``````````````````````````````````

# *Investigating the attentional effect and stimulus selectivity at the brainstem during auditory selective attention to dichotically presented /ba/ and /da/ stimuli*

Azadeh Ghalyanchi-Langeroudi[1,2], Zahra Shirzhiyan[1,4], Elham Shamsi[1,2], Ahmadreza Keihani[1,2], Morteza Farahi[1,2],

Amin Asgharzadeh Alvar[2], Akram Pourbakht[3], Amir Homayoun Jafari[1,2]*

*1- Medical Physics & Biomedical Engineering Department, School of Medicine, Tehran University of Medical Sciences, Tehran, Iran.*

*2- Research Center for Biomedical Technologies and Robotics (RCBTR), Advanced Medical Technologies and Equipment Institute (AMTEI), Tehran, University of Medical Science (TUMS), Tehran, Iran.*

*3- Department of Audiology, School of Rehabilitation Sciences, Iran University of Medical Sciences (IUMS), Tehran, I.R. Iran.*

*4-Computational Neuroscience, Institute of Medical Technology, Brandenburg University of Technology Cottbus-Senftenberg, Cottbus, Germany*

***Corresponding author:*** *Amir Homayoun Jafari* *h_jafari@tums.ac.ir*

***Authors email(s):*** a.ghalyanchi@gmail.com ; z.shirjyan@gmail.com; selham91@gmail.com; ahmadreza_kayhani@yahoo.com; mortezaxfx@gmail.com; amin044@gmail.com; akram48@yahoo.com
``````````````````````````````````

Abstract

While selective attention is known to modulate speech encoding in cortical responses, it is unclear whether such modulation also occurs in brainstem responses. The present study investigates the impact of selective attention on brainstem responses to consonant-vowel stimuli. The study examined auditory brainstem responses to dichotically delivered /ba/ and /da/ in 15 normal-hearing subjects (8 males). Subjects were asked to attend to a stimulus selectively, and their responses were evaluated using the short-time Fourier transform (STFT) and phase difference comparison. Our findings reveal significant changes in the mean phase values for brainstem responses during selective attention. The mean phase values in brainstem responses to /da/ were consistently positive, whereas those in brainstem responses to /ba/ were consistently negative compared to responses without attention. In the steady-state region, the mean difference of the brainstem responses varied in the high frequency (-0.022±0.008, 0.021±0.007) and middle frequency (-0.026±0.008, 0.024±0.007) ranges. Furthermore, the high frequency of the transitional part of the response changed (-0.024±0.01, 0.033±0.009) when attention was directed to /ba/ and /da/, respectively. Our findings suggest selective attention can significantly alter brainstem responses during auditory processing, resulting in significant phase changes in both the middle and high-frequency ranges.

Keywords: Short-Time Fourier Transform Method; Auditory Selective Attention; Brainstem Response; Consonant-Vowel Stimuli

1. Introduction

The ability to focus on a single speaker in a multi-talker environment, known as the cocktail party problem, is critical for effective communication. This is especially important in the domain of auditory selective attention. This field of study investigates attention's ability to code inputs by presenting stimuli dichotically, with people attending to one ear at a time [1-5]. Stimulus selectivity affects auditory cortical responses, enhancing the representation of temporal and spectral properties of the attended speaker and suppressing those of the unattended ones [6, 7]. Existing studies on auditory selective attention have predominantly focused on cortical processing, indicating the impact of attention on the amplitude of cortical evoked response potentials (ERPs) [8]. This highlights the higher-order processing involved in auditory stimuli selection [9, 10] [6]. Studies have demonstrated that cortical processing enhances subcortical activity [11, 12]. During the process of auditory selective attention, the auditory cortex stimulates the inferior colliculus (I.C.), which is responsible for generating brainstem responses. This stimulation occurs via the corticofugal pathway [13]. The midbrain's I.C. is critical in auditory processing. It collects incoming signals and relays them to the auditory cortex via the thalamus. It serves as a central repository for both internal and external auditory data. Changes in the I.C. can affect how we perceive sound and help us determine its location.

Furthermore, the connection between the I.C. and the auditory cortex via the corticofugal pathway can influence how the brainstem responds to auditory stimulation (Figure 1) [11, 14-21]. Recent research has highlighted the impact of selective attention on the human brainstem frequency-following response (FFR), which considers both spatial and frequency features [22, 23]. Selective attention has the potential to alter human brainstem responses[24]. This is demonstrated by the observed differences in FFR amplitudes between attention-received and ignored channels during a selective attention task [25]. Despite this, few studies have investigated the attentional effects and stimulus selectivity of auditory neurons in brainstem responses [24, 26, 27]. This study uses the cross-phaseogram approach to assess mean phase variations in brainstem responses during selective attention to consonant-vowel stimuli, providing insight into the intricate modulation of these responses. This research will contribute to a comprehensive understanding of attention functioning across different levels of the auditory processing hierarchy, which is necessary to close the gap between cortical and brainstem responses in the context of auditory selective attention. Attention signal projection to these early stages of the auditory pathway is essential in overcoming the challenges of the cocktail party effect [28]. The study examines the attentional effect and stimulus selectivity by recording brainstem responses to dichotically presented consonant vowels while subjects selectively attend to each stimulus. Consonant-vowel stimuli (/ba/ and /da/ stimuli) were chosen because they accurately represent spectral and temporal features [29] while preserving the acoustic characteristics of consonant and vowel sounds [30]. Distinguishing between these stimuli (/ba/ and /da/) poses a challenge even for normal-hearing adults in a noisy environment. These stimuli, distinguished by their frequency formants, show discrete brainstem phases, indicating the first use of the cross-phaseogram approach to detect temporal response differences. This technique, which segregates stimuli based on their frequency content [31, 32], has proven effective in identifying temporal variations. Researchers discovered that different frequencies in the /ba/ and /da/ stimuli correspond to distinct phases at the brainstem level, indicating a promising method for distinguishing responses. In the cross-phaseogram method, the brainstem response to the /da/ stimulus phase leads to the brainstem response to the /ba/ stimulus [32] and [33]. This signal-processing technique, dependent on phase correlations among different frequency components, effectively identifies and distinguishes sound sources [34] . In this study, we employ the cross-phaseogram approach, an effective method for detecting significant differences in the mean phase values of brainstem responses. Our research focuses on the selective attention given to auditory stimuli, specifically the phonemes /da/ and /ba/. We compare these responses with those elicited without any attention. Our results shed light on how selective attention influences brainstem response phase modulation.

2. Method

2.1. Data Collection

The study included fifteen volunteer subjects (seven females and eight males) aged 20 to 28 (mean = 25.6; SD = 2.028). Two of the subjects were left-handed. None of the subjects had auditory or neurological problems. All subjects had normal hearing limits (0–25 dB H.L.). They were all Persian speakers and not musicians. The subjects gave written informed consent to participate in the experiment. The experiment used /ba/ and /da/ stimuli from Northwestern University's auditory neuroscience laboratory and beep sounds sampled at 48 kilohertz (kHz). The stimulus duration was 170 milliseconds (ms). The fundamental and formant frequencies of the speech stimuli are shown in Table 1 . Both /ba/ and /da/ stimuli had the same fundamental frequency ($F0 = 100$ Hz) and the formants F1, F4, F5, and F6. F4, F5, and F6 were fixed at 3300, 3750, and 4900 Hz, respectively. The first, second, and third formants changed over the 50-ms formant transition period. F1 increased from 400 Hz to 720 Hz. The speech stimuli had different F2 and F3 at the start but converged at 1240 and 2500 Hz, respectively. F2 of the /da/ stimulus decreased from 1700 Hz to 1240 Hz, while F2 of the /ba/ stimulus increased from 900 Hz to 1240 Hz.

