, as evidenced by an A-type tympanogram and the presence of ipsilateral and contralateral reflexes for broadband noise. Transient-evoked otoacoustic emissions (TEOAEs) confirmed normal outer hair cell function. Additionally, participants scored <6 on the SCAP-A (Screening Checklist for Auditory Processing in Adults) checklist (16), ruling out any risk of central auditory processing disorder (CAPD). This particular checklist has 12 questions that tap auditory separation/closure, auditory integration, temporal ordering, as well as memory and attention. Individuals with a history of otological or neurological disorders were excluded. Further, none of the participants were trained musicians, nor did they report any history of sudden exposure to high-impact noise. However, formal cognitive assessments were not conducted, which may be considered a limitation of the study. Additionally, the duration of headphone usage was not quantified, representing another potential limitation.

Procedure:

The study adhered to the ethical guidelines outlined in the Helsinki Declaration. All participants provided informed written consent before testing. All the participants underwent assessment for Temporal Processing Abilities and Speech Perception Abilities. The Temporal Processing Abilities were assessed using the Temporal Modulation Transfer Function (TMTF) under quiet and in background noise (5dBSNR). SNR-50 was obtained for nonsense CVCV words to assess the speech perception abilities.

Temporal Modulation Transfer Function: The stimuli consisted of 3 intervals of 500ms Gaussian noise (BBN), one of which was sinusoidally modulated with 20ms of cosine ramp at nine modulation frequencies (2, 4, 8, 16, 32, 64, 128, 256, and 512 Hz) and was presented at 60 dB SPL through Sennheiser HDA 200 circum-aural headphones. The procedure employed the 3AFC method, where the participants were instructed to identify the modulated interval out of 3 trials. The BBN was considered instead of any tones in order to avoid possible spectral cues. The modulation detection thresholds (MDTs) were estimated using a 2 down-1 up adaptive procedure with the help of MLP toolbox in MATLAB where, modulation depth was varied based on participants responses and 70.7% criterion point on psychometric function was considered as MDT. MDT was measured in dB using the following equation

MDT in dB= 20 log10m where, m= modulation depth in %

Further MDTs were plotted across nine modulation frequencies to derive TMTF, which resembled a lowpass filter function. Further TMTF data was fitted to a low-pass Butterworth filter (17) with the following regression equation using a MATLAB code (18) from which the peak sensitivity and bandwidth measures were obtained.

Regression equation is m = a+20*log10(1+(mf/b)^2

Where m is MDT, a is the peak sensitivity, ms is the modulation frequency and b is the bandwidth with 3dB cutoff frequency. Peak sensitivity is the modulation frequency where a listener is most responsive to amplitude changes, shown by the lowest MDT. It marks the point where even small fluctuations are easily detected. TMTF bandwidth refers to the range of modulation frequencies where sensitivity remains high before it starts to decline, usually identified by the cut-off frequency.

The Experiment was carried out on a personal computer and the stimulus was routed through a double-channel audiometer. Modulation detection thresholds were measured twice, once under quiet conditions and another in the presence of SSN at +5dBSNR presented ipsilaterally to the stimulus ear through the audiometer. The order of testing conditions (quiet vs noise) was randomized to avoid order effects.

Signal-to-Noise Ratio-50% (*SNR-50):* The SPIN test was conducted using the Smriti-Shravan software (19). The test employed nonsense CVCV words as stimuli as it helps in minimizing semantic influences and focusing solely on acoustic-phonetic processing(bottom-up) for speech perception. Speech shaped noise was used as a competing noise. SSN used for the experiment exhibited a similar spectrum as of the LTAS (Long-Term Average Spectrum) of uploaded nonsense words and RMS level matched that of nonsense words which was generated using a customized MATLAB code. The stimulus was presented using an adaptive method in which the SNR was varied in a 3 down 1 up procedure based on the response at a 2 dB step size. 8 such reversals were carried out and the midpoint of the last 6 reversals provided the SNR 50.

Statistical Analysis: The statistical analysis was carried out using JASP software. The Shapiro-Wilk test of normality was implemented to evaluate the distribution of data. All the data except bandwidth data was found to have a normal distribution($p>0.05$). Thus, parametric tests were considered for inferential statistics except for the analysis of bandwidth.

RESULTS

Comparison of MDTs across the age groups in both quiet and noise conditions.

Descriptive analysis of the MDTs revealed a clear age-related trend across the four groups. Group D (oldest) exhibited the highest MDTs, indicating the poorest temporal processing performance, whereas Group A (youngest) demonstrated the lowest MDTs, reflecting the best performance. This trend was consistent across both quiet and noise conditions as depicted in Figure 1. Results of one-way ANOVA revealed a statistically significant effect of age group on MDT at all modulation frequencies in the quiet condition. Similarly, even in the noise condition, it indicated a significant difference in MDTs across age groups at all modulation frequencies (Table 1).

Further post hoc analysis using Tukey's test post hoc test revealed no significant difference in MDT between groups A vs B at all the modulation frequencies (MF). In contrast, comparisons between Groups B and C showed a significant difference in MDTs only for higher MFs(>16Hz), whereas lower MFs(2Hz-16Hz) did not demonstrate a significant difference. Comparison of MDT between Groups C and D demonstrated significant differences across all modulation frequencies (Table 2).

