Research Article

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-30 s, 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

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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 40 s or 50 s. 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). 80 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 (2 Hz–512 Hz). 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.

Conclusion: 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, influenced by various factors such as rate of speech, background noise, Signal-to-Noise Ratio (SNR), 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 (SPIN) 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 SPIN 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 evidence also shows that individuals with normal audiometric thresholds but subtle cochlear damage exhibit poorer temporal and speech perception abilities in noise and perform worse on gap detection and modulation detection tasks [5, 14]. This underscores the crucial role of temporal processing in real-world communication.

Temporal processing is widely assessed using temporal resolution tasks. Among these, Temporal Modulation Transfer Function (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 TMTF [15], and it results in representative measures such as Peak Sensitivity (PS) and Bandwidth (BW) [15]. There is a well-established correlation between the measures obtained from TMTF (PS, BW, Modulation Detection Thresholds (MDTs)) and SPIN [2, 11].

However, traditional temporal resolution tasks, typically conducted in quiet, often reveal noticeable declines only after the 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 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 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 (mean=22.2, SD=±1.23), group B (mean=26.1, SD=±0.78), group C (mean=32.65, SD=±1.26), and group D (mean=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, 2, 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 Screening Checklist for Auditory Processing in Adults (SCAP-A) 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 TMTF under quiet and in background noise (5 dB SNR). Signal-to-Noise Ratio 50% (SNR50) was obtained for nonsense Consonant Vowel ConsonantVowel (CVCV) words to assess the speech perception abilities.

Temporal modulation transfer function

The stimuli consisted of 3 intervals of 500 ms gaussian noise, one of which was sinusoidally modulated with 20 ms 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 three trials. The BBN was considered instead of any tones in order to avoid possible spectral cues. The 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. Modulation Detection Thresholds was measured in dB using the following equation:

MDT in dB=20 log10 m 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 PS and BW measures were obtained.

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

Where m is MDT, a is the PS, ms is the modulation frequency and b is the BW with 3 dB cutoff frequency. PS 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. MDTs were measured twice, once under quiet conditions and another in the presence of speech shaped noise at +5 dB SNR presented ipsilaterally to the stimulus ear through the audiometer. The order of testing conditions (quiet vs noise) was randomized to avoid order effects.

Speech perception in noise

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 and it exhibited a similar spectrum as of the Long-Term Average Spectrum (LTAS) 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 SNR50.

Statistical analysis

Data were analyzed using JASP software. The Shapiro–Wilk test confirmed normal distribution for all variables except BW. Age effects on MDTs, PS, and SNR50 were examined using one-way analysis of variance with Tukey's post-hoc tests, while Bandwidth was analyzed using the Kruskal–Wallis test with Dunn's post-hoc correction. Paired t-tests compared parameters between quiet and noise conditions, with the Wilcoxon test applied for Bandwidth. Correlations between temporal processing measures and SNR50 were evaluated using Pearson's or Spearman's coefficients, with significance set at $p<0.05$.

Results

Comparison of modulation detection thresholds 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. Statistical analysis showed a 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 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 (>16 Hz), whereas lower MFs (2 Hz–16 Hz) did not demonstrate a significant difference. Comparison of MDT between groups C and D demonstrated significant differences across all modulation frequencies (Table 2).

