Auditory and Vestibular Research

The Binaural Interaction Component of Auditory Late Responses in Simultaneous Bilingualism

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Highlights

- Shorter latency of ALR components observed in simultaneous bilinguals
- Bilinguals demonstrate reduced BIC amplitude in the P1-N1 complex
- BIC amplitude variability in ALR waves observed in two studied groups

ABSTRACT

Background and aim: Bilingualism is linked to modifications in neural pathways that influence auditory processing. Auditory evoked potentials, including auditory late responses (ALRs), are cortical waves generated in response to sound, which provide insights into auditory processing. This study investigated the relationship between simultaneous bilingualism and binaural processing by examining the binaural interaction component (BIC) of ALRs.

Methods: This cross-sectional study included fifty-six participants, aged 19 to 30 years, classified into monolingual (Persian) and simultaneous bilingual (Turkish-Persian) groups (MG and BG). ALRs were recorded during both monoaural and binaural stimulation. P1, N1, and P2 latencies, as well as P1-N1 and N1-P2 inter-peak amplitudes, were recorded. The BIC was calculated by subtracting the binaural response waveform from the sum of the summed monaural response waveforms.

Results: In binaural stimulation and for the BIC values, BG exhibited shorter mean latencies for all ALR components compared to the MG. This latency reduction reached statistical significance for the P2 component during binaural stimulation and for the N1 and P2 components in the BIC ($p<0.05$). Mean inter-peak amplitudes showed variability between groups, with the MG demonstrating a significantly greater P1-N1 component amplitude in the BIC ($p<0.05$).

Conclusion: The reduction in latency and BIC amplitude of the ALR components in simultaneous bilinguals suggests possible changes in the auditory cortical processing. Meanwhile, the variability of BIC amplitude highlights the need for caution in interpreting this component. Also, all analyses were performed without correction for multiple comparisons. Therefore, these exploratory findings require confirmation in future studies.

Keywords: Auditory evoked potentials; auditory late responses; bilingualism; binaural processing; binaural hearing; binaural interaction component

Introduction

The growth of global interconnectedness, influenced by factors such as immigration, politics, and tourism, has emphasized the remarkable human capacity to acquire and communicate in multiple languages [1]. Consequently, over half of the world's population is bilingual. Bilingualism can be defined as the ability to communicate effectively in both one's mother tongue and a secondary acquired language [2]. Simultaneous bilingualism refers to the acquisition of two languages from birth, whereas sequential bilingualism refers to learning a second language after the first has been established [3]. People who speak two languages possess a wealth of experience navigating between their separate language systems and managing this process in daily life. This practice ultimately strengthens their general cognitive processes and functioning. Bilingualism modifies neural pathways associated with cognitive functions and sensory processing, playing a significant role in neuroplastic alterations

