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Age and sex differences in speech FFR suggest early central auditory aging

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This study aimed to examine the effects of age and sex on speech-evoked frequency-following response (FFR) latency, amplitude, and spectral features in Turkish-speaking young and middle-aged adults with normal hearing. Moreover, this study aimed to characterize the properties of speech-FFR in native Turkish speakers. A cross-sectional observational design was utilized. Sixty-one right-handed native Turkish speakers with clinically normal hearing were included: Thirty-one were young adults (aged 19–25 years) and 30 were middle-aged adults (aged 40–60 years), with an equal number of males and females in each group. The 40-ms /da/ syllable was presented monaurally to the right ear at 80 dB SPL using alternating polarity. Six wave peaks (V, A, D, E, F, O) were analyzed in both the temporal (latency, amplitude) and spectral (F0, F1, F2) domains. Statistical analyses included independent t-tests, Mann–Whitney U tests, and Spearman's correlation. In the young group, females showed significantly shorter latencies than males across all peaks. In the middle-aged group, this sex difference was limited to A and D peaks. Latencies of D, F, and O waves positively correlated with age, while V wave amplitude negatively correlated with age. No significant sex-related differences were found in amplitude or spectral features. Both age and sex may affect subcortical auditory processing as reflected in Speech-FFR. Latency prolongation and amplitude reduction with advancing age may indicate early neural changes in time domain at the brainstem level, even in adults with normal hearing.These findings suggest potential clinical relevance for Speech FFR and emphasize the need for language specific normative data.

Keywords Speech-evoked frequency following response, Age, Sex, Electrophysiology

Auditory evoked potentials (AEP) recordings may be a useful tool to assess neural mechanisms associated with speech perception and processing. Tone burst or click stimuli are used routinely in clinical practice to evaluate the neural integrity of auditory pathways at the brainstem level[1]. However, these non-speech stimuli do not provide real information about the processing of speech sounds at the brainstem level when the aim is to investigate how speech sounds in daily life are processed. The use of verbal stimuli such as speech sounds allows a more accurate analysis of the auditory system since speech and non-speech sounds are processed in different ways by following different pathways in the central auditory nervous system[2].

Speech-evoked auditory brainstem response, also known as FFR or speech-FFR, is a valid and reliable tool used to evaluate synchronous sound-evoked neural activity revealing the integrity of sound processing in the brain[3]. In brief, speech-FFR assesses spectro-temporal coding of sound in the auditory pathway.

Speech-FFR testing can provide information on central auditory processes related to the processing of speech sounds in the brainstem, monitoring neural maturation, determining the effects of the aging process on hearing, understanding the hearing and communication status of individuals with special learning disabilities, understanding the processes in conditions such as cochlear implant and auditory neuropathy, diagnosis of auditory processing disorder, understanding of the plasticity of the auditory system, noise discrimination ability and presbycusis[4].

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Recording parameters, equipment, person-related variables, etc. should be taken into consideration when interpreting the responses obtained with speech-FFR. Person-related factors such as age, sex, native language, sleep-wakefulness, body temperature, drug use, hearing loss, muscle artifacts may lead to some differences in responses. For example, considering the sex factor, previous studies in the literature have shown that females have better ABR results with shorter latency and higher amplitudes than males[5,6]. In speech-FFR, earlier and stronger responses especially in initial responses and better representation of spectro-temporal information in the Frequency Following Response (FFR) section were obtained in females compared to males[7]. A study conducted by Kırbac et al. investigated sex differences in Turkish adults via binaural speech-FFR. Their study revealed that sex differences in binaural speech-FFR are significant in some peak latencies, particularly in the temporal domain[8]. Although there are many hypotheses about the better responses of females compared to males, it has been supported by studies that sex hormones play an active role[9]. This information reveals the importance for clinics to create sex-specific norm data.

Studies have been conducted on the influence of native language on speech-FFR and how speech-FFR results may be affected when assessing speakers of different languages. For instance, Liu et al. demonstrated that learning a second language in adulthood can alter subcortical neural encoding, suggesting that linguistic experience can reshape auditory processing at the brainstem level[10]. In another study, Yu and Zhang conducted a cross-linguistic study examining the relationship between FFR and speech perception to test the neural commitment of native language at the brainstem level[11]. Their findings revealed that native language experience plays a crucial role in shaping auditory brainstem responses, as tonal (Mandarin Chinese) and non-tonal (English) language speakers showed significant differences in FFR patterns. Collectively, these findings suggest that native language can profoundly influence the neural mechanisms underlying speech processing, as demonstrated by variations in speech-FFR across different language groups. This highlights the importance of establishing language-specific speech-FFR characteristics and norm values.