Comparison of peak sensitivity (PS) and bandwidth (BW) across the age groups in both quiet and noise conditions.

The descriptive statistics showed a comparable PS & BW across first three age groups, whereas the decline (higher PS & Lower BW) was observed only in group D. Results of One-way ANOVA showed a significant difference in PS across age groups at both quiet (PS ($F(3)=5.023$, $p=0.003$, $\eta^2=0.165$); and noise condition (PS ($F(3)=8.902$, $p<0.01$, $\eta^2=0.260$). Further, Tukey's post hoc analysis was done, which showed no significant difference in PS obtained between A vs B ($t=0.190$, $p=0.998$) and B vs C ($t=0.064$, $p=1.000$). Whereas, a significant difference was found between the C and D age groups in the quiet condition ($t=-3.259$, $p=0.009$). Similarly, in the noise condition, no significant difference in PS was obtained between A vs B ($t=-0.072$, $p=1.000$) and B vs C ($t=0.064$, $p=1.000$). Whereas, a significant difference was found between the C and D age groups ($t=-4.318$, $p<0.01$).

Results of the Kruskal-Wallis showed a significant difference in BW across the age group in both quiet ($H(3)=13.450$, $p<0.05$, $\eta^2=0.137$) and noise conditions ($H(3)=17.674$, $p<0.05$, $\eta^2=0.193$). Further, Dunn's post hoc analysis showed no significant difference in BW obtained between A vs B ($z=0.621$, $p=0.535$) and B vs C ($z=0.632$, $p=0.528$). Whereas, a significant difference was found between the C and D age groups ($z=2.155$, $p<0.05$). Similarly, in the noise condition, there was no significant difference in PS obtained between A vs B ($z=1.841$, $p=0.066$) and B vs C ($z=0.096$, $p=0.923$). Whereas, a significant difference was found between the C and D age groups ($z=2.206$, $p<0.05$).

Additionally, Pearson correlation analysis revealed a significant positive correlation between PS and age in both the quiet ($r=0.299$**, $p<0.05$) and noise situation ($r=0.388$***, $p<0.05$). Results of Spearman correlation analysis revealed a significant negative correlation between PS and age in both the quiet ($r_s=-0.393$***, $p<0.05$) and noise situation ($r_s=-0.453$***, $p<0.05$) (Figure 2).

Comparison of SNR50 across age groups

The descriptive analysis indicated an age-related decline in SNR-50 scores, with Group A achieving the lowest SNR-50 (better) and Group D exhibiting the highest SNR-50 (poorer) as depicted in (Figure 3). The descriptives also depicts a relatively more dispersion of data on last group and it could be due to the greater variability in cognitive functions (e.g., attention, working memory) in the older age group. This trend was statistically confirmed by a one-way ANOVA, which showed a significant effect of age on SNR-50 ($F(3) = 12.250$, $p < 0.001$, $\eta^2 = 0.326$). Post-hoc analysis using Tukey's test revealed no significant difference between Groups A and B ($t = -0.092$, $p = 1.000$). However, a significant difference was observed between Groups B vs C ($t = -2.914$, $p = 0.024$) and Groups C vs D ($t = -2.055$, $p = 0.177$)

Comparison of MDTs between Quiet and Noise Conditions:

The descriptive analysis revealed that modulation detection thresholds (MDTs) were consistently better in quiet conditions compared to noise across all age groups. Additionally, as age increased from Group A to Group D, the difference between MDTs in quiet and noise conditions became more pronounced (Figure 4). This trend was further supported by inferential statistics, where a paired t-test demonstrated significant differences between MDTs in quiet and noise across all modulation frequencies for each age group, as depicted in Table 3.

Comparison of Peak Sensitivity and bandwidth between Quiet and Noise Conditions:

The descriptive analysis showed relatively better PS in the quiet condition as compared to the noisy condition for all four age groups. A mixed modal analysis of variance for repeated measures with 2 levels of testing conditions (quiet and noise) as within-group variables and 4 levels of age group as between-group variables showed a significant main effect of PS on testing conditions (PS ($F(1) = 170.043$, $p<0.05$, $\eta^2=0.135$) and on the age group (PS ($F(3) = 7.590$, $p<0.05$, $\eta^2=0.184$). It was also found that a significant interaction effect was obtained between the testing condition and age group for PS ($F(3) = 3.171$, $p<0.05$, $\eta^2=0.008$). This indicates that the difference in the peak sensitivity obtained between quiet and noise conditions was not the same for all the age groups. It was further confirmed by the results of a paired t-test, which revealed a significant impact of background noise on peak sensitivity (Group A ($t=-10.482$, $p<0.05$); Group B ($t=-11.995$, $p<0.05$); Group C ($t=-4.091$, $p<0.05$); Group D ($t=-7.217$, $p<0.05$)).