and various structural changes within the brain. The extent of these modifications depends on several factors, such as the age at which the second language is acquired, the individual's proficiency in the second language, and other related elements [4].
Considering that "hearing" is the main sensory input for stimuli crucial to learning a second language, the link between this sense and bilingualism is undeniable, despite ongoing research efforts to further explore and understand their relationship [5]. Simultaneous bilinguals experience an enriched auditory environment. During their communication, they must focus on building numerous connections between sounds and their associated meanings. This experience holds the potential to significantly improve auditory processing performance [6]. Prior research suggests that plasticity-driven modifications at both cortical and sub-cortical levels take place during the course of acquiring and mastering two languages. These adaptations result in enhanced auditory processing capabilities that are more efficient and flexible in bilingual individuals [7].
Binaurality refers to the capacity of central auditory nervous system (CANS) to process sound input from both ears, involving the analysis, integration, and separation of auditory information [8]. Binaural hearing offers benefits over monaural hearing in daily life and is supported by research in both behavioral and electrophysiological assessments, for individuals with normal hearing and those with hearing impairments [9]. The CANS processes auditory information using interaural time difference (ITD) and interaural level difference (ILD) cues, which are based on the difference in arrival time and intensity level of sound between the two ears. These binaural cues are essential for sound localization and play a significant role in speech perception in noisy environments [10, 11]. The superior olivary complex (SOC) in the auditory brainstem is responsible for initially processing ITD and ILD cues. This binaural information is then transmitted to higher levels of the CANS for further processing [11]. Since binaural processing relies on temporal synchronization and interhemispheric coordination, and given that bilingual experience continuously trains these mechanisms, simultaneous bilingualism may modulate binaural integration at both cortical and subcortical levels (e.g., SOC) [7, 12]. Auditory evoked potentials (AEPs) offer a noninvasive method to study how the human brain processes these binaural cues [11].
AEPs are electrical responses generated in response to auditory stimuli, representing the electrical activity in the brainstem, subcortical, and cortical regions. Two critical characteristics of AEPs are latency and amplitude. Latency describes the time interval between stimulus presentation and the peak amplitude of a wave, whereas amplitude indicates the difference in electrical potential (voltage) between electrode pairs [13, 14]. Previous research has utilized this method to investigate enhanced auditory processing in bilinguals, identifying variations in latency and amplitude of AEP components. Specifically, bilinguals have shown shorter latencies in Speech-evoked auditory brainstem responses (Speech-ABR) [7, 15], N1 and P2 components of auditory late responses (ALRs) [13], P300 [16], and mismatch negativity (MMN) [17], as well as amplitude differences in auditory middle latency responses (AMLRs) [18] and late negative difference (Nd1) [19].
ALRs, comprising P1, N1, and P2 components, reflect cortical auditory processing [20]. ALRs can be elicited using both monoaural and binaural stimuli, making them a valuable tool for investigating the binaural interaction component (BIC). The BIC represents the neural interaction resulting from simultaneous stimulation of both ears, reflecting how the central auditory system integrates binaural inputs [8]. Derived from AEPs, the BIC is calculated as the algebraic sum of the monoaural responses from the right and left ears, subtracted from the response obtained through bilateral stimulation [8, 21]. Inhibitory processes within the auditory system diminish neural responses to binaural signals, leading to a comparatively smaller electrophysiological response to binaural stimulation than the summed response to individual monaural signals [9].
The BIC of ALRs represents the electrical activity of binaural neurons and serves as an effective tool to examine the CANS structures and assess the functionality of binaural auditory capabilities, including sound localization [8]. To the best of our knowledge, the impact of bilingualism on these components of ALRs has not been previously investigated, and no studies have specifically examined this issue; therefore, the present study aimed to assess bilingualism's effect on binaural hearing abilities by examining the latencies and amplitudes of the BIC of ALRs (including P1, N1, P2). BIC was selected as the primary measure in this study because it provides an objective index of cortical binaural integration and reflects higher-order cortical processing that is sensitive to experience-dependent plasticity such as bilingualism [22]. We hypothesized that bilingual individuals would exhibit modifications in BIC and demonstrate superior binaural processing abilities at the cortical level, including alterations in amplitudes and latencies.

Method

Participants

This cross-sectional study was granted ethical clearance by the Research Ethics Committee of Shahid Beheshti University of Medical Sciences (SBMU). Fifty-six participants, aged 19 to 30 years, were classified into monolingual and bilingual experimental groups based on their self-reported proficiency in a second language. The participants were all graduate and postgraduate students, who were fully informed about the study's content and provided consent prior to participation. Participants were divided into two distinct groups: (1) a monolingual group (MG) consisting of 28 Persian-speaking individuals (MG; mean age = 21.82 years, SD = 2.81 years; 8 females), and (2) a simultaneous bilingual group (BG) comprising 28 Turkish-Persian speaking individuals (BG; mean age = 22.35 years, SD = 2.48 years; 7 females). Participants responded to a self-reported second language proficiency questionnaire, that utilized a subjective rating scale ranging from one to seven (1= very low, 7= native-like) to assess their second language proficiency and usage [23]. Participants who indicated their second language proficiency as levels six or seven (signifying fluency or high fluency, based on Paap and Greenberg learned the second language before the age of six, and actively used that language every day were assigned to the BG [24].

The hearing examination, which included otoscopy, audiometry in the range of 250 Hz to 8000 Hz (using AC40, Interacoustics, Denmark) in a sound-controlled environment, tympanometry (using AZ26, Interacoustics, Denmark), and acoustic reflex testing, was carried out to ensure normal hearing function. Inclusion criteria encompassed bilateral normal hearing thresholds (≤ 20 dB HL), tympanogram type An, and normal ipsilateral and contralateral acoustic reflexes. Individuals with a history of otologic or neurologic disorders and those with musical training were excluded to minimize any possible influence on the study outcomes. Given the variations in ALRs among right- and left-handed individuals in prior study [13], our study involved 3 bilingual and 4 monolingual left-handed participants, making an effort to maintain a relatively equal number of left-handed subjects in both groups. The two groups were closely matched with respect to sex and age.

Auditory late responses recording:

The Bio-logic Navigator Pro System (Natus Medical Inc., USA) was utilized for the recording and analysis of ALRs, with insert earphones (ER-3A) delivering the stimuli. Participants were seated comfortably in a quiet room and were asked to look at a visual target in front of them to reduce blinking and ocular artifacts during ALR recording. They were instructed to focus on the auditory stimuli and report the count of stimuli at the end of each recording session to ensure concentration, as previous research has demonstrated that sustained attention and arousal levels can significantly modulate auditory evoked response amplitudes, particularly at the cortical level. Electrodes were positioned on the Fz (non-inverting), the earlobe of the test ear (A1 or A2) (inverting), and Fpz (ground) areas. In the monaural recording mode, the inverting electrode was placed on the ipsilateral earlobe, while in the binaural recording mode, it was placed simultaneously on both earlobes. The impedance of each electrode was kept below 5 kΩ, and the impedance difference between the electrodes did not exceed 2 kΩ [13]. ALRs were elicited using a 40 ms synthesized /da/ syllable which was provided by the manufacturer of device. This stimulus was presented monaurally to the right ear and the left ear (separately), and simultaneously binaural. It was presented at a rate of 0.9 stimuli per second and calibrated intensity level of 70 dB nHL. Sweeps containing artifacts exceeding ±47.5 µV were automatically rejected online, and 100 accepted sweeps per condition was required for inclusion in the final analysis. The recorded responses were averaged in real-time using a 0.1 to 30 Hz bandpass filter and digitally sampled at 512 points over a 533 ms epoch time window, which incorporated a 100 ms pre-stimulus time frame [13]. To guarantee the reliability of results, waveforms were recorded three times in each condition. The final waveform used for wave marking and additional analysis was obtained by averaging these three recordings. The P1, N1, and P2 components were first marked meticulously by visual inspection by the first author and subsequently validated by the second author.

The P1 peak was recognized as the positive peak occurring between 50 and 75 milliseconds, the N1 peak was identified as the most negative peak between 90 and 150 milliseconds, and the P2 peak was determined as the most positive peak following the N1 component. The amplitude was quantified as the peak-to-peak difference from P1-N1 and N1-P2. Latency of P1, N1, and P2 peaks was measured separately for each component. The binaural interaction waveform was calculated by subtracting the binaural response from the summed monaural responses of the left and right ears, which were recorded separately, and can be expressed mathematically as:

(BIC) = ([R + L] - Binaural) [7]. The primary objectives of this analysis were to compare the mean BIC values for the P1-N1 and N1-P2 inter-peak amplitudes between MG and BG and to assess differences in the latencies of P1, N1, and P2 components of the BIC waveform between these groups.

Data analysis

The collected data was inputted into a computer and analyzed with the IBM SPSS software package, version 17. In order to assess the normality of distribution, the Kolmogorov-Smirnov (K-S) test was applied. Consequently, the Independent Samples t-test was selected as the appropriate statistical analysis method. A confidence level greater than 95% ($p<0.05$) was established as the threshold for statistically significant results.

Results

A total of 56 participants were included in the study, comprising 15 females (MG: 8, BG: 7) and 41 males (MG: 20, BG: 21). Preliminary hierarchical regressions with gender and handedness as predictors revealed no significant main effects or interactions with group assignment on any dependent measure (all $p>0.30$), confirming these variables did not confound the primary results. The overall mean age was 22.08 years, with subgroup means of 21.82 ± 2.81 years for MG and 22.35 ± 2.48 years for BG participants. Regarding academic status, 14 participants were enrolled in master's programs (MG: 6, BG: 8), while 42 were undergraduate students (MG: 22, BG: 20). The Kolmogorov-Smirnov test confirmed that all dependent variables followed a normal distribution ($p>0.05$ for all variables), justifying the use of parametric statistical analyses. A total of 15 independent-samples t-tests were performed (9 latency comparisons and 6 amplitude comparisons). All analyses were conducted without correction for multiple comparisons, consistent with the exploratory nature of this study. With 15 comparisons, the uncorrected analyses yield an approximate 54% chance of at least one false positive. Consequently, all significant findings reported below should be interpreted with extreme caution.

Table 1 provides an overview of the descriptive statistics and the group comparison (independent-samples t-test) outcomes for binaural stimulation, the summed right and left ear stimulation values, and BIC values of ALRs latency for both groups of participants. Detailed analysis of monaural right and left ear parameters from the same sample has been reported in our earlier publication [13]; the present study focuses on the BIC analysis, binaural stimulation, and summation of monaural (R+L) values. The mean latency of all ALR components was shorter in the BG compared to the MG for both binaural stimulation and BIC. This discrepancy in latency was statistically significant for the N1 and P2 components in the (R+L) condition, for the P2 component in binaural stimulation, and for the N1 and P2 components in BIC ($p<0.05$) (Figure 1).

Table 2 presents a summary of the descriptive statistics and the group comparison (independent-samples t-test) results for binaural stimulation, the algebraic summation (R+L), and BIC values of ALRs inter-peak amplitude across both participant groups. Under binaural conditions, the mean inter-peak amplitude of P1-N1 was larger in the BG while the mean amplitude of N1-P2 was greater in the MG. The mean amplitude of the N1-P2 component in the BIC was larger in the BG. However, these differences in amplitude were not found to be statistically significant ($p>0.05$). The mean inter-peak amplitude of the P1-N1 component in the BIC was significantly larger in the MG ($p<0.05$) (Figure 2).