From early middle age onwards, many bodily functions gradually begin to decline. The most common hearing-related complaint with aging is that speech is increasingly difficult to hear but cannot be understood. This may be due to the slowdown and decrease in neural processing and neural inhibition with aging and the difficulty in processing the complex and rapidly changing features of speech[12]. Delayed neural timing, decreased temporal processing ability, synchronization disorders in neural firing, inconsistencies in neural response, decreased phase locking and decreased power of spectral responses can be mentioned with aging[13]. The effects of aging on the hearing system can be determined and monitored with speech-FFR. The studies in literature mostly compared young individuals with older individuals, and although there was a significant difference in the findings, different results were observed between the studies[14,15].

Speech-FFR has a wide range of clinical applications and speech-FFR, in addition to being useful for diagnosis, also plays an important role in monitoring intervention processes. While numerous studies have investigated speech-FFR, research on the effects of age and sex in Turkish-speaking individuals remains limited. Moreover, there is a significant gap in studies involving middle-aged individuals. Therefore, the present study aims to analyze the temporal and frequency domain characteristics of speech-FFR in young and middle-aged Turkish-speaking adults with normal hearing level and to compare these groups in the context of age and sex.

Materials and methods

Participants

A total of 31 healthy young adults (15 females, 16 males; 19–25 years) and 30 healthy middle-aged adults (15 females, 15 males; 40–60 years) years were included in the study.

Inclusion/Exclusion criteria

Inclusion Young adults (18-25) or middle-aged adults (40–60); monolingual native Turkish speakers; right-hand dominance determined by the Edinburgh Handedness Inventory[16]; hearing within normal limits defined as pure-tone average ≤ 25 dB HL at 250–8000 Hz with normal speech audiometry; normal acoustic immittance with a Type A tympanogram characterized by tympanometric pressure between − 100 and + 50 daPa and compliance between 0.3 and 1.6 mmho, as well as positive acoustic reflexes at 500, 1000, 2000, and 4000 Hz[17]; and normal diagnostic ABR results based on Hall's normative values[18].

Exclusion History of otologic surgery/disease, any current audiologic symptoms, neurological or psychiatric disorders, speech–language disorders, or learning disabilities.

Screening and procedure

All participants underwent medical history and otoscopy, followed by behavioral audiometry (PTA and speech audiometry), acoustic immitansmetry (tympanometry and acoustic reflexes), and diagnostic click-ABR. Individuals meeting the inclusion thresholds then proceeded to speech-FFR recording. This comprehensive approach was adopted because speech-FFR is a sensitive test, and it was essential to rule out atypical auditory responses using both behavioral and electrophysiological methods. Although PTA is the standard for assessing hearing, ABR provides a more complete view of auditory neural function[19]. All assessments were completed in a single session.

Equipment

Behavioral audiometry was performed in a sound-treated booth (OTATECH) using an AC40 hybrid audiometer (Interacoustics A/S, Assens, Denmark) with DD45 headphones. Acoustic immitansmetry were obtained with Titan Suite (226-Hz probe; Interacoustics A/S). Electrophysiology recordings (click-ABRand speech-FFR) were

performed using Intelligent Hearing Systems SmartEP v5.10 with ER-3 A insert earphones (IHS, Miami, FL, USA).

Click-ABR recording

Click-ABR was recorded at 80 dB nHL, stimulus rate 19.3/s, 2000 sweeps, 100–3000 Hz filter, 15 ms window (−3 ms pre-stimulus), alternating polarity, 100,000× gain, and 40% artifact rejection. Waves I, III, V were identified at 80 dB nHL; absolute and interpeak latencies (I–III, I–V, III–V), amplitudes, and amplitude ratios were evaluated. Wave V presence was confirmed at 80, 60, 40, and 20 dB nHL. Only participants with normative latency/amplitude values and detectable Wave V at 20 dB nHL advanced to speech-FFR.

Speech-FFR recording and analysis

Speech-FFR was recorded using two replications of 3000 sweeps (total 6000), 76.8 ms window (−10 ms pre-stimulus), 10% artifact rejection, 100,000× gain, and 100–3000 Hz filters. A 40-ms/da/syllable was presented monaurally to the right ear at 80 dB SPL, alternating polarity, at a rate of 10.9 ms. Temporal analysis followed literature guidelines[20]: six peaks (V, A, D, E, F, O) were marked; C was excluded due to < 80% detectability. Marking was performed blindly by two researchers. Peaks were identified by overlaying two waveforms per participant. Absolute latency (ms) and amplitude (μV) values were calculated. Waveforms were exported in ASCII and analyzed spectrally with the MATLAB-based Brainstem Toolbox[21]; FFT yielded F0, F1, and F2 amplitudes.