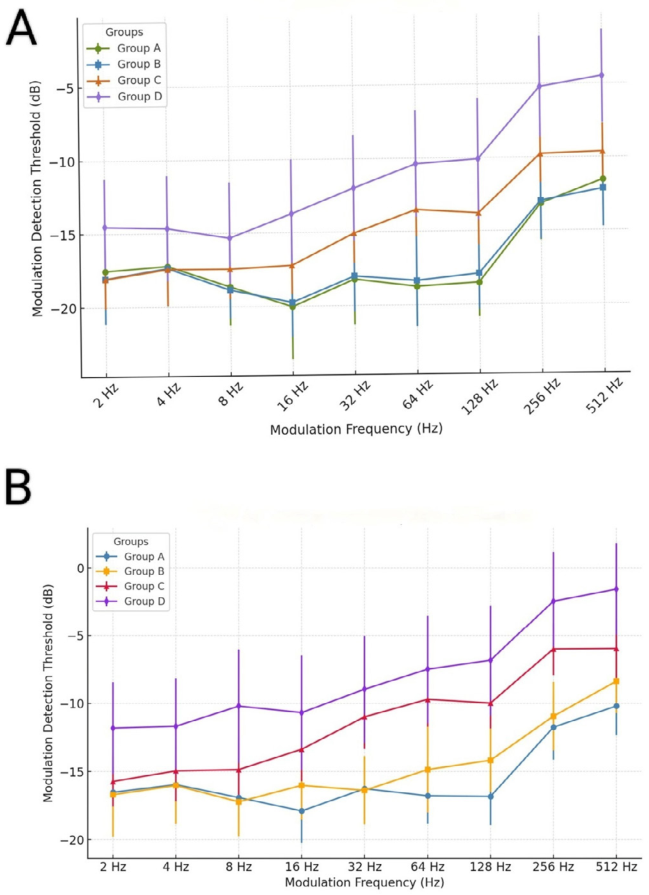

Figure 1. Depicts the temporal modulation transfer function across the four groups in (A) quiet and (B) noise condition

Table 1. One-way analysis of variance results for comparison of modulation detection thresholds across age groups for both quiet and noise conditions across all modulation frequencies

			Quiet condition		Background noise condition	
MFs	df2	df2	F	P	F	p
2 Hz	3	76	76.713	<0.001	88.341	<0.001
4 Hz	3	76	65.175	<0.001	76.750	<0.001
8 Hz	3	76	77.404	<0.001	76.553	<0.001
16 Hz	3	76	73.209	<0.001	77.237	<0.001
32 Hz	3	76	79.461	<0.001	84.106	<0.001
64 Hz	3	76	64.386	<0.001	67.941	<0.001
128 Hz	3	76	62.291	<0.001	79.449	<0.001
256 Hz	3	76	66.214	<0.001	72.575	<0.001
512 Hz	3	76	73.199	<0.001	73.804	<0.001

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		
		95% CI for mean difference			95% CI for mean difference		
	MFs	Lower limit	Upper limit	p	Lower limit	Upper limit	p
A vs B	2 Hz	–1.80	2.86	0.927	–2.12	2.48	0.997
	4 Hz	–2.23	2.52	0.998	–2.33	2.46	1.000
	8 Hz	–2.15	2.60	0.994	–2.19	2.81	0.987
	16 Hz	–2.91	2.32	0.990	–4.47	0.71	0.210
	32 Hz	–2.70	2.26	0.995	–2.38	2.62	0.999
	64 Hz	–2.93	2.13	0.974	–4.46	0.61	0.176
	128 Hz	–3.13	1.91	0.912	–5.06	–0.27	0.078
	256 Hz	–2.52	2.15	0.996	–3.15	1.54	0.788
	512 Hz	–1.57	2.80	0.872	–4.06	0.41	0.130
B vs C	2 Hz	–2.30	2.35	1.000	–3.28	1.32	0.658
	4 Hz	–2.31	2.44	1.000	–3.47	1.32	0.619
	8 Hz	–3.80	0.95	0.369	–4.87	0.13	0.058
	16 Hz	–5.14	0.09	0.052	–5.24	–0.06	0.054
	32 Hz	–5.40	–0.45	0.011	–7.91	–2.91	<0.001
	64 Hz	–7.37	–2.30	<0.001	–7.69	–2.62	<0.001
	128 Hz	–6.63	–1.59	<0.001	–6.59	–1.80	<0.001
	256 Hz	–5.52	–0.85	0.002	–7.29	–2.61	<0.001
	512 Hz	–4.70	–0.33	0.013	–4.65	–0.17	0.024
C vs D	2 Hz	–5.84	–1.30	<0.001	–6.16	–1.68	<0.001
	4 Hz	–5.11	–0.48	0.009	–5.61	–0.94	0.002
	8 Hz	–4.43	0.20	0.002	–7.10	–2.22	<0.001
	16 Hz	–6.07	–0.97	0.002	–5.22	–0.17	0.025
	32Hz	–5.49	–0.66	0.005	–4.47	0.41	0.019
	64 Hz	–5.59	–0.65	0.005	–4.69	0.26	0.008
	128 Hz	–6.14	–1.23	<0.001	–5.49	–0.82	0.003
	256 Hz	–6.85	–2.29	<0.001	–5.83	–1.26	<0.001
	512 Hz	7.29	–3.02	<0.001	–6.58	–2.22	<0.001