The results of bandwidth were in contrast with the results of peak sensitivity as confirmed by the results of the Wilcoxon signed-rank test, showing no significant difference (p-value>0.05) on BW for both the quiet and noise conditions across all groups.

Correlation of peak sensitivity and bandwidth with SNR50

Pearson correlation analysis revealed a significant positive correlation between PS and SNR50 in both testing conditions with a relatively better correlation coefficient in the quiet condition ($r=0.277$, $p<0.05$) than in Noise ($r=0.403$, $p<0.05$). Similarly, Spearman's correlation analysis revealed a significant negative correlation between BW and SNR50, with a relatively better correlation coefficient in quiet conditions ($rs=-0.300$, $p<0.05$) than in Noise ($r=-0.349$, $p<0.05$) (Figure 5)

Discussion

The present study was conducted to explore the age-related changes in temporal processing abilities measured under silence and noisy conditions in order to investigate the early changes in young adults, which could possibly be a contributing factor for the challenges faced by normal hearing individuals for speech perception in noisy situations.

Age-Related Differences in Modulation Detection Thresholds, Peak Sensitivity & Bandwidth

The findings indicate a gradual decline in MDTs with increasing age from 20-40 years. While MDTs remained relatively stable during early adulthood and the late 20s, a noticeable deterioration was observed only after the age of 35 (Group C). This decline was consistent across both testing conditions, with a relatively pronounced decline observed in noisy conditions. Previous studies (20, 21) have attributed such declines to reduced neural synchrony and weakened phase-locking abilities, though they primarily compared younger (18–30 years) and older (60–80 years) adults, overlooking changes within midlife. In contrast, Kumar et al. (10)examined a broader age range (20–85 years) and reported that sensitivity declines become more pronounced after 40. However, our findings suggest an even earlier onset, with noticeable deterioration beginning around 35 years. This downward trend in temporal processing is evident, yet MDT thresholds remain within normal limits. A key factor contributing to this earlier decline may be the time gap between previous studies and our research, which is being conducted nearly 15 years later. Over this period, lifestyle patterns have changed significantly, with individuals experiencing greater exposure to environmental noise daily. Increased noise pollution, combined with evolving modern lifestyles, may have accelerated auditory aging. Previous studies (22- 24) have reported that prolonged noise exposure negatively impacts both auditory and cognitive functions and is a major contributor to reduced temporal processing.

Results also revealed a low-pass filtering effect, where participants showed greater sensitivity to lower modulation frequencies (2–64 Hz) and reduced sensitivity at higher frequencies (>64 Hz). This occurs because slower amplitude fluctuations are easier to perceive, while faster modulations exceed the auditory system's temporal resolution capacity. This pattern aligns with previous studies (15, 25) , which found MDT sensitivity declines beyond ~50 Hz and attributed to difficulties in resolving rapid fluctuations. Age-related reductions in neural synchrony (10) further exacerbate this effect, resembling patterns observed in individuals with auditory neuropathy spectrum disorder (2, 26) demonstrating elevated thresholds at higher modulation frequencies. Our findings suggest that a comparable decline in temporal processing may be present in early-aging populations. This suggests that early-age-related declines in temporal processing begin with reduced sensitivity to faster modulations.

Analysis of PS and BW showed that PS increased and BW narrowed with age, particularly after the mid-30s, indicating a decline in temporal modulation detection abilities. This decline was evident in both quiet and noise conditions but was more pronounced in noise. Younger participants exhibited lower PS and wider BW, reflecting greater sensitivity to fine modulation changes across a broader range of frequencies. In contrast, older individuals showed higher PS and narrower BW, indicating reduced sensitivity and difficulty detecting higher modulation frequencies. Previous studies (10, 11, 20) have reported similar age-related declines in PS and BW but suggested these changes become prominent after the 4th or 5th decade. Our findings, however, indicate an earlier onset of decline, emerging after the mid-30s,which may be due to the reasons listed earlier. Further, the pronounced decline under noisy conditions in the present study may be due to a further reduction in available modulation depth, requiring higher detection thresholds.

Effects of Noise on Modulation Detection Thresholds, Peak Sensitivity & Bandwidth

The study also demonstrated that MDTs were significantly higher in the Noise condition than in the Quiet condition across all modulation frequencies. This is likely due to noise masking the temporal cues of the signal, reducing the depth available for detection and leading to higher thresholds. Additionally, noise can act as a cognitive load, diverting attention and making it more challenging to focus on the target signal, further elevating MDTs. These results align with previous research (15, 21, 26), which reported that noise interferes with temporal fluctuation detection, negatively impacting speech intelligibility and overall auditory perception. Further, many studies (27- 29) on TMTF and temporal resolution tasks were conducted have used background noise and have reported higher detection thresholds, aligning with the findings of the present study. However, the rationale for using background noise differs from the current study. In previous research, background noise was often used to mask spectral cues introduced by modifications to the temporal properties of the stimuli. In contrast, our study utilized background noise specifically to examine early age-related declines in temporal resolution abilities. Similar results have been reflected in the measures of peak sensitivity, which indicates the higher requirement of temporal resolution abilities in noisy situations.