Statistics

Analyses were conducted in SPSS v25.0 (SPSS Inc., Chicago, IL, USA). Normality was assessed with Shapiro–Wilk ($p > 0.05$ indicates normality). Descriptive statistics (mean ± SD, frequency, and percentage) were computed. The independent samples t-test or Mann-Whitney U test was conducted for between-group comparisons. Spearman correlation analysis was used to evaluate the relationship between variables. Statistical significance was set at $p < 0.05$.

Results

The study included 31 young adults aged between 19 and 25 years and 30 middle-aged adults aged between 40 and 60 years. The groups were divided into two groups according to age: young adults group (YAG) and middle-aged adults group (MAG). The groups were divided into 4 groups according to age and sex factors: female-young adults group (F-YAG), male-young adults group (M-YAG), female-middle-aged adults group (F-MAG) and male-middle-aged adults group (M-MAG).

As shown in Table 1, there was no significant age difference in the subgroups (F-YAG-M-YAG, $p = 0.513$; F-MAG-M-MAG, $p = 0.665$). The groups were homogeneously distributed in terms of age and sex. Speech-FFR of a participant from the young adult group is presented in Fig. 1 (Raw Data).

Descriptive statistics for the absolute latency and amplitude values of the V, A, D, E, F and O peaks, and the mean and standard deviation values of the spectral peak amplitude values for the groups separated according to age and sex are given in Table 2.

As seen in Table 3, significant differences were obtained between YAG-MAG and sex-matched age groups with higher latency values in the older group.

Significant differences were obtained between F-YAG and M-YAG for V, A, D, E, F and O peaks with higher latency values in the male group. Also, significant differences were obtained between F-MAG and M-MAG for A and D peaks with higher latency values in the male group (Table 4).

Significant differences were obtained between YAG and MAG, F-YAG and F-MAG, and M-YAG and M-MAG for V peak amplitude with lower values in the older group (Table 5).

There was no statistically significant difference between the age-matched groups in terms of all amplitude variables (Table 6). The spectral peak amplitudes (μV) of speech-FFR were also compared between the groups considering the age and sex variables. No statistically significant differences were observed in the spectral amplitude values of F0, F1, and F2 across any of the groups or subgroups (F-YAG vs. M-YAG: F0: $p = 0.133$; F1: $p = 0.179$; F2: $p = 0.089$; F-MAG vs. M-MAG: F0: $p = 0.756$; F1: $p = 0.419$; F2: $p = 0.576$; MAG-YAG: F0: $p = 0.100$;

Variable	Group	*n*	Mean ± SD	Min.- Max.	*p* Value
Age	F-YAG	15	21.24 ± 0.97	19.7–23.3	0.513
	M-YAG	16	21.5 ± 1.19	20.3–25.0	
	Total	31	21.37 ± 1.08	19.7–25.0	
	F-MAG	15	45.98 ± 4.83	40.1–56.8	0.665
	M-MAG	15	46.77 ± 5.08	56.8–56.8	
	Total	30	46.37 ± 4.89	40.0–56.8.0.8	

Table 1. Demographic information of the participants. (SD: Standard deviation, Min: minimum, Max: maximum, MAG: middle-aged adults group, YAG: young adults group, F-YAG: female-young adults group, M-YAG: male-young adults group, F-MAG: female-middle-aged adults group, M-MAG: male-middle-aged adults group, Independent t-test, $^{*}p < 0.05$).

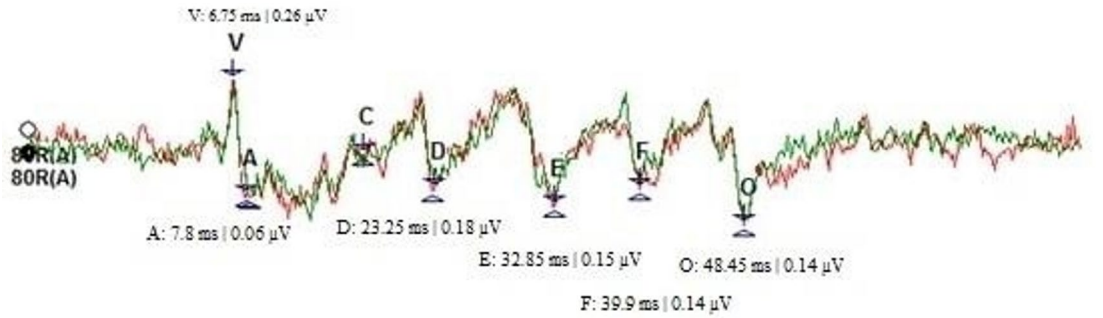


Fig. 1. Speech-FFR (Raw Data) of a participant from the young adult group.