Furthermore, F3 of the /da/ stimulus decreased from 2580 Hz to 2500 Hz, whereas F3 of the /ba/ stimulus increased from 2400 Hz to 2500 Hz. During the experiments, subjects were instructed to remain motionless while leaning on their chairs. At the beginning of each trial, the instructor explained the corresponding task to the subjects. The experiment involved two tasks. For the first task (without attention), /ba/ and /da/ stimuli were presented dichotically, with /ba/ stimuli presented to the right ear and /da/ stimuli to the left ear. Subjects were not required to attend to the stimuli but to watch a muted film [29]. In the selective attention task, two types of stimuli were introduced: standard and deviant. The deviant stimulus, a beep sound, was randomly played within the total number of standard stimulus sweeps (Figure 2).

The standard stimuli (/ba/ and /da/) were presented as in the first task. The deviant stimulus was played within 5% of the total number of standard stimulus sweeps, which is rare enough to elicit event-related potentials (ERPs). In this task, subjects were instructed to pay attention to the sounds from one of the ears (/ba/ or /da/ stimuli). In addition, the instructor gave the subjects a button to hold in their right hand and instructed them to press it whenever they heard the beep sound in their ears. This allowed us to evaluate the subjects' attention and reaction times. The process was repeated for both ears. Each brainstem response was recorded in a 30-minute session, with rest intervals determined by the subjects' comfort preferences. The stimuli were played using a synchronized stimulus playing system at a presentation rate of 1.16/s, presented in both positive and negative polarities [29]. The stimuli were delivered to the ears through Etymotic ER-3 insert earphones (Etymotic Research, Elk Grove Village, IL) at an intensity of 85 dB SPL for /da/ and /ba/ and 60 dB SPL for the beep sound. EEG signals were recorded using g. USBamp (G. Tech Medical Engineering GmbH, Austria) with a sampling frequency of 4800 Hz. Active g.LADYbird electrodes were placed on Cz, Fpz, and the right earlobe for ground and reference . An online bandpass filter with a bandpass of 0.5 to 2000 Hz and a notch filter with a center frequency of 50 Hz were used [35].

2.2. Analysis

We recorded an EEG signal with 6,000 sweeps from standard and deviant stimuli. We used suitable offline filtering techniques to extract brainstem responses from recorded signals. An offline filter with 70 to 2000 Hz cutoff frequencies was used [29]. Because the inter-stimulus interval for evoking a brainstem response in this study was chosen as 290 ms [36], the filter was applied to 290-ms intervals of the recorded signals. An amplitude threshold of $\pm$35 μV was used to eliminate epochs with myogenic artifacts [37]. Following that, epochs containing deviant stimuli were removed. We averaged 5500 (± 20) sweeps per subject to improve the signal-to-noise ratio (Figure 3) [29, 37].

2.2.1. Evaluation of the attention level of the selected stimulus

When a subject pressed the button in their right hand, a pulse was recorded, which was used to assess the level of attention paid to the chosen stimulus in the selective attention task. The flowchart below depicts the steps in calculating each subject's attention level to the selected stimulus (Figure 4).

2.2.2. STFT

The STFT was used to extract the phase and investigate the attentional effect and stimulus selectivity in the brainstem during auditory selective attention. We used this method to assess brainstem responses to dichotically presented /ba/ and /da/ stimuli to demonstrate the attentional impact. During each trial, subjects selectively attended to each stimulus (/ba/ or /da/), which we compared to the brainstem response to dichotically presented /ba/ and /da/ stimuli without attention. Furthermore, we used the STFT method on the dichotically presented /ba/ and /da/ stimuli to demonstrate stimulus selectivity in brainstem responses during auditory selective attention. At the same time, subjects paid attention to each stimulus in each trial.

In the STFT process, a time signal was divided into shorter or equivalent-length segments. We then computed the Fourier transform of each segment, as well as the magnitude and phase of the signal over time and frequency. Utilizing a Hamming window, each window had a length of 96 samples, with 95 samples of overlap between adjacent segments. The number of sampling points was 512, and the sampling frequency was 4800 Hz. The phase of each brainstem response was obtained, and the phase differences between each response were calculated. The x-axis and y-axis corresponded to time and frequency, respectively. The z-axis, depicted in color, represented the phase differences between the responses. The green color in the z-axis indicates no phase difference between the two responses. Because phase differences in the brainstem response to complex stimuli (cABR) were not consistent across the frequency spectrum, we divided them into two time intervals: 15 to 60 ms (transition part of the response) and 60 to 170 ms (steady-state response). In addition, three frequency ranges were considered: 70–400 Hz (low frequency), 400–720 Hz (middle frequency), and 720–1100 Hz (high frequency). The phase differences were divided into six windows (Figure 5) [32]. We calculated the mean and standard deviation of phase values in each window. Figure 6 depicts a block diagram of the general study steps.

2.2.3. Statistical analysis of the phase values

We used a repeated measures ANOVA with Greenhouse-Geisser correction (significance level $\alpha = 0.01$) to compare phase variation of each window in each group of brainstem responses (the brainstem response with selective attention to each stimulus (/ba/ or /da/) versus the brainstem response without attention, and the brainstem responses to dichotically presented /ba/ and /da/ while subjects selectively attended to each stimulus). A post-hoc analysis with Bonferroni correction compared mean phase values in each window ($\alpha = 0.017$).

3. Results

In this study, all analyses were conducted using the Matlab software. We first extracted the brainstem responses to consonant-vowel stimulus. Figure 7 shows the time-domain representation of a 170 ms stimulus (/da/) and the brainstem response. The brainstem response can be divided into two distinct parts: the formant transition, which occurs between 15 to 60 ms, and the steady-state region, which spans from 60 to 170 ms. Both of these components are represented in the data. Figure 8 depicts brainstem responses to dichotically presented /ba/ and /da/ stimuli, comparing them without and with selective attention for each stimulus. Our study of the effects of selective attention on brainstem responses found distinct patterns for the /ba/ and /da/ stimuli. Specifically, the brainstem response to the /ba/ stimulus was slower than when no attention was paid to the stimuli.

In contrast, the brainstem response with selective attention to the /da/ stimulus exhibited a faster temporal profile than the response without attention. We compared brainstem responses to /ba/ and /da/ stimuli delivered dichotically while receiving selective attention (Figure 9). The findings revealed significant differences in their temporal dynamics. The brainstem response with selective attention to the /da/ stimulus was faster than the response with selective attention to the /ba/ stimulus.