The findings also demonstrate that the impact of background noise was relatively more on older age groups (C and D), indicating that aging significantly worsens the ability to process amplitude modulations in noisy environments. This suggests that as individuals age, their auditory system becomes less efficient at extracting temporal cues from complex acoustic environments, making it increasingly difficult to detect fluctuations in sound amplitude when background noise is present. This finding underscores the interaction between age-related auditory decline and environmental challenges, revealing how background noise compounds the natural deterioration of temporal processing abilities.

Correlation of SNR50 and TMTF:

The correlation analysis revealed significant relationships between peak sensitivity, bandwidth, SNR50, and age across both quiet and noise conditions. A strong positive correlation was found between peak sensitivity and SNR50, while a negative correlation was observed between bandwidth and SNR50. Additionally, peak sensitivity showed a positive correlation with age, whereas bandwidth was negatively correlated with age.

A comparison of Pearson correlation coefficients (r-values) indicated that the relationship between peak sensitivity and SNR50 was stronger in noise than in quiet. This suggests that individuals with higher peak sensitivity, who require stronger modulation cues to detect amplitude fluctuations, struggle even more with speech perception in noisy environments. Since noise disrupts essential temporal cues, those with diminished temporal resolution need a higher SNR to achieve 50% speech recognition. The stronger correlation in noise suggests that measuring TMTF in noise may be a more effective predictor of speech perception difficulties and early age-related declines. Conversely, the negative correlation between bandwidth and SNR50 suggests that individuals with a wider bandwidth, who have better sensitivity to a broader range of modulation frequencies, perform better in speech perception tasks in noise. A wider bandwidth reflects better temporal resolution, allowing for more efficient tracking of amplitude fluctuations, which aids speech understanding in complex auditory environments. These findings align with structural equation modeling results from (11), which demonstrated that while age had a negligible direct effect on speech perception in noise (SPIN), it significantly affected temporal processing abilities. In turn, temporal processing had a direct impact on SPIN, highlighting the importance of early identification and intervention for temporal processing deficits. The degradation of temporal envelope and fine structure cues, which are essential for both modulation detection and speech perception, has been well-documented with aging (30-32). This decline impairs the auditory system's ability to separate speech from background noise, leading to increased difficulty tracking rapid modulations necessary for speech extraction, particularly in individuals over their mid-30s (32). Similar correlations between temporal processing and speech perception have been reported in previous studies (31, 33), further reinforcing the connection between age-related auditory changes and speech perception challenges.

Conclusion

The findings of this study highlight the early onset of age-related decline in temporal processing, particularly after the mid-30s, with a more pronounced deterioration in noisy conditions. The results emphasize that traditional assessments in quiet may overlook subtle deficits that become apparent in ecologically relevant listening environments. By demonstrating a strong correlation between peak sensitivity, bandwidth of TMTF obtained under noisy conditions and speech perception in noise, this study underscores the importance of evaluating temporal processing under challenging auditory conditions may serve as a more sensitive tool for detecting early auditory decline.

Ethical Consideration: The study adhered to the ethical guidelines outlined in the Helsinki Declaration and received approval from the Institutional Ethics Committee of KSHEMA, Deralakatte (EC/NEW/INST/2022/KA/0174). Informed written consent was obtained from all the participants for their voluntary participation.

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Table 1: One-way analysis of variance results for comparison of Modulation Detection Thresholds between age groups for both quiet and noise conditions across all modulation frequencies

		Quiet condition		**Background noise condition**	
MFs	**df**	**F**	**P**	**F**	**P**
2Hz	76	76.713	.000	88.341	.000
4Hz	76	65.175	.000	76.750	.000
8Hz	76	77.404	.000	76.553	.000
16Hz	76	73.209	.000	77.237	.000
32Hz	76	79.461	.000	84.106	.000
64Hz	76	64.386	.000	67.941	.000
128Hz	76	62.291	.000	79.449	.000
256Hz	76	66.214	.000	72.575	.000
512Hz	76	73.199	.000	73.804	.000

MFs- Modulation Frequencies, df- Degree of Freedom

Table 2: Tukey's post-Hoc results for pairwise comparison of Modulation detection thresholds between age groups for both quiet and noise conditions across all modulation frequencies.