MFs; modulation frequencies

Comparison of peak sensitivity and bandwidth across the age groups in both quiet and noise conditions

The descriptive statistics showed a comparable PS and BW across first three age groups, whereas the decline (higher PS and lower BW) was observed only in group D. Statistical analysis showed a significant difference in PS across age groups at both quiet (PS ($F_{(3,76)}$=5.023, p=0.003, η^2=0.165); and noise condition (PS ($F_{(3,76)}$=8.902, p<0.01, η^2=0.260). Further, post-hoc analysis 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).

Similarly, significant age-related differences were observed in BW for both quiet ($H_{(3,80)}$=13.450, p<0.05, η^2=0.137) and noise conditions ($H_{(3,80)}$=17.674, p<0.05, η^2=0.193). Pairwise comparisons 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). except C vs 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) except C vs D age groups (z=2.206, p<0.05).

Additionally, a significant positive correlation was found between PS and age in both the quiet (r=0.299, p<0.05) and noise situation (r=0.388, p<0.05). Whereas, a significant negative correlation was found between BW and age in both the quiet (rs=–0.393, p<0.05) and noise situation (rs=–0.453, p<0.05) (Figure 2).

Comparison of signal-to-noise ratio 50% across age groups

The descriptive analysis indicated an age-related decline in SNR 50 scores, with group A achieving the lowest SNR50 (better) and group D exhibiting the highest SNR50 (poorer) as depicted in (Figure 3). The data also depicts a relatively more dispersion on last group. This trend was statistically confirmed with a significant effect

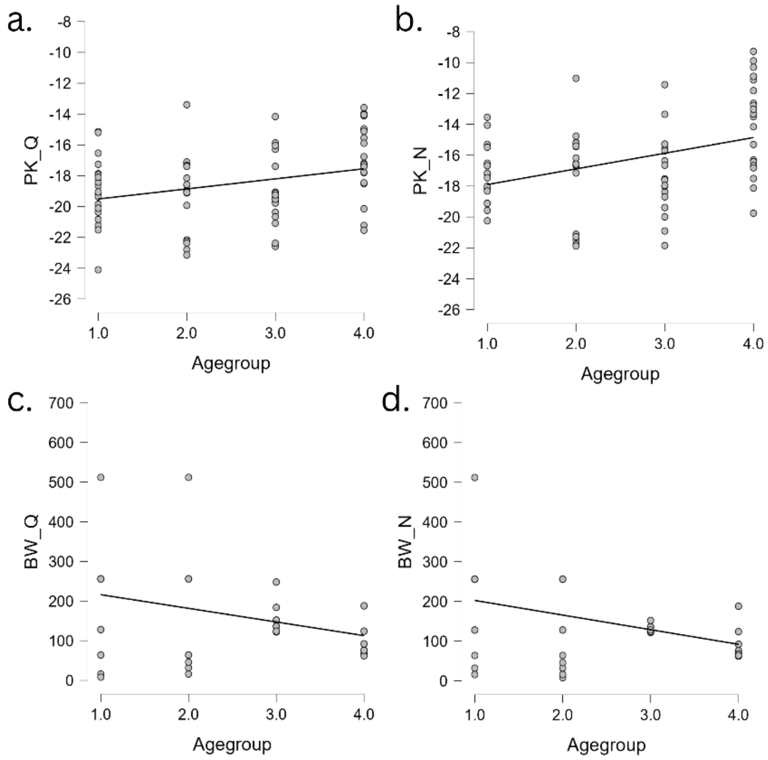

Figure 2. Scatterplots depicting correlation between (a) peak sensitivity(dB) in quiet and age, (b) peak sensitivity (dB) in noise and age, (c) bandwidth (Hz) in quiet and age, (d) bandwidth (Hz) in noise and age. PK_Q; peak sensitivity (dB) in quiet, PK_N; peak sensitivity (dB) in noise, BW_Q; bandwidth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