3.1. Results of the evaluation of the attention level of the selected stimulus

Table 2 shows the mean and standard deviation of the subjects' attention-related parameters, such as accuracy, sensitivity, precision, and specificity. Figure 10 illustrates the STFT technique to investigate brainstem responses to dichotically presented /ba/ and /da/ stimuli. The study compares brainstem responses with and without selective attention to each stimulus. The phase aspect is investigated in two scenarios: attention is directed to the /da/ stimulus, and attention is presented to the /ba/ stimulus. Figure 11 shows the difference in phase values of the STFT method in brainstem responses to dichotically presented /ba/ and /da/ stimuli when selectively attending to /da/ versus selectively attending to /ba/. Figure 12 shows the mean STFT phase values of brainstem responses with and without selective attention to each stimulus (/ba/ or /da/). These differences are investigated at various time and frequency intervals. In three distinct windows (3, 5, and 6), the brainstem response with selective attention to the /da/ stimulus had significantly higher mean phase values than the brainstem response without attention. In contrast, selective attention to the /ba/ stimulus resulted in significantly lower mean phase values in the brainstem response than in the absence of attention. Figure 13 shows that in Windows 4, the average phase of the STFT method for the brainstem response with selective attention to /da/ was significantly higher than the brainstem response with selective attention to the /ba/ stimulus.

4. Discussion

This experiment used auditory selective attention tasks involving dichotically presented /ba/ and /da/ stimuli to examine the effects of attention and stimulus selectivity on the brainstem. Compared to the brainstem response without attention, the results point to a discernible time shift in the grand average of auditory brainstem responses when a subject paid attention to each stimulus individually. Specifically, when attention was selectively given to the /da/ stimulus, the brainstem responses were quicker than those without attention. Conversely, the brainstem responses were slower when attention was directed towards the /ba/ stimulus than when no attention was given. Several studies have found significant differences in brainstem latency during auditory selective attention, with a substantial shift in brainstem reaction latency at speech frequency between attended and unattended scenarios [38-40]. However, some studies found no significant differences [22, 41]. These discrepancies could be attributed to neural adaptation and the diminishing effect of efferent feedback [42, 43]. We used the STFT to extract phase differences and assess the attentional effect and stimulus selectivity of brainstem responses during auditory selective attention. Although there were no significant differences in the overall representation of STFT phase values, we calculated the mean phase values over various time and frequency ranges. Significant differences existed in the mean phase values of brainstem responses between the attention group and those without attention, particularly in the steady-state region's middle-frequency range (400 - 720 Hz) (60 - 170 ms). In this frequency range, the mean value of the brainstem response with selective attention was lower than the brainstem response without attention. These results are consistent with previous research that has shown that attention influences the steady-state region of the auditory brainstem response [40, 44, 45]. According to studies that used advanced computational models to simulate the auditory brainstem's response to continuous speech, attention has a significant impact on the steady-state region of these responses. The auditory brainstem's role in speech processing modulates neural activity, changing its response to continuous speech [38]. Previous research has found that when a subject selectively attends to an auditory stimulus rather than a visual stimulus, the magnitude of the auditory steady-state response (ASSR) increases [46] . However, some studies have found no attention modulation in the steady-state region [47, 48], possibly due to differences in task design across studies. The attentional effect at the brainstem level may result from the corticofugal feedback from the auditory cortex to the brainstem level [11, 14-16, 20, 21, 49]. This suggests that mechanisms of selective attention may occur during the subcortical processing stage [44, 50]. In this study, we compared brainstem responses to dichotically presented /ba/ and /da/ stimuli while subjects selectively attended each stimulus to demonstrate stimulus selectivity during auditory selective attention. Our findings revealed that the brainstem response with selective attention to /da/ appears before the brainstem response with selective attention to /ba/. The phase values of the STFT method of brainstem responses during selective attention to each stimulus were compared. The phase value of the low-frequency range varied significantly in the steady-state region; the brainstem response with selective attention to /da/ was different from the brainstem response with selective attention to /ba/. The STFT method results showed that in this frequency range, the brainstem response with selective attention to the /da/ phase leads to the brainstem response with selective attention to /ba/. The brainstem response with selective attention to /da/ was faster than the response with selective attention to /ba/. Previous research found that different formant frequencies of /ba/ and /da/ (F2 and F3) would result in latency shifts in brainstem responses to /ba/ and /da/ [30, 33, 51, 52]. Because the /da/ stimulus has higher frequencies than the /ba/ stimulus, the brainstem response to /da/ is faster [29, 32, 33]. We used the stimulus characteristics of /ba/ and /da/ to indicate stimulus selectivity at the brainstem during auditory selective attention. Similarly, selective attention to one of two stimuli with different frequency content alters the frequency of subsequent auditory brainstem responses [38, 44]. We investigated how attention and stimulus selectivity affected brainstem responses to /ba/ and /da/ stimuli during auditory tasks. Significant temporal variations in auditory brainstem responses were observed, indicating that selective attention has a definite impact on response latency. Using STFT, we identified specific frequency ranges and time intervals where attention influenced brainstem response. Specifically, the steady-state region in the middle-frequency range showed significant mean phase changes, indicating that selective attention influences brainstem responses during auditory processing. Furthermore, the brainstem response to /da/ during selective attention earlier in the study showed stimulus selectivity, which supports our findings.

References:

1. Driver, J. "A selective review of selective attention research from the past century", *British Journal of Psychology*, **92**(1), pp. 53-78 (2001). DOI: 10.1348/000712601162103
2. Cherry, E.C. "Some experiments on the recognition of speech, with one and with two ears", *The Journal of the acoustical society of America*, **25**(5), pp. 975-979 (1953). DOI: 10.1121/1.1907229
3. Treisman, A. and Geffen, G. "Selective attention: Perception or response?", *The Quarterly journal of experimental psychology*, **19**(1), pp. 1-17 (1967). DOI: 10.1080/14640746708400062
4. Deutsch, J.A. and Deutsch, D. "Attention: Some theoretical considerations", *Psychological review*, **70**(1), pp. 80 (1963). DOI: 10.1037/h0039515
5. Conway, A.R., Cowan, N., and Bunting, M.F. "The cocktail party phenomenon revisited: the importance of working memory capacity", *Psychon Bull Rev*, **8**(2), pp. 331-335 (2001). DOI: 10.3758/bf03196169
6. Ahveninen, J., Hämäläinen, M., Jääskeläinen, I.P., et al. "Attention-driven auditory cortex short-term plasticity helps segregate relevant sounds from noise", *Proceedings of the National Academy of Sciences*, **108**(10), pp. 4182-4187 (2011). DOI: 10.1073/pnas.1016134108
7. Brodbeck, C., Jiao, A., Hong, L.E., et al. "Neural speech restoration at the cocktail party: Auditory cortex recovers masked speech of both attended and ignored speakers", *PLoS biology*, **18**(10), pp. e3000883 (2020). DOI: 10.1371/journal.pbio.3000883
8. Hillyard, S.A., Hink, R.F., Schwent, V.L., et al. "Electrical signs of selective attention in the human brain", *Science*, **182**(108), pp. 177-180 (1973). DOI: 10.1126/science.182.4108.177
9. Strait, D.L., Slater, J., Abecassis, V., et al. "Cortical response variability as a developmental index of selective auditory attention", *Dev Sci*, **17**(2), pp. 175-186 (2014). DOI: 10.1111/desc.12107
10. Price, C.N. and Moncrieff, D. "Defining the role of attention in hierarchical auditory processing", *Audiology Research*, **11**(1), pp. 112-128 (2021). DOI: 10.3390/audiolres11010012
11. Russo, N.M., Nicol, T.G., Zecker, S.G., et al. "Auditory training improves neural timing in the human brainstem", *Behavioural brain research*, **156**(1), pp. 95-103 (2005). DOI: 10.1016/j.bbr.2004.05.012
12. Musacchia, G., Sams, M., Skoe, E., et al. "Musicians have enhanced subcortical auditory and audiovisual processing of speech and music", *Proceedings of the National Academy of Sciences*, **104**(40), pp. 15894-15898 (2007). DOI: 10.1073/pnas.0701498104
13. Blackwell, J.M., Lesicko, A.M., Rao, W., et al. "Auditory cortex shapes sound responses in the inferior colliculus", *elife*, **9**, pp. e51890 (2020). DOI: 10.7554/eLife.51890