		Quiet		Noise	
	MFs	**t**	**P**	**t**	**P**
A vs B	**2 Hz**	0.615	0.927	0.210	0.997
	4 Hz	0.167	0.998	0.078	1.000
	8 Hz	0.253	0.994	0.337	0.987
	16 Hz	-0.305	0.990	-1.967	0.210
	32Hz	-0.237	0.995	0.132	0.999
	64 Hz	-0.425	0.974	-2.059	0.176
	128 Hz	-0.659	0.912	-3.015	0.078
	256 Hz	-0.219	0.996	-0.931	0.788
	512 Hz	0.761	0.872	-2.203	0.130
B vs C	**2 Hz**	0.028	1.000	-1.153	0.658
	4 Hz	0.078	1.000	-1.215	0.619
	8 Hz	-1.628	0.369	-2.568	0.058
	16 Hz	-2.613	0.052	-2.774	0.054
	32Hz	-3.198	0.011	-5.857	<0.001
	64 Hz	-5.172	<0.001	-5.513	<0.001
	128 Hz	-4.422	<0.001	-4.747	<0.001
	256 Hz	-3.698	0.002	-5.722	<0.001
	512 Hz	-3.120	0.013	-2.916	0.024
C vs D	**2 Hz**	-4.254	<0.001	-4.741	<0.001
	4 Hz	-3.268	0.009	-3.800	0.002
	8 Hz	-2.474	0.002	-5.176	<0.001
	16 Hz	-3.734	0.002	-2.888	0.025
	32Hz	-3.445	0.005	-2.252	0.019
	64 Hz	-3.421	0.005	-2.427	0.008
	128 Hz	-4.063	<0.001	-3.658	0.003
	256 Hz	-5.433	<0.001	-4.199	<0.001
	512 Hz	-6.553	<0.001	-5.463	<0.001

MFs- Modulation Frequencies

Table 3: Results of the paired t-test for the comparison of Modulation Detection thresholds between quiet and noise conditions for all the age groups across all modulation frequencies.

	Group A			**Group B**			**Group C**			**Group D**		
MFs	**t**	**P**	**Cohen's d**	**t**	**p**	**Cohen's d**	**t**	**p**	**Cohen's d**	**t**	**p**	**Cohen's d**
2Hz	-9.857	<0.001	-2.204	-8.229	-9.857	-1.888	-14.067	<0.001	-3.146	-7.520	<0.001	-1.641
4Hz	-11.491	<0.001	-2.596	-9176	-11.491	-2.105	-15.167	<0.001	-3.392	-7.314	<0.001	-1.596
8Hz	-5.157	<0.001	-1.153	-9.543	-5.157	-2.189	-13.398	<0.001	-2.996	-11.691	<0.001	-2.551
16Hz	-5.841	<0.001	-1.306	-20.050	-5.841	-4.600	-22.602	<0.001	-5.054	-7.419	<0.001	-1.619
32Hz	-6.926	<0.001	-1.549	-10.363	-6.926	-2.377	-19.204	<0.001	-4.294	-7.064	<0.001	-1.541
64Hz	-5.703	<0.001	-1.275	-25.733	-5.703	-5.903	-20.717	<0.001	-4.633	-7.426	<0.001	-1.620
128Hz	5.557	<0.001	-1.247	-22.833	-5.557	-5.238	-21.613	<0.001	-4.833	-6.628	<0.001	-1.446
256Hz	-7.993	<0.001	-1.787	-9.831	-7.993	-2.255	-14.806	<0.001	-3.311	-7.439	<0.001	-1.623
512Hz	-10.559	<0.001	-2.361	-29.13	-10.559	-6.684	-18.086	<0.001	-4.045	-7.165	<0.001	-1.563