F1: $p = 0.323$; F2: $p = 0.453$; F-YAG vs. F-MAG: F0: $p = 0.065$; F1: $p = 0.419$; F2: $p = 0.330$; M-YAG vs. M-MAG: F0: $p = 0.553$; F1: $p = 0.693$; F2: $p = 0.968$). 6).

Spearman correlation analysis revealed a moderate positive correlation between age and D ($p = 0.000$, $r = 0.603$) and O peak latencies ($p = 0.000$, $r = 0.616$), and a weak positive correlation with F peak latency ($p = 0.007$, $r = 0.343$). Age was negatively correlated with V peak amplitude ($p = 0.001$, $r = -0.428$). No significant correlations were found between age and F0, F1, or F2 spectral amplitudes ($p = 0.127$, 0.116, 0.651).

Discussion

This study aimed to characterize the properties of speech-FFR in native Turkish speakers while also examining the effects of age and sex differences. The literature suggests that aging and sex significantly impact various aspects of the human lifespan, thereby contributing to distinct physiological and anatomical differences in auditory processing. For instance, Bethlehem et al. provided a comprehensive analysis of lifespan changes in brain morphology, examining 123,984 MRI scans from 101,457 participants[22]. Their findings revealed that cortical gray matter volume peaks around 5.9 years of age before gradually declining, whereas white matter volume reaches its maximum at approximately 28.7 years, followed by an accelerated decline after the age of 50. Additionally, subcortical gray matter volume peaks during adolescence, around 14.4 years. Our findings suggest that such age-related reductions in gray and white matter volume may underlie aging effect and diminished sex differences in speech-FFR latencies over time, which is consistent with previous neuroanatomical studies.

In our study, significant effects of age were observed. Middle-aged adults exhibited prolonged latencies in multiple peaks compared to young adults, and V peak amplitude was significantly reduced in the older group. These results suggest that early-stage central auditory aging may begin to affect brainstem speech coding; however, these observations are preliminary and require replication in larger and older cohorts before any clinical inference. Bidelman and Momtaz emphasized that Speech-FFR predominantly originates from subcortical sources, governed by strong phase-locking mechanisms at the brainstem and auditory nerve[23]. The weakening of these mechanisms with aging may explain the observed latency prolongations and amplitude reductions.

Our findings are consistent with the study conducted by Lunardelo et al., which reported that middle-aged adults performed worse than young adults in speech perception in noise, dichotic listening, and temporal processing[24]. McFarlane and Sanchez also showed in their study that temporal coding deficits at the subcortical level contribute to speech-in-noise difficulties, even in listeners with clinically normal hearing, highlighting that central auditory and cognitive mechanisms play a role in age-related changes[25].

Studies in literature similarly report delayed latencies and reduced amplitudes with age. Sanju et al. found significantly longer V peak latencies in middle-aged adults and suggested that myelin degeneration after 50 years contributes to slowed conduction[26]. Vander Werff and Burns[14] observed decreased amplitudes in V, A, and O peaks and delayed O latency in elderly adults. Anderson et al.[12] demonstrated that older adults exhibited delays in onset and transition peaks, with decreased phase-locking and response coherence. Further, decreased F0 and harmonic amplitudes in spectral analysis were reported in elderly participants[15]. Other mechanisms may also underlie these changes, including synaptic damage between inner hair cells and the cochlear nerve[27], reduced GABA inhibition[28], and age-related reductions in the number of auditory nerve fibers contributing to synchronous neural activity[29].

In our study, correlation analyses were consistent with the primary group comparisons, indicating age-related slowing in brainstem timing (D, F, O) and reduced V amplitude; however, these associations were modest and do not establish electrophysiological markers. Rather, D, F, O latencies and V amplitude may be considered candidate markers that require validation in larger, independent samples Although spectral analysis did not reveal significant group differences, young adults showed numerically better F0 and F2 amplitudes. The fact that the older group was still in the middle age group may have led to no significant difference in spectral analysis.

Sex effects were also observed. Young adult females exhibited shorter latency durations across all peaks compared to males, whereas in the middle-aged group this difference was preserved only for A and D peaks.