14. Bidelman, G.M., Weiss, M.W., Moreno, S., et al. "Coordinated plasticity in brainstem and auditory cortex contributes to enhanced categorical speech perception in musicians", *European Journal of Neuroscience*, **40**(4), pp. 2662-2673 (2014). DOI: 10.1111/ejn.12627
15. Luo, F., Wang, Q., Kashani, A., et al. "Corticofugal modulation of initial sound processing in the brain", *J Neurosci*, **28**(45), pp. 11615-11621 (2008). DOI: 10.1523/jneurosci.3972-08.2008
16. Rinne, T., Balk, M.H., Koistinen, S., et al. "Auditory selective attention modulates activation of human inferior colliculus", *Journal of Neurophysiology*, **100**(6), pp. 3323-3327 (2008). DOI: 10.1152/jn.90607.2008
17. Lesenfants, D. and Francart, T. "The interplay of top-down focal attention and the cortical tracking of speech", *Scientific Reports*, **10**(1), pp. 6922 (2020). DOI: 10.1038/s41598-020-63587-3
18. Saiz Alia, M. "Neural feedback mechanisms for speech-in-noise listening", (2021).
19. Price, C.N. and Bidelman, G.M. "Attention reinforces human corticofugal system to aid speech perception in noise", *Neuroimage*, **235**, pp. 118014 (2021). DOI: 10.1016/j.neuroimage.2021.118014
20. Gao, E. and Suga, N. "Experience-dependent plasticity in the auditory cortex and the inferior colliculus of bats: role of the corticofugal system", *Proc Natl Acad Sci U S A*, **97**(14), pp. 8081-8086 (2000). DOI: 10.1073/pnas.97.14.8081
21. Krishnan, A., Gandour, J.T., and Bidelman, G.M. "Experience-dependent plasticity in pitch encoding: from brainstem to auditory cortex", *Neuroreport*, **23**(8), pp. 498-502 (2012). DOI: 10.1097/WNR.0b013e328353764d
22. Forte, A.E., Etard, O., and Reichenbach, T. "The human auditory brainstem response to running speech reveals a subcortical mechanism for selective attention", *elife*, **6**, pp. e27203 (2017). DOI: 10.7554/eLife.27203
23. Kegler, M., Weissbart, H., and Reichenbach, T. "The neural response at the fundamental frequency of speech is modulated by word-level acoustic and linguistic information", *Frontiers in Neuroscience*, **16**, pp. 915744 (2022). DOI: 10.3389/fnins.2022.915744
24. Asgharzadeh-Alavr, A., Jafari, A.H., Shirzhiyan, Z., et al. "A study of the effect of two meaningful syllables stimuli in auditory brainstem responses using correlation and coherence analyses", *Frontiers in Biomedical Technologies*, **2**(2), pp. 80-86 (2015).
25. Shukla, B. and Bidelman, G.M. "Enhanced brainstem phase-locking in low-level noise reveals stochastic resonance in the frequency-following response (FFR)", *Brain research*, **1771**, pp. 147643 (2021). DOI: 10.1016/j.brainres.2021.147643
26. Shirzhiyan, Z., Shamsi, E., Jafarpisheh, A.S., et al. "Objective classification of auditory brainstem responses to consonant-vowel syllables using local discriminant bases", *Speech Communication*, **114**, pp. 36-48 (2019). DOI: 10.1016/j.specom.2019.09.003
27. Jafarpisheh, A.S., Jafari, A.H., Abolhassani, M., et al. "Nonlinear feature extraction for objective classification of complex auditory brainstem responses to diotic perceptually critical consonant-vowel syllables", *Auris Nasus Larynx*, **43**(1), pp. 37-44 (2016). DOI: 10.1016/j.anl.2015.06.003
28. Kuo, T.-Y., Liao, Y., Li, K., et al. "Inferring Mechanisms of Auditory Attentional Modulation with Deep Neural Networks", *Neural Computation*, **34**(11), pp. 2273-2293 (2022). DOI: 10.1162/neco_a_01537

29. Skoe, E. and Kraus, N. "Auditory brainstem response to complex sounds: a tutorial", *Ear and hearing*, **31**(3), pp. 302 (2010). DOI: 10.1097/AUD.0b013e3181cdb272
30. Rocha-Muniz, C.N. and Schochat, E. "Investigation of the neural discrimination of acoustic characteristics of speech sounds in normal-hearing individuals through Frequency-following Response (FFR)", *Codas*, **33**(1), pp. e20180324 (2021). DOI: 10.1590/2317-1782/20202018324
31. Elmahallawi, T.H., Gabr, T.A., Darwish, M.E., et al. "Children with developmental language disorder: a frequency following response in the noise study", *Brazilian Journal of Otorhinolaryngology*, **88**(6), pp. 954-961 (2022). DOI: 10.1016/j.bjorl.2021.01.008
32. Skoe, E., Nicol, T., and Kraus, N. "Cross-phaseogram: objective neural index of speech sound differentiation", *Journal of neuroscience methods*, **196**(2), pp. 308-317 (2011). DOI: 10.1016/j.jneumeth.2011.01.020
33. Johnson, K.L., Nicol, T., Zecker, S.G., et al. "Brainstem encoding of voiced consonant-vowel stop syllables", *Clin Neurophysiol*, **119**(11), pp. 2623-2635 (2008). DOI: 10.1016/j.clinph.2008.07.277
34. Purwins, H., Li, B., Virtanen, T., et al. "Deep learning for audio signal processing", *IEEE Journal of Selected Topics in Signal Processing*, **13**(2), pp. 206-219 (2019). DOI: 10.48550/arXiv.1905.00078
35. Klem, G.H., Lüders, H.O., Jasper, H.H., et al. "The ten-twenty electrode system of the International Federation. The International Federation of Clinical Neurophysiology", *Electroencephalogr Clin Neurophysiol Suppl*, **52**, pp. 3-6 (1999). DOI: 10.1080/00029238.1961.11080571
36. Wible, B., Nicol, T., and Kraus, N. "Correlation between brainstem and cortical auditory processes in normal and language-impaired children", *Brain*, **128**(Pt 2), pp. 417-423 (2005). DOI: 10.1093/brain/awh367
37. Parbery-Clark, A., Marmel, F., Bair, J., et al. "What subcortical–cortical relationships tell us about processing speech in noise", *European Journal of Neuroscience*, **33**(3), pp. 549-557 (2011). DOI: 10.1111/j.1460-9568.2010.07546.x
38. Saiz-Alía, M. and Reichenbach, T. "Computational modeling of the auditory brainstem response to continuous speech", *Journal of Neural Engineering*, **17**(3), pp. 036035 (2020). DOI: 10.1088/1741-2552/ab970d
39. Ikeda, K., Sekiguchi, T., and Hayashi, A. "Concentrated pitch discrimination modulates auditory brainstem responses during contralateral noise exposure", *Neuroreport*, **21**(5), pp. 359-366 (2010). DOI: 10.1097/WNR.0b013e328337750f
40. Kumar, S., Nayak, S., and Pitchai Muthu, A.N. "Effect of selective attention on auditory brainstem response", *Hearing, Balance and Communication*, **21**(2), pp. 139-147 (2023). DOI: 10.1080/21695717.2023.2168413
41. Connolly, J.F., Aubry, K., McGillivary, N., et al. "Human brainstem auditory evoked potentials fail to provide evidence of efferent modulation of auditory input during attentional tasks", *Psychophysiology*, **26**(3), pp. 292-303 (1989). DOI: 10.1111/j.1469-8986.1989.tb01920.x
42. Kumar Neupane, A., Gururaj, K., Mehta, G., et al. "Effect of Repetition Rate on Speech Evoked Auditory Brainstem Response in Younger and Middle Aged Individuals", *Audiol Res*, **4**(1), pp. 106 (2014). DOI: 10.4081/audiores.2014.106
43. Reichenbach, C.S., Braiman, C., Schiff, N.D., et al. "The Auditory-Brainstem Response to Continuous, Non-repetitive Speech Is Modulated by the Speech Envelope and Reflects Speech Processing", *Front Comput Neurosci*, **10**, pp. 47 (2016). DOI: 10.3389/fncom.2016.00047