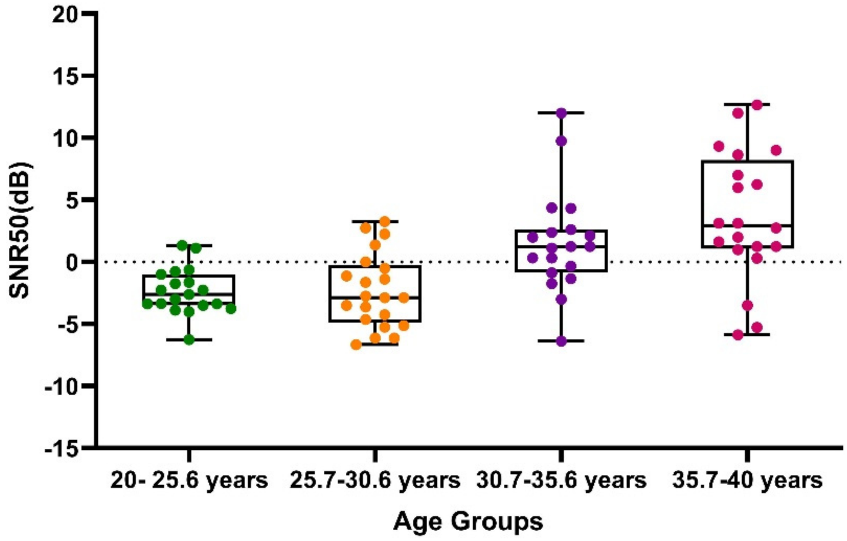

Figure 3. Box-and-whisker plot showing the comparison of signal-to-noise ratio at 50% across age groups. SNR50; signal-to-noise ratio at 50%

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

MFs	Group A				Group B				Group C				Group D			
	95% CI for mean difference				95% CI for mean difference				95% CI for mean difference				95% CI for mean difference			
	Lower limit	Upper limit	p	Cohen's d	Lower limit	Upper limit	p	Cohen's d	Lower limit	Upper limit	p	Cohen's d	Lower limit	Upper limit	p	Cohen's d
2 Hz	–1.23	–0.80	<0.001	–2.20	–1.69	–1.03	<0.001	–1.89	–2.74	–2.06	<0.001	–3.15	–2.49	–0.90	<0.001	–1.64
4 Hz	–1.50	–1.03	<0.001	–2.60	–1.65	–1.06	<0.001	–2.11	–2.84	–2.18	<0.001	–3.39	–2.84	–1.06	<0.001	–1.60
8 Hz	–2.44	–1.03	<0.001	–1.15	–2.00	–1.31	<0.001	–2.19	–3.06	–2.26	<0.001	–3.00	–3.06	–1.13	<0.001	–2.55
16 Hz	–2.92	–1.38	<0.001	–1.31	–2.19	–1.40	<0.001	–4.60	–3.20	–2.48	<0.001	–5.05	–2.92	–1.12	<0.001	–1.62
32 Hz	–2.54	–1.37	<0.001	–1.55	–2.02	–1.34	<0.001	–2.38	–3.53	–2.63	<0.001	–4.29	–2.98	–1.08	<0.001	–1.54
64 Hz	–2.69	–1.25	<0.001	–1.28	–1.82	–1.25	<0.001	–5.90	–3.21	–2.44	<0.001	–4.63	–2.75	–1.03	<0.001	–1.62
128 Hz	–2.31	–1.05	<0.001	–1.25	–2.02	–1.37	<0.001	–5.24	–3.22	–2.57	<0.001	–4.83	–3.34	–1.17	<0.001	–1.45
256 Hz	–1.79	–1.04	<0.001	–1.79	–2.40	–1.53	<0.001	–2.26	–3.34	–2.30	<0.001	–3.31	–2.62	–0.99	<0.001	–1.62
512 Hz	–1.64	–1.09	<0.001	–2.36	–2.08	–1.55	<0.001	–6.68	–3.17	–2.32	<0.001	–4.05	–2.80	–1.00	<0.001	–1.56