Group Mean (SD)	V Lat	V Amp	A Lat	A Amp	D Lat	D Amp	E Lat	E Amp	F Lat	F Amp	O Lat	O Amp	F0 Amp	F1 Amp	F2 Amp
F-YAG ($n=15$)	6.60 (0.26)	0.32 (0.10)	7.62 (0.24)	−0.16 (0.08)	22.62 (0.47)	−0.22 (0.09)	31.56 (0.48)	−0.26 (0.12)	39.59 (0.56)	−0.20 (0.09)	47.85 (0.31)	−0.22 (0.10)	0.062 (0.024)	0.017 (0.004)	0.005 (0.001)
M-YAG ($n=16$)	6.86 (0.16)	0.26 (0.07)	8.03 (0.26)	−0.14 (0.07)	23.20 (0.48)	−0.19 (0.11)	32.46 (0.84)	−0.21 (0.11)	40.73 (1.05)	−0.19 (0.08)	48.54 (0.32)	−0.22 (0.12)	0.053 (0.030)	0.015 (0.005)	0.004 (0.001)
F-MAG ($n=15$)	6.80 (0.25)	0.20 (0.09)	7.78 (0.32)	−0.15 (0.07)	23.74 (0.94)	−0.23 (0.15)	32.13 (1.28)	−0.21 (0.09)	41.09 (1.04)	−0.27 (0.17)	48.72 (0.48)	−0.21 (0.13)	0.049 (0.024)	0.019 (0.007)	0.004 (0.001)
M-MAG ($n=15$)	7.00 (0.30)	0.17 (0.08)	8.26 (0.65)	−0.12 (0.06)	24.71 (1.14)	−0.22 (0.13)	32.73 (1.24)	−0.20 (0.13)	41.10 (1.20)	−0.23 (0.15)	49.16 (0.76)	−0.19 (0.12)	0.046 (0.025)	0.016 (0.006)	0.004 (0.001)
YAG Total ($n=31$)	6.74 (0.25)	0.29 (0.09)	7.83 (0.32)	−0.15 (0.07)	22.92 (0.55)	−0.20 (0.10)	32.02 (0.81)	−0.23 (0.12)	40.18 (1.02)	−0.19 (0.08)	48.21 (0.47)	−0.22 (0.11)	0.057 (0.027)	0.016 (0.004)	0.004 (0.001)
MAG Total ($n=30$)	6.90 (0.29)	0.19 (0.08)	8.02 (0.56)	−0.13 (0.07)	24.23 (1.14)	−0.23 (0.14)	32.43 (1.27)	−0.21 (0.11)	41.10 (1.10)	−0.25 (0.16)	48.94 (0.66)	−0.20 (0.13)	0.048 (0.024)	0.017 (0.006)	0.004 (0.001)

Table 2. Latency (LAT, ms), amplitude (AMP, μV), and spectral amplitudes (F0, F1, F2) of speech-FFR components across groups. Values are expressed as Mean (SD). LAT = latency; AMP = amplitude. V, A = onset responses; D, E, F = sustained responses; O = offset response. F0, F1, F2 = spectral peaks derived from Fast Fourier Transform (FFT). YAG = Young Adult Group; MAG = Middle-Aged Group; F = female; M = male.

Peak	*n*	YAG Mean ± SD	MAG Mean ± SD	Z	*r*	Cohen's d	*P*
V_latency	61	6.74 ± 0.25	6.90 ± 0.29	−1.976	−0.253	−0.52	0.048*
A_latency	61	7.83 ± 0.32	8.02 ± 0.56	−1.069	−0.137	−0.28	0.285
D_latency	61	22.92 ± 0.55	24.23 ± 1.14	−4.713	−0.603	−1.51	< 0.001*
E_latency	61	32.02 ± 0.81	32.43 ± 1.27	−1.814	−0.232	−0.48	0.070
F_latency	61	40.18 ± 1.02	41.10 ± 1.10	−3.078	−0.394	−0.86	0.002*
O_latency	61	48.21 ± 0.47	48.94 ± 0.66	−4.450	−0.570	−1.39	< 0.001*
Peak	***n***	**F-YAG Mean ± SD**	**F-MAG Mean ± SD**	**Z**	***r***	**Cohen's d**	***P***
V_latency	30	6.60 ± 0.26	6.80 ± 0.25	−1.999	−0.365	−0.78	0.046*
A_latency	30	7.62 ± 0.24	7.78 ± 0.32	−1.516	−0.277	−0.58	0.129
D_latency	30	22.62 ± 0.47	23.74 ± 0.94	−3.561	−0.650	−1.71	< 0.001*
E_latency	30	31.56 ± 0.48	32.13 ± 1.28	−2.270	−0.414	−0.91	0.023*
F_latency	30	39.59 ± 0.56	41.09 ± 1.04	−3.535	−0.645	−1.69	< 0.001*
O_latency	30	47.85 ± 0.31	48.72 ± 0.48	−4.010	−0.732	−2.15	< 0.001*
Peak	***n***	**M-YAG Mean ± SD**	**M-MAG Mean ± SD**	**Z**	***r***	**Cohen's d**	***P***
V_latency	31	6.86 ± 0.16	7.00 ± 0.30	−1.496	−0.269	−0.56	0.135
A_latency	31	8.03 ± 0.26	8.26 ± 0.65	−0.697	−0.125	−0.25	0.486
D_latency	31	23.20 ± 0.48	24.71 ± 1.14	−3.645	−0.655	−1.73	< 0.001*
E_latency	31	32.46 ± 0.84	32.73 ± 1.24	−0.753	−0.135	−0.27	0.451
F_latency	31	40.73 ± 1.05	41.10 ± 1.20	−1.052	−0.189	−0.38	0.293
O_latency	31	48.54 ± 0.32	49.16 ± 0.76	−2.590	−0.465	−1.05	0.010*