Discussion

This study investigated the impact of simultaneous bilingualism on binaural hearing abilities by examining the BIC of ALRs. We hypothesized that simultaneous bilingual individuals would show alterations in BIC, reflecting enhanced cortical-level binaural processing capabilities. Our findings revealed significant differences in BIC latencies and amplitudes between MG and BG, with the mean latency of all ALR components occurring earlier in the BG than in the MG for both binaural stimulation and BIC. Moreover, the mean inter-peak amplitude of the P1-N1 component in the BIC was significantly larger in the MG. However, it must be emphasized that all analyses were performed without correction for multiple comparisons, and therefore, results should be interpreted with extreme caution.

Behavioral assessments of binaural processing involve tasks like diotic/dichotic word presentation, masking level differences (MLDs), and sound localization, but these rely on subject attention and response. This can be problematic for older or younger patients with attention or cognitive issues. AEPs, an electrophysiological measure of brain responses to sound, offer an alternative approach to assessing binaural processing [10]. Binaural stimulation of the auditory system involves more than just adding together the responses from each ear. The complex connections within the binaural auditory system allow for both summation and inhibition [10]. Inhibition, defined as a relative decrease in evoked potentials during binaural stimulation compared to the sum of monaural responses, is thought to be a key mechanism in binaural processing [22]. Prior research indicating increased binaural interaction at middle- and long-latency potentials compared to brainstem potentials suggests that cortical activity plays a larger role in binaural processing than brainstem activity [25, 26].

Both binaural and summed monaural (R+L) responses, as well as BIC responses, revealed shorter ALR component latencies in simultaneous bilinguals. These differences reached statistical significance for the N1 and P2 components in the summed monaural (R+L) condition, for the P2 component under binaural stimulation, and for the N1 and P2 components in the BIC. Consistent with our exploratory findings, previous research indicates that bilinguals exhibit shorter AEP latencies. Specifically, studies by Molnar et al. demonstrated earlier MMN latency in bilinguals compared to monolinguals [17]. Similarly, Jafari et al. and Koravand et al. observed shorter latencies in speech-evoked ABR components among bilinguals [7, 15], while Marques et al. reported shorter P300 latencies in bilingual children [16]. In current study, shorter latencies of ALR's BIC, summed (R+L) and binaural responses in simultaneous bilinguals likely reflect enhanced efficiency in auditory cortical processing driven by the cognitive demands of managing two languages. This is largely attributed to learning-induced neuroplasticity resulting from second language acquisition, leading to structural and functional brain changes [7, 15]. These changes can stimulate the auditory neural pathway and enhance neural synchrony within the CANS, resulting in a more optimized system and ultimately leading to faster processing and reduced latencies [16, 17]. While this study did not directly assess myelination, it has been suggested that simultaneous bilingualism is associated with experience-driven myelination, which may play a role in enhancing neural conduction velocity, potentially contributing to the shorter latencies observed in simultaneous bilinguals [27].

Our study revealed differences in inter-peak amplitudes between simultaneous bilinguals and monolinguals during binaural listening. Although bilinguals tended to exhibit larger P1-N1 amplitudes, and monolinguals larger N1-P2 amplitudes in binaural responses, these differences were not statistically significant. However, monolinguals demonstrated statistically significant larger BIC amplitudes for P1-N1, while bilinguals showed larger BIC amplitudes for N1-P2, a difference that was not statistically significant. These insignificant and heterogeneous amplitude results are consistent with prior research, as Marques et al. and Rämä et al. similarly found no significant differences in MMN and P300 potentials between monolinguals and bilinguals, suggesting that bilingualism may not significantly impact the overall level of electrical activity in the primary and secondary auditory cortices [16, 19].

A significantly larger BIC amplitude for the P1–N1 complex was observed in monolingual listeners; however, as this finding was very close to the significance threshold ($p=0.042$), it should be interpreted with caution. One possible interpretation is that the lower BIC values seen in simultaneous bilinguals may be related to their lower (R+L) amplitude or larger binaural response amplitudes; however, as these differences was not statistically significant ($p>0.05$), the precise mechanism underlying the observed BIC differences remains unclear. It has been hypothesized that this pattern might reflect less efficient inhibitory processes in the CANS, potentially resulting from experience-dependent neural changes associated with simultaneous bilingualism. This reduced inhibitory efficiency could have negative functional consequences for multiple benefits of binaural auditory processing, including localization, loudness summation and speech perception in noise [28, 29]. Research using speech-ABRs has shown that bilingual listeners often display differences in neural timing and auditory processing compared with monolinguals, particularly in noisy conditions, where neural responses may be more disrupted and speech perception poorer [28]. Additionally, Krizman et al. reported that activating two language systems at the same time creates processing competition, which can use up inhibitory control resources and reduce efficiency in sensory tasks such as speech-in-noise perception and auditory discrimination [12]. Furthermore, Skoe and Karayanidi have found that bilinguals tend to perform worse than monolinguals on speech-in-noise tasks, supporting the idea that inhibitory and cognitive control demands of bilingual listening can negatively impact auditory tasks [30]. In current study, the significant BIC amplitude differences observed in the P1-N1 component, but not in N1-P2, could potentially suggest that altered binaural auditory processing mechanisms in the simultaneous bilinguals primarily influence early cortical stages [22]. This may be consistent with the role of P1 and N1 in reflecting early, automatic sensory processing of the physical and temporal characteristics of auditory stimuli, whereas P2 could represent later, more complex stages such as the conscious detection of auditory changes [31].