44. Lehmann, A. and Schönwiesner, M. "Selective attention modulates human auditory brainstem responses: relative contributions of frequency and spatial cues", *PloS one*, **9**(1), pp. e85442 (2014). DOI: 10.1371/journal.pone.0085442

45. Varghese, L., Bharadwaj, H.M., and Shinn-Cunningham, B.G. "Evidence against attentional state modulating scalp-recorded auditory brainstem steady-state responses", *Brain Res*, **1626**, pp. 146-164 (2015). DOI: 10.1016/j.brainres.2015.06.038

46. Wittekindt, A., Kaiser, J., and Abel, C. "Attentional modulation of the inner ear: a combined otoacoustic emission and EEG study", *J Neurosci*, **34**(30), pp. 9995-10002 (2014). DOI: 10.1523/jneurosci.4861-13.2014

47. Lazzouni, L., Ross, B., Voss, P., et al. "Neuromagnetic auditory steady-state responses to amplitude modulated sounds following dichotic or monaural presentation", *Clin Neurophysiol*, **121**(2), pp. 200-207 (2010). DOI: 10.1016/j.clinph.2009.11.004

48. Linden, R.D., Picton, T.W., Hamel, G., et al. "Human auditory steady-state evoked potentials during selective attention", *Electroencephalogr Clin Neurophysiol*, **66**(2), pp. 145-159 (1987). DOI: 10.1016/0013-4694(87)90184-2

49. van Kempen, J., Gieselmann, M.A., Boyd, M., et al. "Top-down coordination of local cortical state during selective attention", *Neuron*, **109**(5), pp. 894-904. e898 (2021). DOI: 10.1016/j.neuron.2020.12.013

50. Souto, D. and Kerzel, D. "Visual selective attention and the control of tracking eye movements: A critical review", *Journal of Neurophysiology*, **125**(5), pp. 1552-1576 (2021). DOI: 10.1152/jn.00145.2019

51. Hornickel, J., Skoe, E., Nicol, T., et al. "Subcortical differentiation of stop consonants relates to reading and speech-in-noise perception", *Proceedings of the National Academy of Sciences*, **106**(31), pp. 13022-13027 (2009). DOI: 10.1073/pnas.0901123106

52. Rishiq, D., Harkrider, A., Springer, C., et al. "Effects of Spectral Shaping on Speech Auditory Brainstem Responses to Stop Consonant-Vowel Syllables", *Journal of the American Academy of Audiology*, **33**(04), pp. 232-243 (2022). DOI: 10.1055/a-1764-9805

53. Pickles, J.O. "Auditory pathways: anatomy and physiology", *Handbook of clinical neurology*, **129**, pp. 3-25 (2015). DOI: 10.1016/B978-0-444-62630-1.00001-9

Figures' caption list:

Figure 1. Auditory pathway connections. Auditory information flows from the auditory cortex to the I.C. and medial geniculate body (MGB) in the midbrain. These structures are involved in processing sound location and other auditory features. (L/R: left/right; C: contralateral)[21, 53].

Figure 2. Representation of the auditory stimulus during selective attention to one of the ears. The gray box represents the standard stimulus, whereas the white box represents the deviant stimulus.

Figure 3. Block diagram of the signal preprocessing of the brainstem response.

Figure 4. Steps for calculating the attention level of the selected stimulus.

Figure 5. The phase of the STFT is represented across six windows [32].

Figure 6. Block diagram of the general steps.

Figure 7. Time domain representation of a 170-millisecond stimulus /da/ (top) and the corresponding brainstem response to /da/ (bottom).

Figure 8. Brainstem response to dichotic /ba/ and /da/ stimuli with and without selective attention. Top panel: Brainstem response with selective attention to /ba/ was slower than without attention. Bottom panel: Brainstem response with selective attention to /da/ was faster than without attention.

Figure 9. The brainstem response with selective attention to /da/ (red) was faster than the response to /ba/ (blue).

Figure 10. Representation of the phase using the STFT method in terms of brainstem response with selective attention to /ba/ versus brainstem response without attention (top) and phase of the STFT method for the brainstem response with selective attention to /da/ versus brainstem response without attention (bottom).

Figure 11. Representation of the phase using the STFT method in terms of the brainstem response, comparing selective attention to /da/ versus selective attention to /ba/.

Figure 12. Mean and standard deviation of brainstem responses with and without selective attention to /ba/ (top) and /da/ (bottom) in six windows using the STFT method.

Figure 13. Mean and standard deviation of phase of the STFT method of the brainstem response with selective attention to /da/ compared to the brainstem response with selective attention to /ba/.

Tables' caption list:

Table 1. Fundamental and formant frequencies of /ba/ and /da/ stimuli [33].

Table 2. The standard deviation and the mean value of all subjects' attention-related parameters.

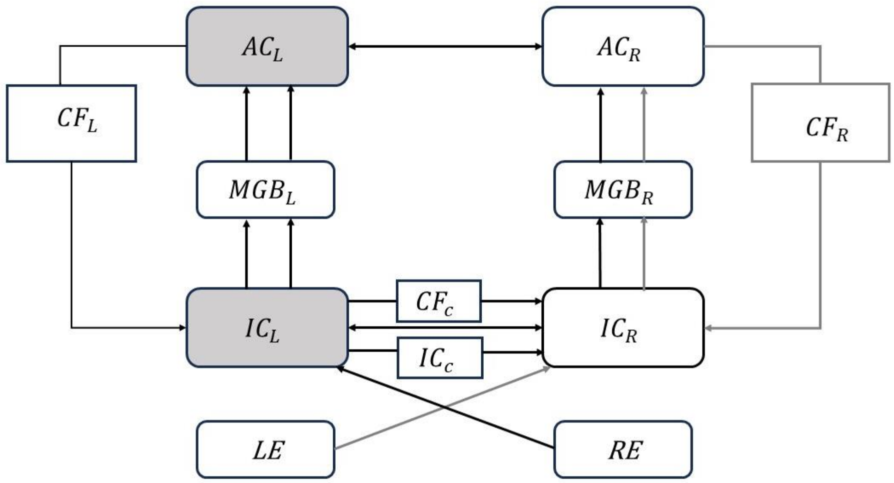


Figure 10.