Table 3. Comparison of the latency (ms) values of peaks between groups by age (Young and Middle-Aged adult groups/Subgroups). (SD: Standard deviation, MAG: middle-aged adults group, YAG: young adults group, F-YAG: female-young adults group, M-YAG: male-young adults group, F-MAG: female-middle-aged adults group, M-MAG: male-middle-aged adults group, Mann-Whitney-U test, *$p < 0{,}05$).

Peak	*n*	F-YAG Mean ± SD	M-YAG Mean ± SD	Z	*r*	Cohen's d	*P*
V_latency	31	6.60 ± 0.26	6.86 ± 0.16	−2.960	−0.532	−1.26	0.003*
A_latency	31	7.62 ± 0.24	8.03 ± 0.26	−3.604	−0.647	−1.70	< 0.001*
D_latency	31	22.62 ± 0.47	23.20 ± 0.48	−2.995	−0.538	−1.28	0.003*
E_latency	31	31.56 ± 0.48	32.46 ± 0.84	−2.860	−0.514	−1.20	0.004*
F_latency	31	39.59 ± 0.56	40.73 ± 1.05	−3.697	−0.664	−1.78	< 0.001*
O_latency	31	47.85 ± 0.31	48.54 ± 0.32	−4.470	−0.803	−2.69	< 0.001*
Peak	***n***	**F-MAG Mean ± SD**	**M-MAG Mean ± SD**	**Z**	***r***	**Cohen's d**	***P***
V_latency	30	6.80 ± 0.25	7.00 ± 0.30	−1.808	−0.330	−0.70	0.071
A_latency	30	7.78 ± 0.32	8.26 ± 0.65	−2.217	−0.405	−0.89	0.027*
D_latency	30	23.74 ± 0.94	24.71 ± 1.14	−2.369	−0.433	−0.96	0.018*
E_latency	30	32.13 ± 1.28	32.73 ± 1.24	−1.081	−0.197	−0.40	0.280
F_latency	30	41.09 ± 1.04	41.10 ± 1.20	−0.395	−0.072	−0.14	0.693
O_latency	30	48.72 ± 0.48	49.16 ± 0.76	−1.640	−0.299	−0.63	0.100

Table 4. Comparison of the latency (ms) values of peaks between groups by sex (Female and male groups/Subgroups). (SD: Standard deviation, MAG: middle-aged adults group, YAG: young adults group, F-YAG: female-young adults group, M-YAG: male-young adults group, F-MAG: female-middle-aged adults group, M-MAG: male-middle-aged adults group, Mann-Whitney-U test, *$p < 0{,}05$).

Significant sex differences in amplitude were not consistently observed, and the magnitude of sex effects diminished with age. This pattern aligns with the interpretation that age-related neural changes reduce sex differences in brainstem auditory processing[22,23].

Previous studies have suggested that sex hormones may play a role in sex-related differences observed in speech-FFR. For instance, one study in adults analyzed six peaks (V, A, D, E, F, O) and reported significantly shorter latencies and larger V, A, and F amplitudes in women, with these differences correlating with hormone levels[9]. Such findings indicate that hormones may influence brainstem encoding of speech by modulating neural