In summary, this study demonstrated significant differences in ALR latencies and amplitudes during three conditions including summed (R+L), binaural stimulation, and BIC between monolinguals and simultaneous bilinguals. These findings were not heterogeneous, especially regarding amplitude parameters. The coexistence of shorter latencies and lower BIC amplitude in simultaneous bilinguals suggests enhanced neural efficiency in early sensory processing, as indexed by shorter ALR latencies. However, the constant management of two competing language systems places greater demands on inhibitory control resources, potentially reducing efficiency in tasks requiring suppression of irrelevant information [12]. These findings suggest that the advantages of simultaneous bilingualism are contradictory, and given the limitations of the study, which are discussed below, caution should be exercised in interpreting the results.
Limitations of this study should be acknowledged. First, our sample focused on Turkish-Persian simultaneous bilinguals, and future research could explore a broader range of language pairings and a more diverse bilingual population. Second, prior studies have noted that the high inter-subject variability of BIC may limit its clinical utility as a binaural function measure [32], which warrants consideration and suggests that our findings should be interpreted with caution. Third, while our sample size is comparable to previous studies, it may be underpowered for moderate effects, and thus Type II error for non-significant findings cannot be ruled out. Fourth, multiple comparisons were performed without correction for family-wise error rate; therefore, the significant findings should be interpreted with caution. Future research could also investigate both the neural mechanisms underlying the observed differences in binaural processing, using neuroimaging techniques like functional magnetic resonance imaging, and employ behavioral testing to validate our findings. Additionally, factors such as age of second language acquisition, daily language use, and proficiency levels should be considered in future studies.

Conclusion

This exploratory study demonstrated shorter latency of auditory late response' components (P2 in binaural stimulation and N1 and P2 of binaural interaction component) in simultaneous bilinguals. A significantly lower binaural interaction component amplitude for the P1-N1 complex was also observed in this group, which could result from a decrease in monaural summation amplitude or an increase in binaural stimulation. Variability in amplitude results was also evident. These differences in latency and amplitude may reflect alterations in simultaneous bilinguals' cortical processing. Shorter latencies confirm the advantage of simultaneous bilingualism, while the opposite of these findings is inferred from the binaural interaction component amplitude. In other words, the findings are conflicting regarding the impact of simultaneous bilingualism on auditory cortical levels.

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Conflict of Interest Statement

The authors declare that they have no competing interests.

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Author Contributions

AH: Data acquisition, writing – original draft, formal analysis; FH: Study design, supervision, writing – review and editing.

Ethics approval and consent to participate

This study received ethical approval from the Research Ethics Committee of Shahid Beheshti University of Medical Sciences (approval code IR.SBMU.RETECH.REC.1405.251). All participants provided informed consent after being fully briefed on the objectives and procedures of the research.

References:

1. Cisneros JD. Multilingualism, Multiculturalism, and Migration: A Critical Assessment. American Literary History. 2019;31(3):519-29. [DOI:10.1093/alh/ajz018]
2. Mouthon M, Annoni JM, Asaid Khateb A. The bilingual brain. Swiss Arch Neurol Psychiatry Psychother. 2013;164(8):266-73. [DOI:**10.4414/sanp.2013.00210**]
3. VAN Dijk C, VAN Wonderen E, Koutamanis E, Kootstra GJ, Dijkstra T, Unsworth S. Cross-linguistic influence in simultaneous and early sequential bilingual children: a meta-analysis. J Child Lang. 2022;49(5):897-929. [DOI:10.1017/S0305000921000337]
4. Desjardins JL, Bangert A, Gomez N. What Does Language Have to Do With It? The Impact of Age and Bilingual Experience on Inhibitory Control in an Auditory Dichotic Listening Task. J Speech Lang Hear Res. 2020;63(5):1581-94. DOI: 10.1044/2020_JSLHR-19-00238
5. Gresele AD, Garcia MV, Torres EM, Santos SN, Costa MJ. Bilingualism and auditory processing abilities: performance of adults in dichotic listening tests. Codas. 2013;25(6):506-12. [DOI:10.1590/S2317-17822014000100003]
6. Kraus N, White-Schwoch T. The bilingualism paradox. The Hearing Journal. 2017;70(1):40, 42. [*DOI:* 10.1097/01.HJ.0000511727.48959.2d]
7. Jafari Z, Villeneuve C, Thompson J, Koravand A. Subcortical plasticity and enhanced neural synchrony in multilingual adults. Bilingualism: Language and Cognition. 2022;26(2):307-16. DOI:10.1017/S1366728922000645
8. Oliveira LS, Oliveira ACS, Alcântara YB, Vieira CA, Ferreira DMO, Chagas EFB, Frizzo ACF. Study of Binaural Auditory Cortical Response in Children with History of Recurrent Otitis. Int Arch Otorhinolaryngol. 2020;25(4):e490-e495. DOI: 10.1055/s-0040-1718527
9. Roup CM, Leigh ED. Individual Differences in Behavioral and Electrophysiological Measures of Binaural Processing Across the Adult Life Span. Am J Audiol. 2015 Jun;24(2):204-15. DOI: 10.1044/2015_AJA-14-0017
10. Leigh-Paffenroth ED, Roup CM, Noe CM. Behavioral and electrophysiologic binaural processing in persons with symmetric hearing loss. J Am Acad Audiol. 2011 Mar;22(3):181-93; quiz 194-5. DOI: 10.3766/jaaa.22.3.6
11. Zhang F, Boettcher FA. Effects of interaural time and level differences on the binaural interaction component of the 80 Hz auditory steady-state response. J Am Acad Audiol. 2008 Jan;19(1):82-94. DOI: 10.3766/jaaa.19.1.7
12. Krizman J, Tierney A, Nicol T, Kraus N. Listening in the Moment: How Bilingualism Interacts With Task Demands to Shape Active Listening. Front Neurosci. 2021 Dec 10;15:717572. DOI: 10.3389/fnins.2021.717572
13. Hajimohammadi A, Heidari F. The effect of bilingualism on obligatory components of auditory late responses in young adults: a cross-sectional study. Egypt J Otolaryngol. 2025;41:6. [doi:10.1186/s43163-025-00757-y]
14. Rinker T, Yu YH, Wagner M, Shafer VL. Language Learning Under Varied Conditions: Neural Indices of Speech Perception in Bilingual Turkish-German Children and in Monolingual Children With Developmental Language Disorder (DLD). Front Hum Neurosci. 2022 Jan 4;15:706926. DOI: 10.3389/fnhum.2021.706926
15. Koravand A, Thompson J, Chénier G, Kordjazi N. The Effects of Bilingualism on Speech Evoked Brainstem Responses Recorded in Quiet and in Noise. Can Acoust. 2019;47(2):23-30.
16. Marques PM, Mattiazzi ÂL, Ferreira L, Oppitz SJ, Biaggio EPV. The Effect of Learning English on P300 in Children. Int Arch Otorhinolaryngol. 2021 Apr;25(2):e284-e288. DOI: 10.1055/s-0040-1710304
17. Molnar M, Baum S, Polka L, Ménard L, Steinhauer K. Automatic auditory discrimination of vowels in simultaneous bilingual and monolingual speakers as measured by the mismatch negativity (MMN). J Acoust Soc Am. 2009;125:2754. [DOI:10.1121/1.4784621]
18. Shokri S, Mohamadkhani G, Pourbakht A, Jalayi S, Sanayi R. [Comparison of auditory middle latency responses in Azari-Persian bilinguals and Persian monolingual]. J Res Rehabil Sci. 2014;9(5):1-10. Persian
19. Rämä P, Leminen A, Koskenoja-Vainikka S, Leminen M, Alho K, Kujala T. Effect of language experience on selective auditory attention: An event-related potential study. Int J Psychophysiol. 2018 May;127:38-45. DOI: 10.1016/j.ijpsycho.2018.03.007
20. Hajimohammadi A, Heidari F. Monitoring the Efficacy of Auditory Training through Changes in Brainstem and Cortical Auditory Evoked Potentials: A Systematic Review. *Egypt J Otolaryngol. 2024;* **40:**95. [DOI:10.1186/s43163-024-00606-4]
21. ElMoazen D, Sobhy O, Abdou R, AbdelMotaleb H. Binaural interaction component of the auditory brainstem response in children with autism spectrum disorder. Int J Pediatr Otorhinolaryngol. 2020 Apr;131:109850. DOI: 10.1016/j.ijporl.2019.109850
22. Henkin Y, Yaar-Soffer Y, Givon L, Hildesheimer M. Hearing with Two Ears: Evidence for Cortical Binaural Interaction during Auditory Processing. J Am Acad Audiol. 2015 Apr;26(4):384-92. DOI: 10.3766/jaaa.26.4.6
23. Li P, Zhang F, Tsai E, Puls B. Language history questionnaire (LHQ 2.0): A new dynamic web-based research tool. Bilingualism: Language and Cognition. 2014;17(3):673-80. DOI:10.1017/S1366728913000606
24. Paap KR, Greenberg ZI. There is no coherent evidence for a bilingual advantage in executive processing. Cogn Psychol. 2013 Mar;66(2):232-58. DOI: 10.1016/j.cogpsych.2012.12.002
25. McPherson DL, Starr A. Binaural interaction in auditory evoked potentials: brainstem, middle- and long-latency components. Hear Res. 1993 Mar;66(1):91-8. DOI: 10.1016/0378-5955(93)90263-z
26. Wong WY, Stapells DR. Brain stem and cortical mechanisms underlying the binaural masking level difference in humans: an auditory steady-state response study. Ear Hear. 2004 Feb;25(1):57-67. DOI: 10.1097/01.AUD.0000111257.11898.64
27. Rossi E, Cheng H, Kroll JF, Diaz MT, Newman SD. Changes in White-Matter Connectivity in Late Second Language Learners: Evidence from Diffusion Tensor Imaging. Front Psychol. 2017 Nov 21;8:2040. DOI: 10.3389/fpsyg.2017.02040
28. Bsharat-Maalouf D, Karawani H. Bilinguals' speech perception in noise: Perceptual and neural associations. PLoS One. 2022 Feb 23;17(2):e0264282. DOI: 10.1371/journal.pone.0264282
29. Boroujeni FM, Heidari F, Rouzbahani M, Kamali M. Comparison of auditory stream segregation in sighted and early blind individuals. Neurosci Lett. 2017 Jan 18;638:218-221. DOI: 10.1016/j.neulet.2016.12.022
30. Skoe E, Karayanidi K. Bilingualism and Speech Understanding in Noise: Auditory and Linguistic Factors. J Am Acad Audiol. 2019 Feb;30(2):115-130. DOI: 10.3766/jaaa.17082
31. Wagner M, Shafer VL, Haxhari E, Kiprovski K, Behrmann K, Griffiths T. Stability of the Cortical Sensory Waveforms, the P1-N1-P2 Complex and T-Complex, of Auditory Evoked Potentials. J Speech Lang Hear Res. 2017 Jul 12;60(7):2105-2115. DOI: 10.1044/2017_JSLHR-H-16-0056
32. Haywood NR, Undurraga JA, Marquardt T, McAlpine D. A Comparison of Two Objective Measures of Binaural Processing: The Interaural Phase Modulation Following Response and the Binaural Interaction Component. Trends Hear. 2015 Dec 30;19:2331216515619039. DOI: 10.1177/2331216515619039