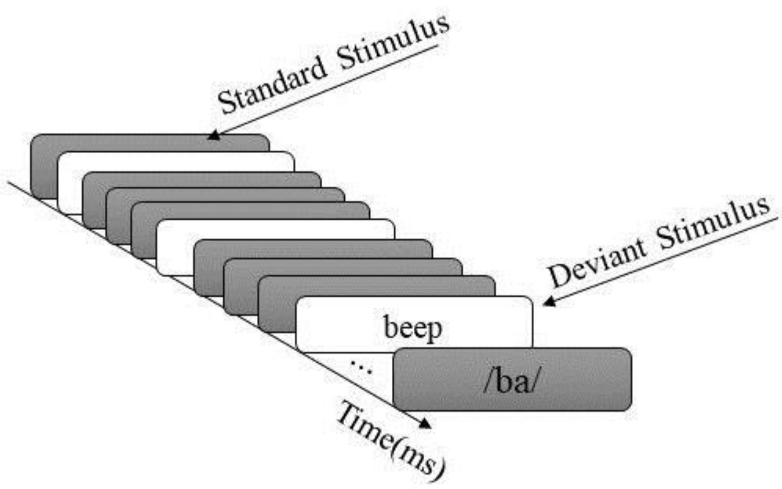


Figure 2.

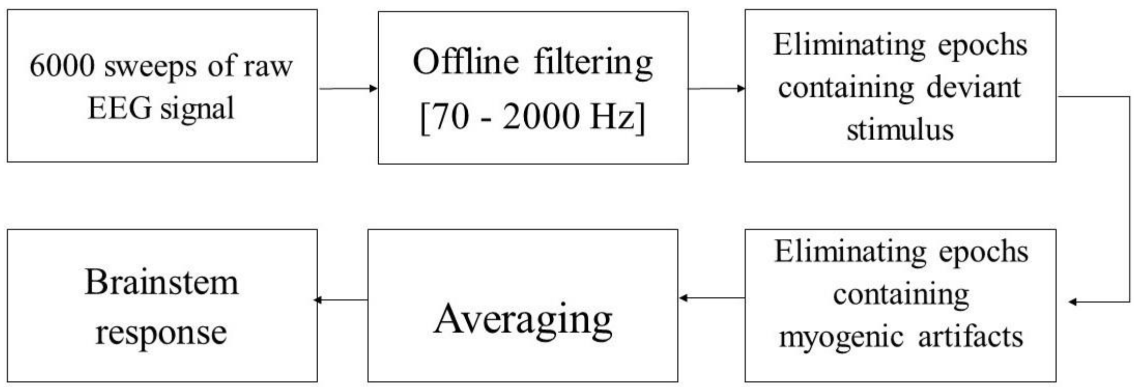

6000 sweeps of raw EEG signal
Offline filtering [70 - 2000 Hz]
Eliminating epochs containing deviant stimulus
Eliminating epochs containing myogenic artifacts
Averaging
Brainstem response

Figure 3.

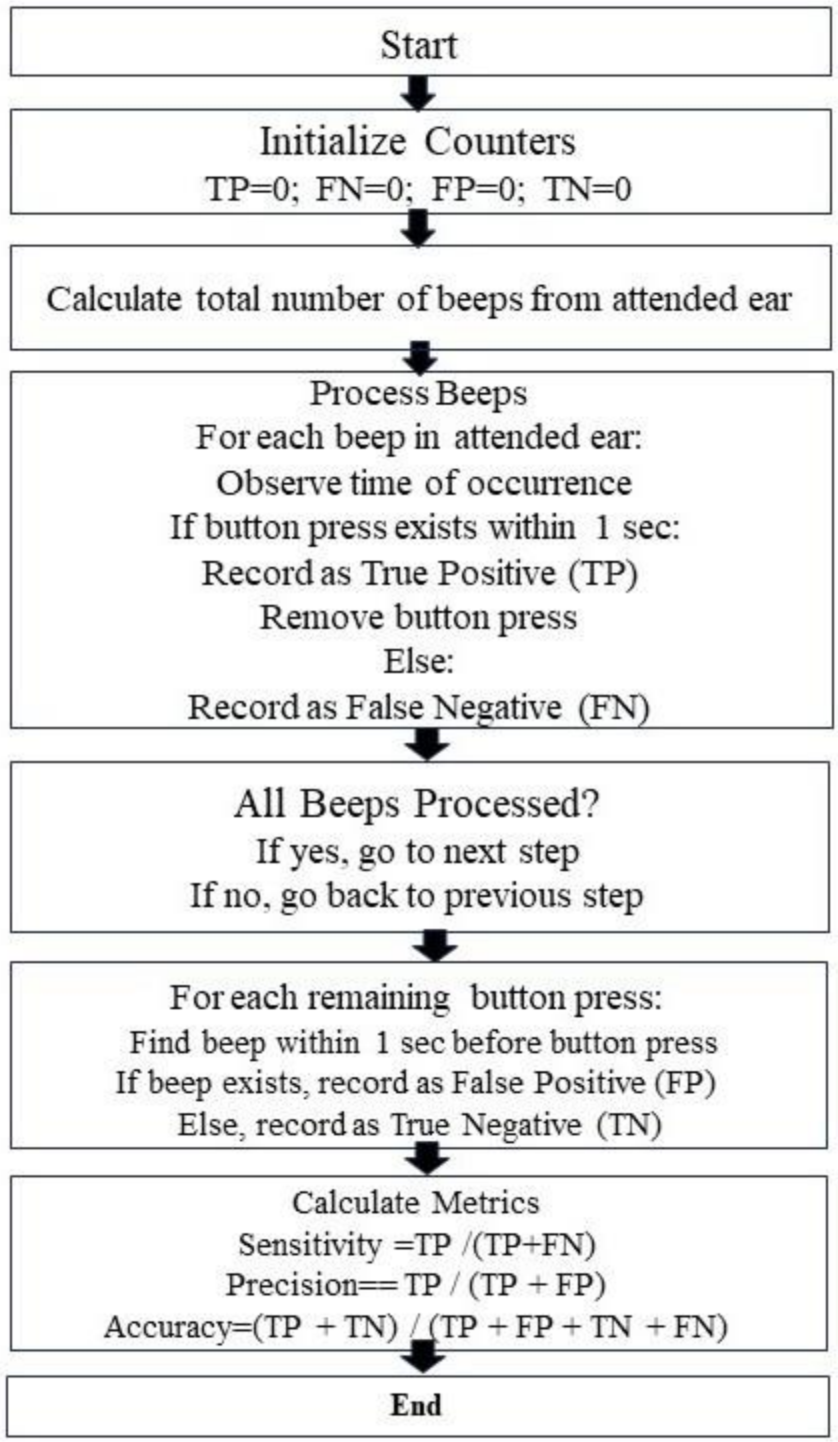

Start
Initialize Counters
TP=0; FN=0; FP=0; TN=0
Calculate total number of beeps from attended ear
Process Beeps
For each beep in attended ear:
Observe time of occurrence
If button press exists within 1 sec:
Record as True Positive (TP)
Remove button press
Else:
Record as False Negative (FN)
All Beeps Processed?
If yes, go to next step
If no, go back to previous step
For each remaining button press:
Find beep within 1 sec before button press
If beep exists, record as False Positive (FP)
Else, record as True Negative (TN)
Calculate Metrics
Sensitivity =TP /(TP+FN)
Precision== TP / (TP + FP)
Accuracy=(TP + TN) / (TP + FP + TN + FN)
End

Figure 4.