MFs; modulation frequencies

of age on SNR50 ($F_{(3,76)}$=12.250, p<0.001, η^2=0.326). Post-hoc analysis 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 modulation detection thresholds between quiet and noise conditions

The descriptive analysis revealed that MDTs were consistently better in quiet conditions compared to noise across all age groups. Additionally, as age increased

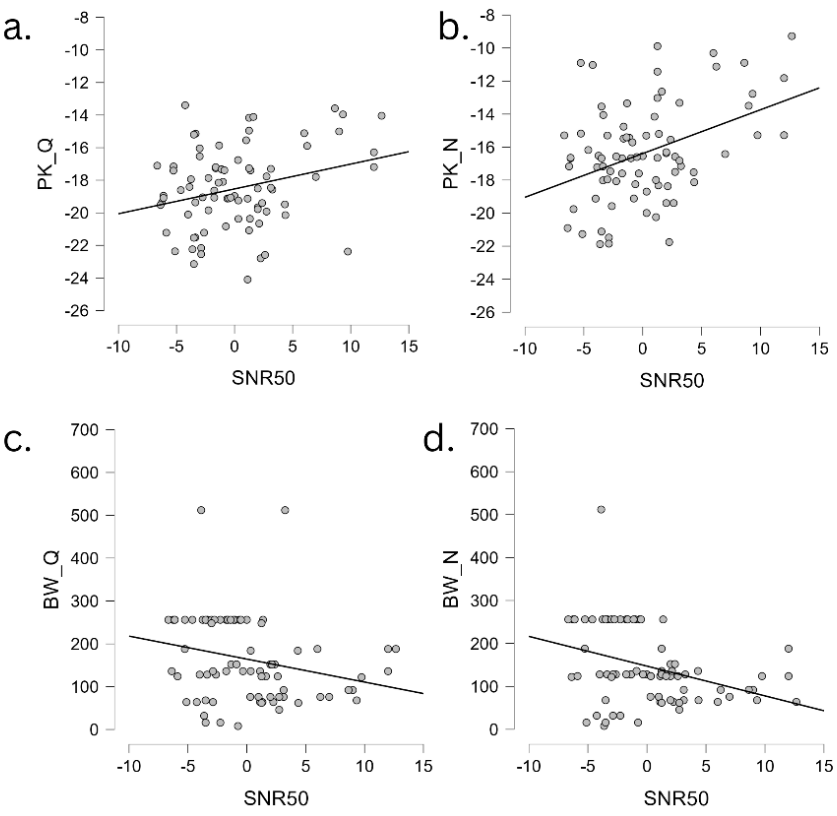

Figure 4. Scatterplots depicting correlation between (a) signal-to-noise ratio 50% and peak sensitivity (dB) in quiet, (b) signal-to-noise ratio 50% and peak sensitivity (dB) in noise, (c) signal-to-noise ratio 50% and bandwidth (Hz) in quiet, (d) signal-to-noise ratio 50% and bandwidth (Hz) in noise. PK_Q; peak sensitivity (dB) in quiet, PK_N; peak sensitivity (dB) in noise, SNR50; signal-to-noise ratio 50%, BW_Q; bandwidth (Hz) in quiet, BW_N; bandwidth (Hz) in noise

from group A to group D, the difference between MDTs in quiet and noise conditions became more pronounced. This trend was statistically confirmed with a significant difference 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. Statistical analysis showed a significant main effect of PS on testing conditions (PS ($F_{(1,76)}$=170.043, $p<0.05$, η^2=0.135) and on the age group (PS ($F_{(3,76)}$=7.590, $p<0.05$, η^2=0.184). Also, a significant interaction effect was obtained between the testing condition and age group for PS ($F_{(3,76)}$=3.171, $p<0.05$, η^2=0.008). This indicates that the difference in the PS obtained between quiet and noise conditions was not the same for all the age groups. It was further confirmed by a significant impact of background noise on PS 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 BW were in contrast with the results of PS showing no significant difference ($p>0.05$) on BW for both the quiet and noise conditions across all groups.