MFs- Modulation Frequencies

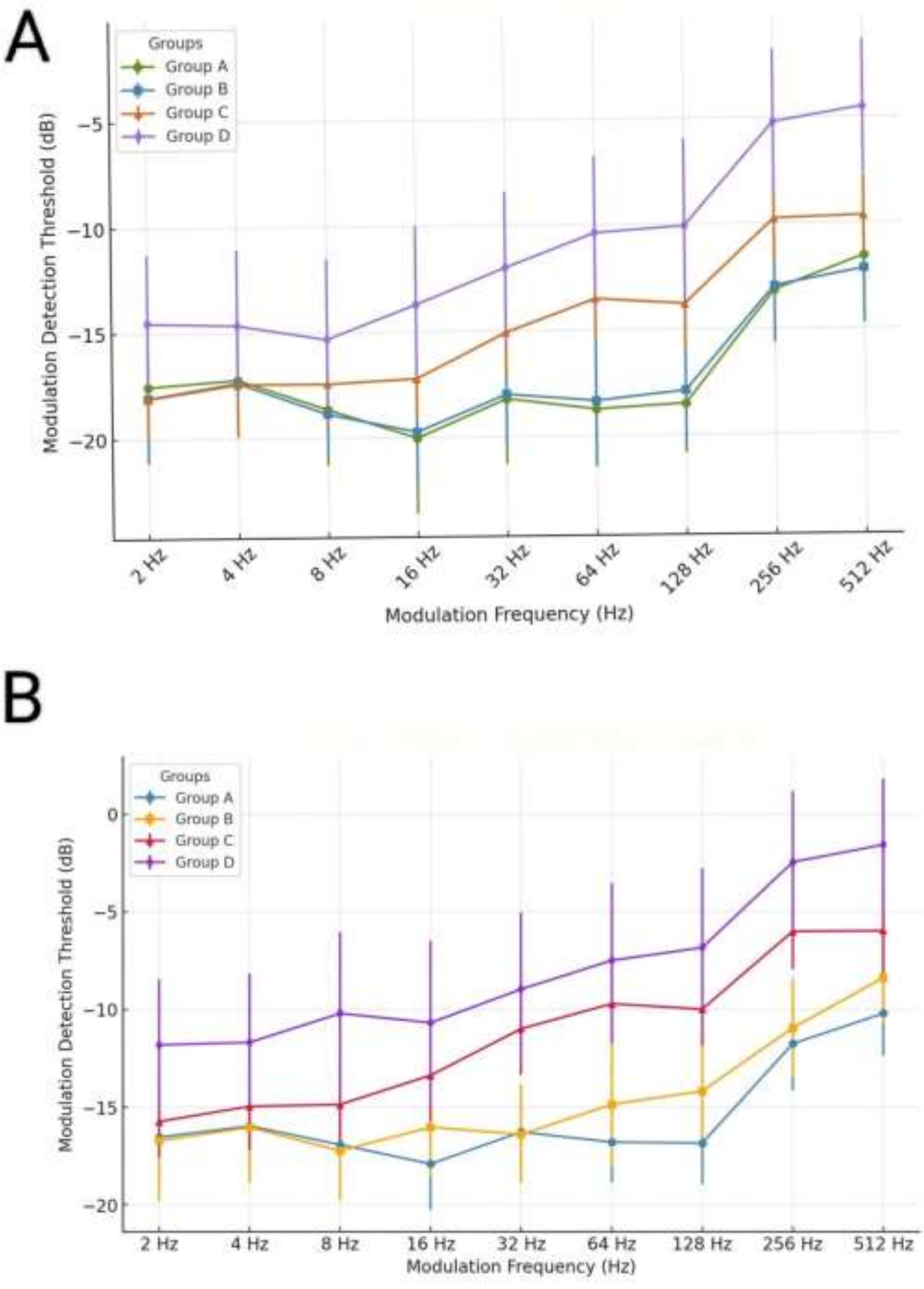

Figure 1: Depicts the Temporal Modulation Transfer Function across the four groups in (A) quiet and (B) noise condition.

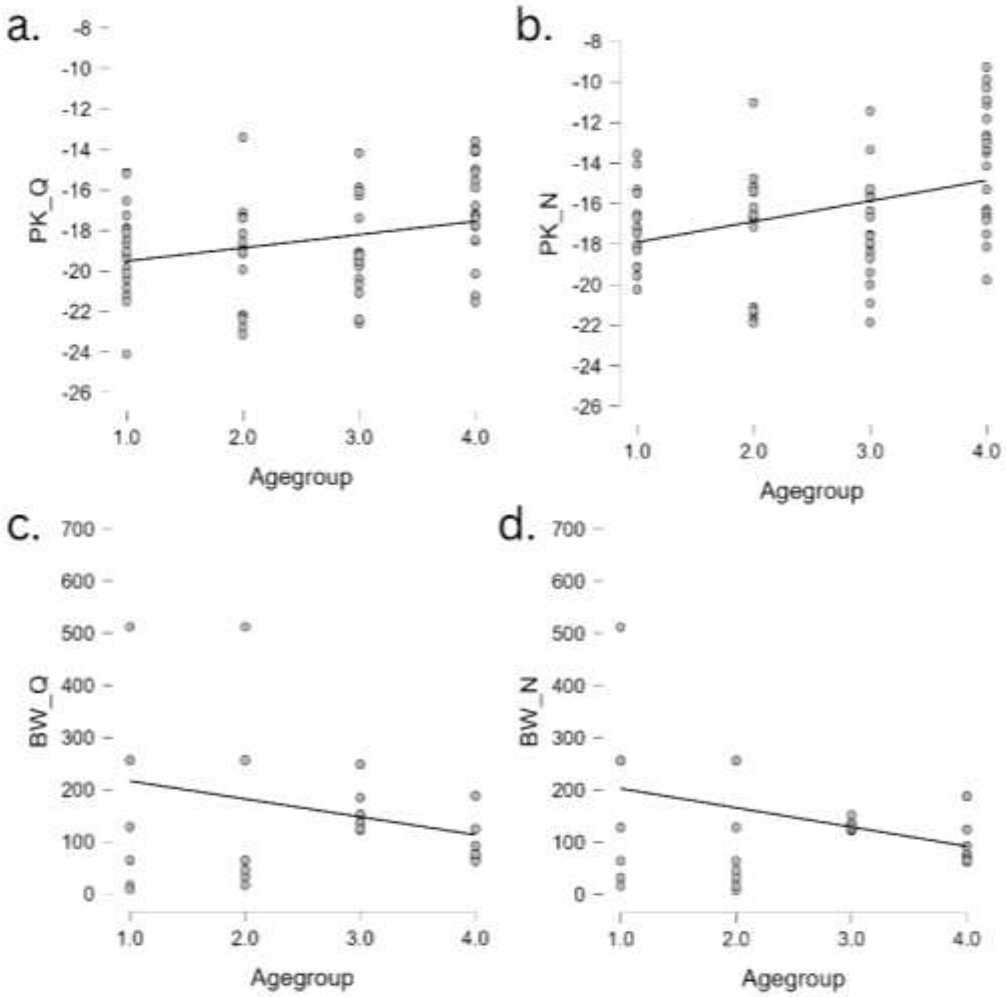

Figure 2: Scatterplots depicting correlation between (a) peak sensitivity(dB) in quiet and age, (b) peak sensitivity(dB) in noise and age, (c) bandwidth(Hz) in quiet and age, (d) bandwidth(Hz) in noise and age.