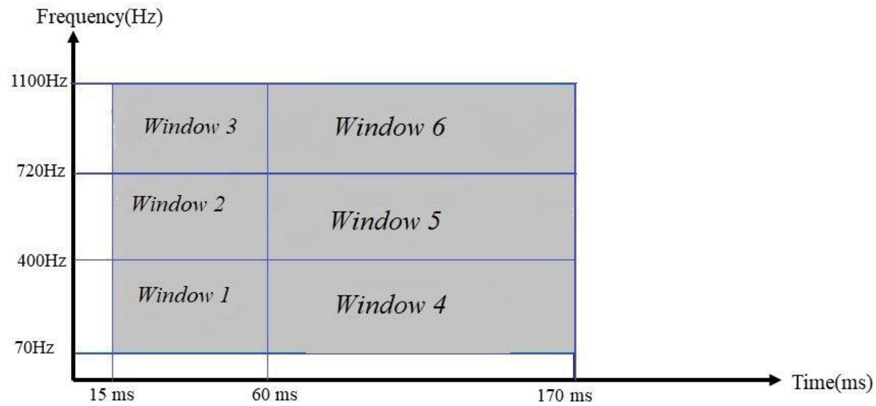


Figure 5.

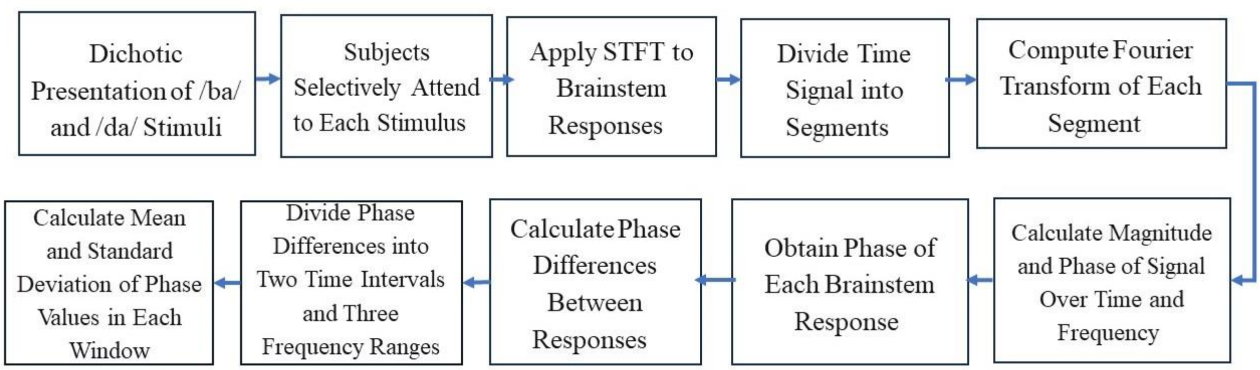


Figure 6.

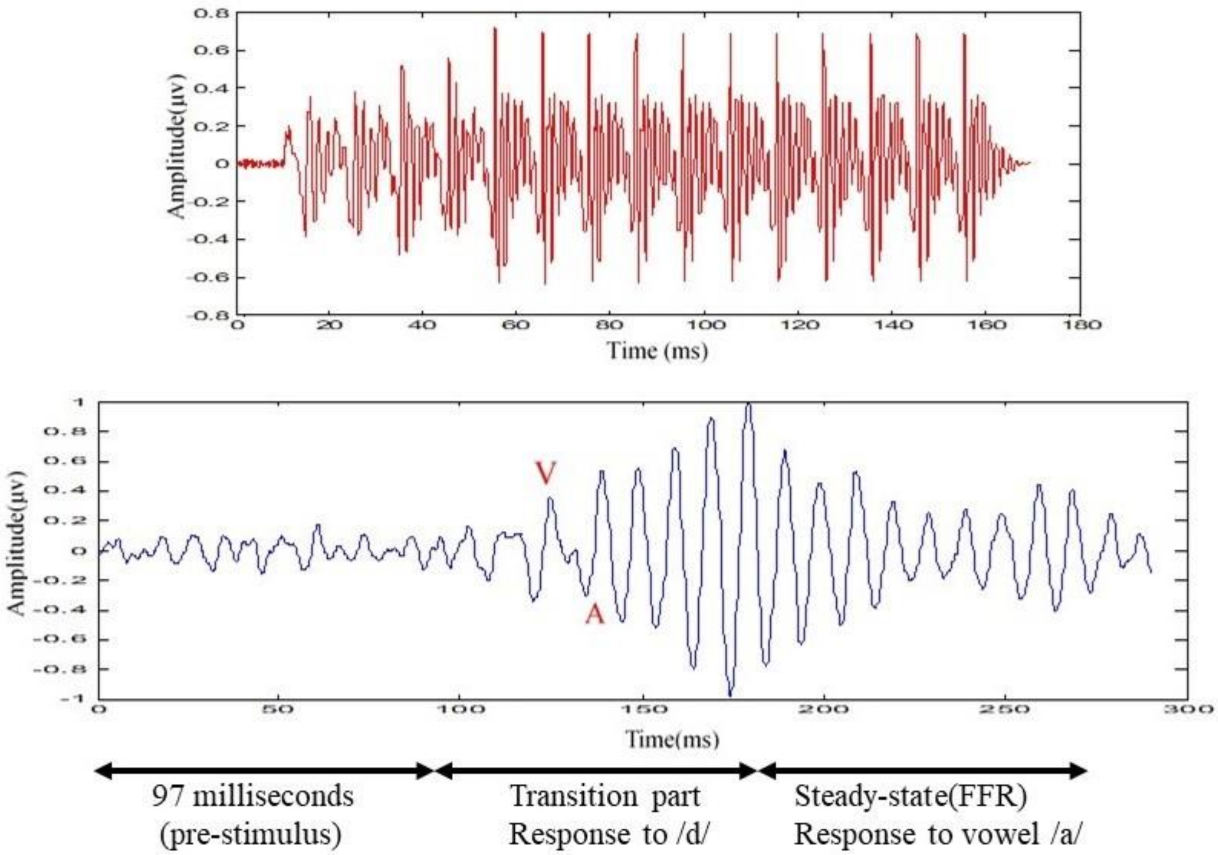

Amplitude(µv)
Time (ms)
V
A
Time(ms)
97 milliseconds
(pre-stimulus)
Transition part
Response to /d/
Steady-state(FFR)
Response to vowel /a/

Figure 7.