Peak	*n*	YAG Mean ± SD	MAG Mean ± SD	Z	*r*	Cohen's d	*P*
V_amp	61	0.29 ± 0.09	0.19 ± 0.08	−3.835	−0.491	−1.13	< 0.001*
A_amp	61	−0.15 ± 0.07	−0.13 ± 0.07	−0.845	−0.108	−0.22	0.398
D_amp	61	−0.20 ± 0.10	−0.23 ± 0.14	−0.202	−0.026	−0.05	0.840
E_amp	61	−0.23 ± 0.12	−0.21 ± 0.11	−0.794	−0.102	−0.20	0.427
F_amp	61	−0.19 ± 0.08	−0.25 ± 0.16	−0.729	−0.093	−0.19	0.466
O_amp	61	−0.22 ± 0.11	−0.20 ± 0.13	−0.881	−0.113	−0.23	0.378
Peak	***n***	**F-YAG Mean ± SD**	**F-MAG Mean ± SD**	**Z**	***r***	**Cohen's d**	***P***
V_amp	30	0.32 ± 0.10	0.20 ± 0.09	−2.867	−0.523	−1.23	0.004*
A_amp	30	−0.16 ± 0.08	−0.15 ± 0.07	−0.541	−0.099	−0.20	0.589
D_amp	30	−0.22 ± 0.09	−0.23 ± 0.15	−0.415	−0.076	−0.15	0.678
E_amp	30	−0.26 ± 0.12	−0.21 ± 0.09	−0.996	−0.182	−0.37	0.319
F_amp	30	−0.20 ± 0.09	−0.27 ± 0.17	−0.935	−0.171	−0.35	0.350
O_amp	30	−0.22 ± 0.10	−0.21 ± 0.13	−0.430	−0.079	−0.16	0.663
Peak	***n***	**M-YAG Mean ± SD**	**M-MAG Mean ± SD**	**Z**	***r***	**Cohen's d**	***P***
V_amp	31	0.26 ± 0.07	0.17 ± 0.08	−2.616	−0.470	−1.06	0.009*
A_amp	31	−0.14 ± 0.07	−0.12 ± 0.06	−0.714	−0.128	−0.26	0.475
D_amp	31	−0.19 ± 0.11	−0.22 ± 0.13	−0.575	−0.103	−0.21	0.565
E_amp	31	−0.21 ± 0.11	−0.20 ± 0.13	−0.337	−0.061	−0.12	0.736
F_amp	31	−0.19 ± 0.08	−0.23 ± 0.15	−0.218	−0.039	−0.08	0.828
O_amp	31	−0.22 ± 0.12	−0.19 ± 0.12	−0.712	−0.128	−0.26	0.476

Table 5. Comparison of the amplitude (μV) values of peaks between groups by age (Young and Middle-Aged adult groups/Subgroups). (SD: Standard deviation, amp: amplitude, MAG: middle-aged adults group, YAG: young adults group, F-YAG: female-young adults group, M-YAG: male-young adults group, F-MAG: female-middle-aged adults group, M-MAG: male-middle-aged adults group, Mann-Whitney-U test, *$p < 0{,}05$).

Peak	*n*	F-YAG Mean ± SD	M-YAG Mean ± SD	Z	*r*	Cohen's d	*P*
V_amp	31	0.32 ± 0.10	0.26 ± 0.07	−1.783	−0.320	−0.68	0.075
A_amp	31	−0.16 ± 0.08	−0.14 ± 0.07	−1.051	−0.189	−0.38	0.293
D_amp	31	−0.22 ± 0.09	−0.19 ± 0.11	−1.466	−0.263	−0.55	0.143
E_amp	31	−0.26 ± 0.12	−0.21 ± 0.11	−1.444	−0.259	−0.54	0.149
F_amp	31	−0.20 ± 0.09	−0.19 ± 0.08	−0.238	−0.043	−0.09	0.812
O_amp	31	−0.22 ± 0.10	−0.22 ± 0.12	−0.198	−0.036	−0.07	0.843
Peak	***n***	**F-MAG Mean ± SD**	**M-MAG Mean ± SD**	**Z**	***r***	**Cohen's d**	***P***
V_amp	30	0.20 ± 0.09	0.17 ± 0.08	−0.874	−0.160	−0.32	0.382
A_amp	30	−0.15 ± 0.07	−0.12 ± 0.06	−1.059	−0.193	−0.39	0.289
D_amp	30	−0.23 ± 0.15	−0.22 ± 0.13	−0.083	−0.015	−0.03	0.934
E_amp	30	−0.21 ± 0.09	−0.20 ± 0.13	−0.727	−0.133	−0.27	0.467
F_amp	30	−0.27 ± 0.17	−0.23 ± 0.15	−0.872	−0.159	−0.32	0.383
O_amp	30	−0.21 ± 0.13	−0.19 ± 0.12	−0.519	−0.095	−0.19	0.604

Table 6. Comparison of the amplitude (μV) values of peaks between groups by sex (Female and male groups/Subgroups). (SD: Standard deviation, amp: amplitude, MAG: middle-aged adults group, YAG: young adults group, F-YAG: female-young adults group, M-YAG: male-young adults group, F-MAG: female-middle-aged adults group, M-MAG: male-middle-aged adults group, Mann-Whitney-U test, *$p < 0{,}05$).

phase-locking (amplitude) and conduction speed (latency). Although our study did not include hormonal measurements, our results regarding sex-related differences in speech-FFR are consistent with this report as well as with other studies highlighting sex effects in auditory brainstem responses[5,6,30–32]. Our results are consistent with these findings, showing clearer sex-related differences in younger adults that become less pronounced with aging.