Table 1. Statistics and t-test outcomes of mean auditory late responses' latency in participant groups

Latency (condition)	Group	Mean	SD	T-Test				
				P-value	MD	SED	Cohen's d	95% CI
P1 (R+L)	MG	128.29	17.02	0.241	5.98	5.05	0.31	-4.14 to 16.11
	BG	122.30	20.60					
N1 (R+L)	MG	257.93	27.22	0.016	16.34	6.55	0.66	3.21 to 29.48
	BG	241.58	21.45					
P2 (R+L)	MG	388.43	22.59	0.002	21.75	6.68	0.86	8.34 to 35.16
	BG	366.68	27.24					
P1 (B)	MG	68.17	9.62	0.064	4.98	2.63	0.50	-0.30 to 10.26
	BG	63.19	10.07					
N1 (B)	MG	126.51	14.36	0.084	5.91	3.35	0.47	-0.82 to 12.64
	BG	120.60	10.44					
P2 (B)	MG	195.48	9.28	0.002	11.89	3.70	0.85	4.47 to 19.32
	BG	183.58	17.25					
P1 (BIC)	MG	64.57	8.27	0.212	3.00	2.37	0.33	-1.77 to 7.77
	BG	61.57	9.40					
N1 (BIC)	MG	127.10	13.18	0.022	7.39	3.12	0.63	1.12 to 13.67
	BG	119.71	10.02					
P2 (BIC)	MG	193.03	9.39	0.001	10.82	3.12	0.92	4.56 to 17.09
	BG	182.21	13.60					

B, binaural; BG, bilingual group; MG, monolingual group; R+L, right–left ear summed values; BIC, binaural interaction component; SD, standard deviation; MD, mean difference; SED, standard error difference; CI, confidence interval.