Correlation of peak sensitivity and bandwidth with signal-to-noise ratio 50%

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, $p<0.05$). Whereas, 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 4).

Discussion

The present study explored the age-related changes in temporal processing abilities under silence and noisy conditions aiming to investigate early changes in young adults, that may contribute to speech perception difficulties in noise.

Age-related differences in modulation detection thresholds, peak sensitivity and bandwidth

Findings indicate a gradual decline in MDTs from 20–40 years with stability in early adulthood and deterioration emerging after 35 years (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 and Sangamanatha [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. 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.

Participants showed a low-pass filtering pattern, exhibiting greater sensitivity to lower modulation frequencies (2–64 Hz) and poorer 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 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 with auditory neuropathy [2, 26], demonstrating elevated thresholds at higher modulation frequencies. Thus, our findings suggest that reduced sensitivity to faster modulations may mark early temporal processing decline. 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 noisy condition. 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 such changes after the 4th or 5th decade, whereas our results suggest an earlier onset, which may be due to the reasons listed earlier. Further, the pronounced decline under noisy conditions may be due to a further reduction in available modulation depth, increasing detection difficulty.

Effects of noise on modulation detection thresholds, peak sensitivity and bandwidth

MDTs were significantly higher in noise across all modulation frequencies, suggesting that noise masks temporal cues, reducing modulation depth and increasing cognitive load. This elevates thresholds by diverting attention from the target signal, consistent with prior findings [15, 21, 26]. Studies employing background noise in temporal tasks [27-29] similarly report higher thresholds. However, unlike earlier work where noise was used to mask spectral cues, our study used noise to evaluate early age-related temporal resolution decline. The stronger effect of noise on older groups (C and D) indicates that aging exacerbates difficulties in extracting temporal cues from complex environments, highlighting how noise compounds natural auditory decline.

Correlation of signal-to-noise ratio 50% and temporal modulation transfer function

Significant correlations were observed among PS, BW, SNR50, and age under both listening conditions. PS showed a positive correlation with SNR50 and age, while BW was negatively correlated with both. The stronger PS-SNR50 relationship in noise suggests that individuals requiring stronger modulation cues for detection struggle more with speech perception in noise. Since noise distorts temporal cues, reduced temporal resolution demands higher SNRs for equivalent performance. Hence, TMTF in noise may better predict Speech-in-Noise (SPIN) challenges and early auditory decline. Conversely, wider BW, reflecting better modulation sensitivity, was associated with superior SPIN performance. These findings align with earlier study [11], indicating that temporal processing mediates the effect of age on SPIN performance, highlighting the importance of early identification and intervention for temporal processing deficits. The degradation of temporal envelope and fine structure cues with age [30-32] impairs separation of speech from background noise, particularly beyond the mid-30s. Similar correlations between temporal processing and speech perception have been consistently reported [31-33], further reinforcing the connection between age-related auditory changes and speech perception challenges.

Conclusion

The study highlights 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. The strong correlations between peak sensitivity and bandwidth, and signal-to-noise ratio50 under noise emphasize the importance of evaluating temporal processing in challenging auditory contexts may serve as a more sensitive tool for detecting early auditory decline.

Ethical Considerations

Compliance with ethical guidelines

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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Authors' contributions

ANS: Data collection, Interpretation of data, drafting of manuscript and statistical analysis; PKE: Study design, supervision, data interpretation and critical revision of manuscript; JSB: Study design, supervision

Conflict of interest

The authors declare no conflict of interest.

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