Although no statistically significant spectral amplitude differences (F0, F1, F2) were observed, this null result may reflect the limited sensitivity of spectral measures to early-to-middle aging. Previous studies suggest that

spectral degradation, particularly reduced F0 encoding, becomes more evident in older adults (>60 years)[33]. Therefore, the absence of group differences in the present study should not be interpreted as a lack of spectral effects but rather underscores the need for broader age ranges and longitudinal investigations.

The onset complex (V–A–C) reflects the rapid acoustic features of consonants, with the V–A complex indexing the onset and C marking the transition to the vowel. The sustained portion (D–E–F) corresponds to the periodic and harmonic structure of the vowel, while O represents the offset response, indicating a decline in neural synchrony. In our study, prolonged latencies in D, F, and O and reduced V amplitude with age suggest diminished temporal precision for consonant onsets and weaker periodic encoding of vowels. These alterations may contribute to age-related challenges in speech-in-noise perception. The sex-related latency differences observed in younger adults may further reflect variations in neural synchrony that appear to converge with age.

Our study also contributes language-specific normative data for Turkish speakers. Studies in literature show that native language can profoundly affect the neural mechanisms underlying speech processing, as demonstrated by variations in Speech-FFR across different language groups[10,11]. Previous cross-linguistic studies have shown that tonal language speakers exhibit stronger pitch tracking than non-tonal language speakers[34]. While such findings suggest that native language experience may shape subcortical speech processing, the present study did not directly test such effects. Thus, our findings therefore provide pre-normative data specific to Turkish speakers, and future cross-linguistic research is required to determine how these results compare with other language groups.

Clinically, establishing age and sex stratified normative ranges for Turkish speakers may help hypothesis generation and could inform future studies on early detection, but clinical implementation requires replication and prospective validation. Age- and sex-specific norms can reduce misinterpretation due to demographic variability and support more precise diagnosis in populations at risk for auditory processing disorders or early presbycusis.

Conclusion

In conclusion, this study provides preliminary normative data on speech-FFR in native Turkish speakers. Age was associated with prolonged latencies (particularly D, F, and O) and reduced V amplitude, while sex-related latency differences were evident in younger adults but diminished with age. These findings emphasize the clinical need for age- and sex-specific normative data in Turkish speakers to support accurate interpretation of speech-FFR in both research and clinical practice. Moreover, the results suggest that early stage of central auditory aging can be detected even in middle-aged individuals.

Limitations

This study has several limitations. First, the total sample size ($n = 61$) and subgroup distribution ($n = 15$–16) may have limited statistical power, particularly for sex-based comparisons; we therefore report effect sizes alongside p-values, but replication with larger cohorts is warranted. Second, the age range was restricted to young and middle-aged adults (18–60 years), so the findings reflect early-to-middle auditory aging rather than late-life changes; future work including adults > 60 years is needed to map lifespan trajectories. Third, as the study is cross-sectional, it cannot address within-person change. Fourth, generalizability may be constrained by the Turkish-language stimulus and sociocultural context. Finally, some potentially influential factors (e.g., musical training, cognitive/attentional status, and hormonal status in females) were not systematically controlled, and multiple peak-wise comparisons increase type I error risk; accordingly, interpretation should emphasize effect sizes and the consistency of patterns across peaks.

Data availability

The datasets used and/or analysed during the current study available from the corresponding author (İlayda BAŞOĞLU; [ilayda.basoglu@medipol.edu.tr](mailto: ilayda.basoglu@medipol.edu.tr)) on reasonable request.

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Author contributions

The concept and design of the study was decided by İB, GÖ, EB; data was acquired and analyzed by İB, YB; İB, GÖ, EB, YB drafted an important part of the article, EB reviewed the final version.

Declarations

Competing interests

The authors declare no competing interests.

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Ethical approval

The study was conducted at the Audiology Laboratory of Istanbul Medipol University between January 1, 2021, and July 1, 2021. Ethical approval for the research titled "Comparison Of Speech-FFR by Age and Sex in Young and Middle-Aged Adults" was obtained from the Non-Interventional Clinical Research Ethics Committee of Istanbul Medipol University (Approval Number: E-10840998-772.02-2612; Approval Date: January 27, 2021). All procedures were performed in accordance with the principles of the Declaration of Helsinki. Written informed consent was obtained from all participants prior to their inclusion in the study.

Additional information

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