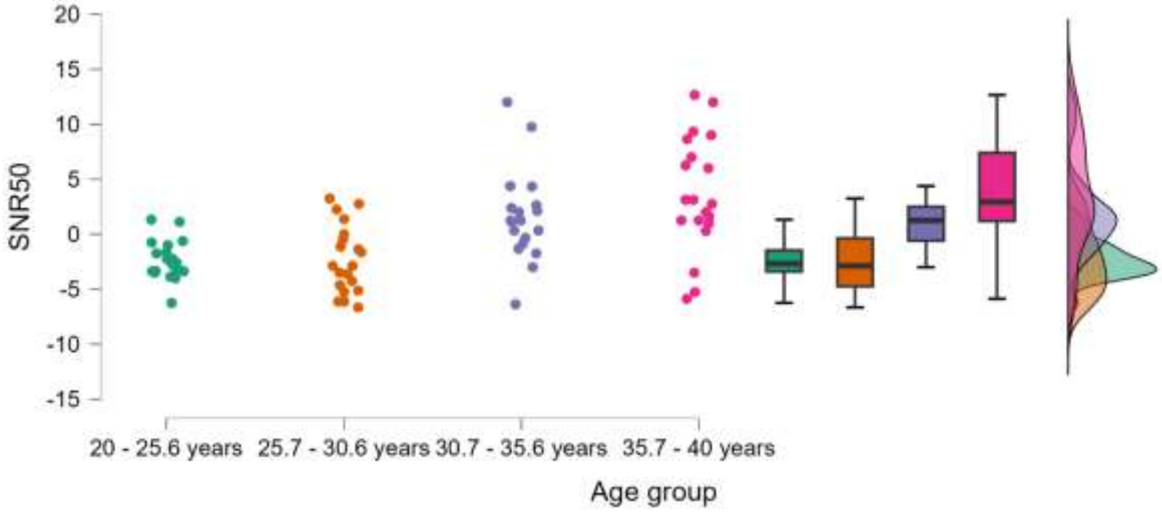

Figure 3: Depicts the Whisker plot depicts comparison of Signal-to-Noise Ratio-50% (SNR50(dB)) across age-groups.