Table ٢. Statistics and t-test outcomes of mean auditory late responses' inter-peak amplitude in participant groups

Amplitude (condition)	Group	Mean	SD	T-Test				
				P-value	MD	SED	Cohen's d	95% CI
P1-N1 (R+L)	MG	7.27	2.40	0.589	0.42	0.79	0.14	-1.16 to 2.01
	BG	6.84	3.42					
N1-P2 (R+L)	MG	6.60	3.40	0.57	0.54	0.95	0.15	-1.37 to 2.47
	BG	6.06	3.75					
P1-N1 (B)	MG	3.17	1.42	0.471	-0.35	0.48	-0.19	-1.33 to 0.62
	BG	3.52	2.13					
N1-P2 (B)	MG	4.48	1.88	0.066	0.87	0.46	0.50	-0.06 to 1.81
	BG	3.60	1.60					
P1-N1 (BIC)	MG	4.09	2.51	**0.042**	1.28	0.61	**0.55**	0.05 to 2.52
	BG	2.80	2.07					
N1-P2 (BIC)	MG	2.12	2.94	0.685	-0.32	0.78	-0.11	-1.89 to 1.25
	BG	2.44	2.92					

B, binaural; BG, bilingual group; MG, monolingual group; R+L, right–left ear summed values; BIC, binaural interaction component; SD, standard deviation; MD, mean difference; SED, standard error difference; CI, confidence interval.

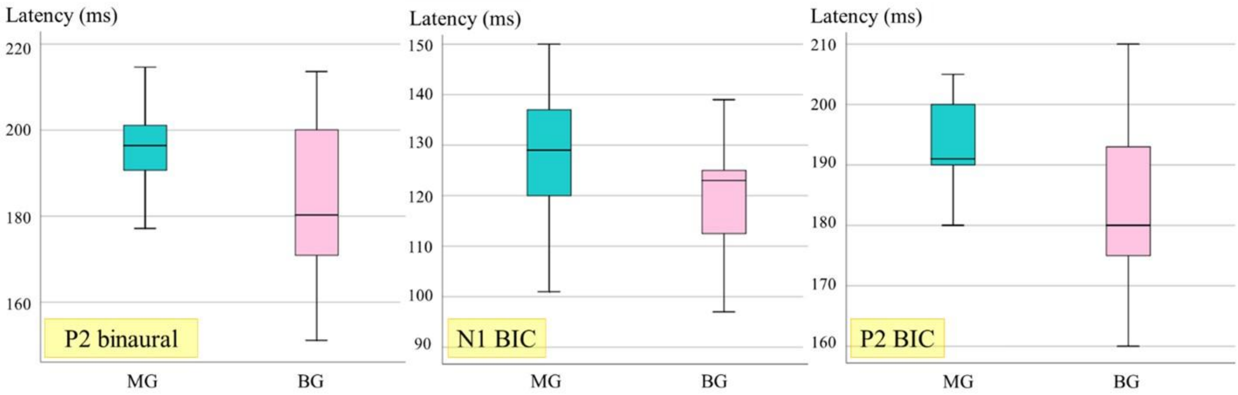

Figure 1. The box plots of latencies for the P2 component (binaural) and the N1 and P2 for binaural interaction component between the monolingual and bilingual groups.
BIC, binaural interaction component; MG, monolingual group; BG, bilingual group.

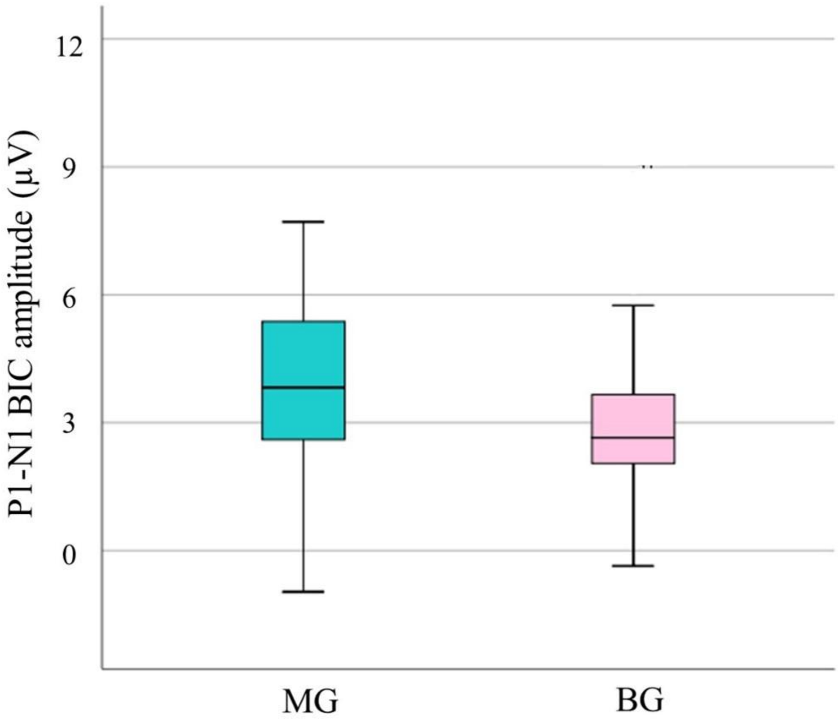

Figure 2. Box plot comparison of inter-peak amplitude of the P1-N1 in the for binaural interaction component between the monolingual and bilingual groups.
BIC, binaural interaction component; MG, monolingual group; BG, bilingual group.