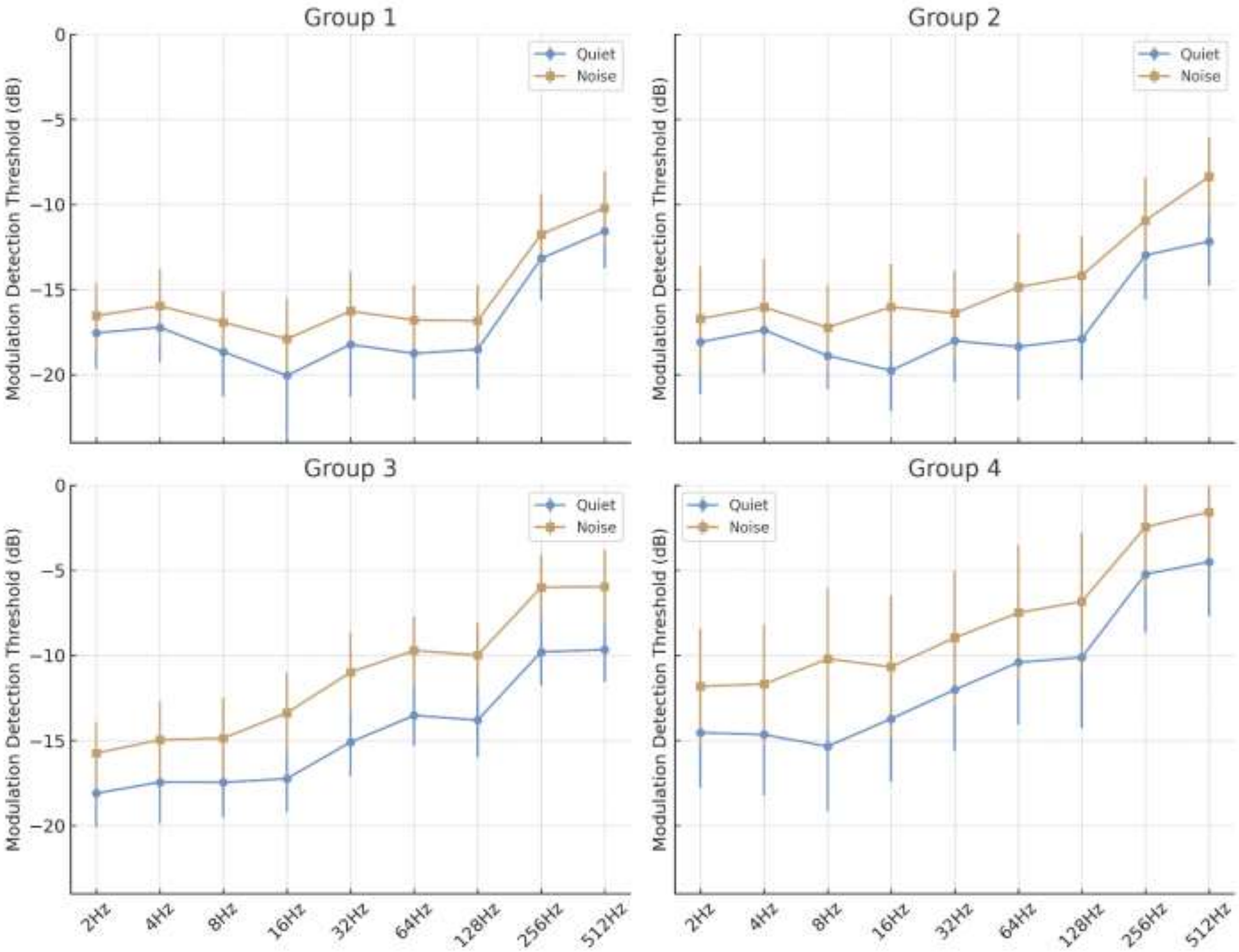

Figure 4: Depicts the comparison of Modulation Detection Thresholds between the quiet and noise conditions for the all the age groups across the modulation frequencies.

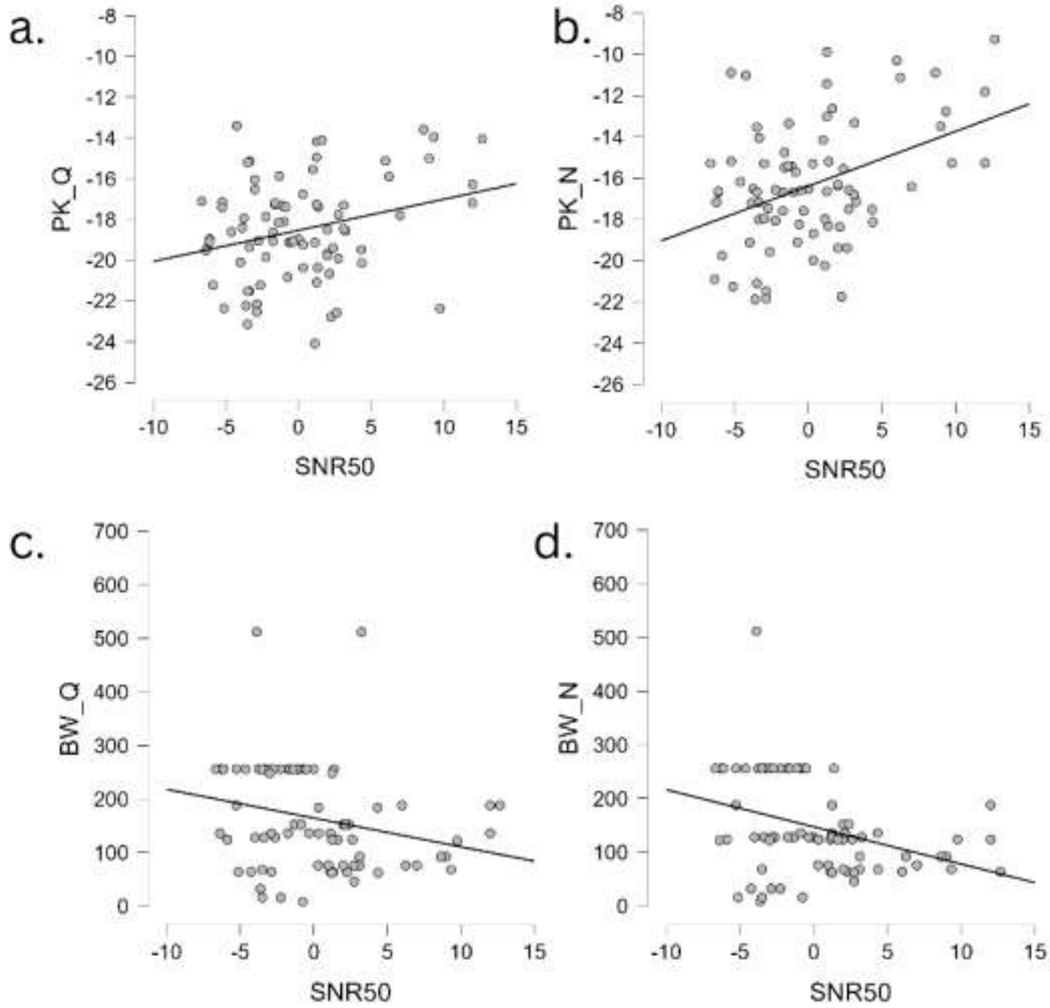

Figure 5: Scatterplots depicting correlation between (a) Signal-to-Noise Ratio-50% (SNR50) and peak sensitivity(dB) in quiet (PK_Q), (b) SNR50 and peak sensitivity(dB) in noise (PK_N), (c) SNR50 and bandwidth(Hz) in quiet (BW_Q), (d) SNR50 and bandwidth(Hz) in noise (BW_N).