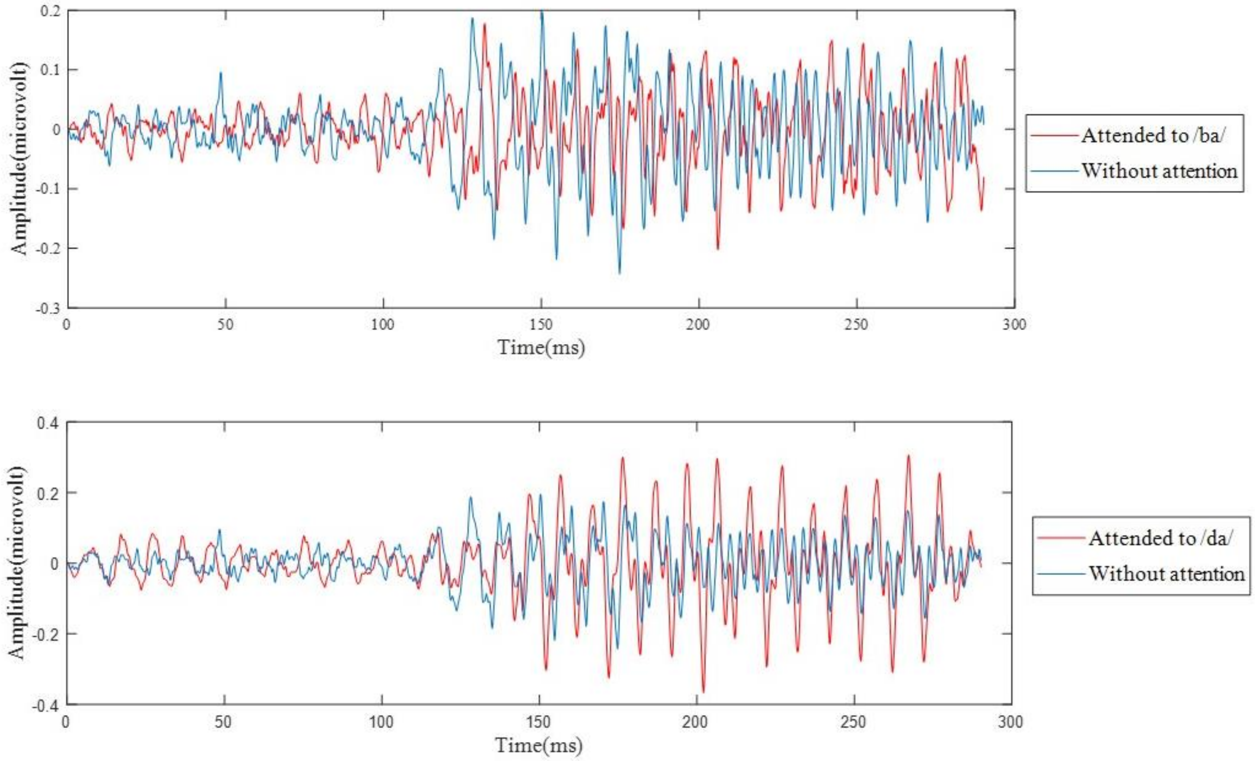
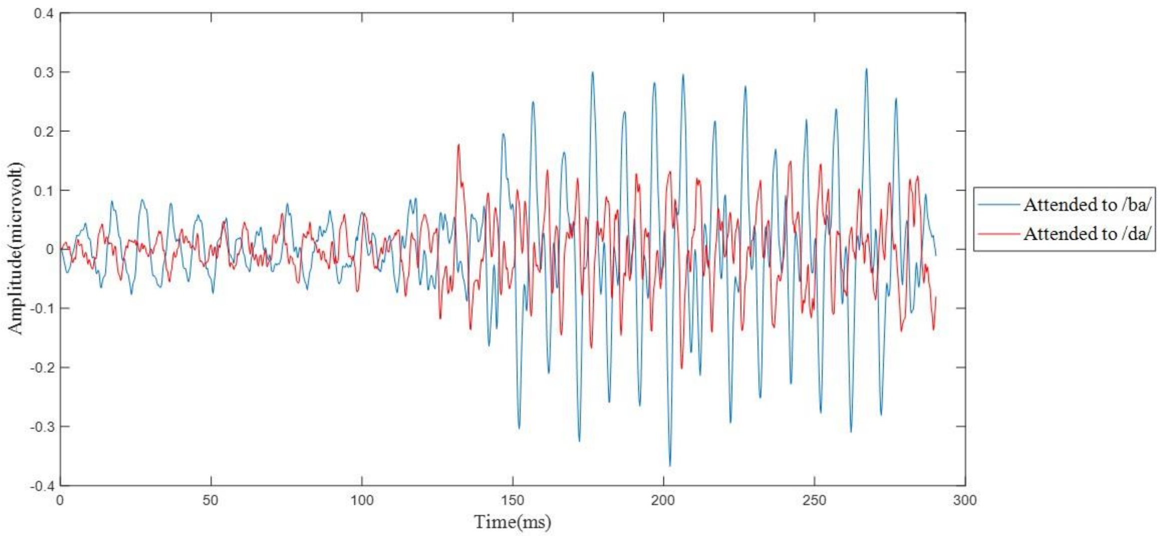

0.2
0.1
0
-0.1
-0.2
-0.3
Amplitude(microvolt)
0
50
100
150
200
250
300
Time(ms)
Attended to /ba/
Without attention
0.4
0.2
0
-0.2
-0.4
Amplitude(microvolt)
0
50
100
150
200
250
300
Time(ms)
Attended to /da/
Without attention

Figure 8.



0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
Amplitude(microvolt)
0
50
100
150
200
250
300
Time(ms)
Attended to /ba/
Attended to /da/

Figure 9.

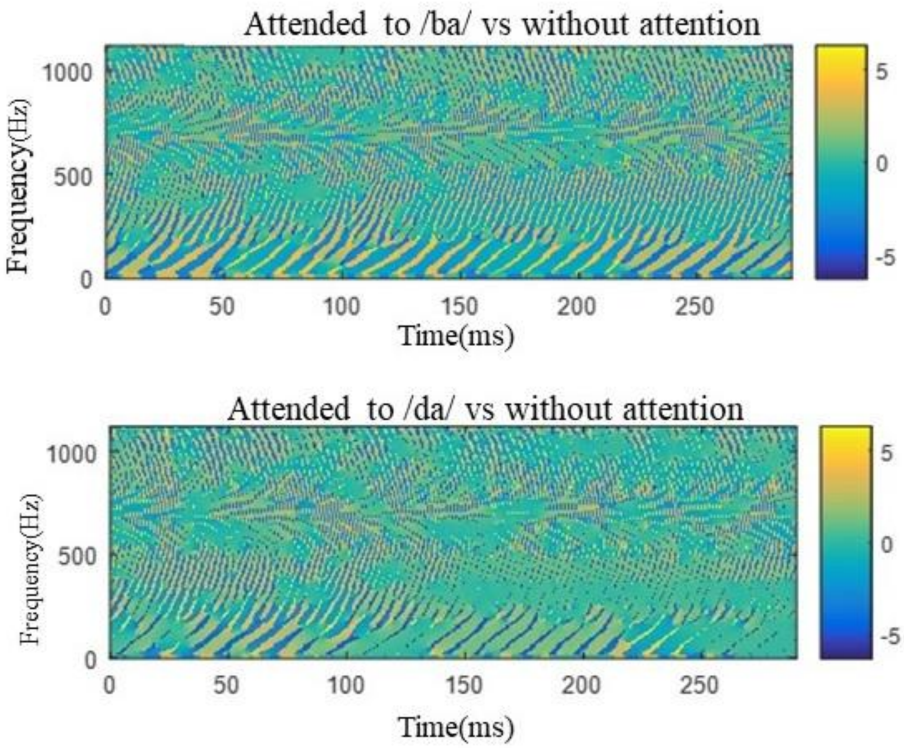

Attended to /ba/ vs without attention
Frequency(Hz)
1000
500
0
0
50
100
150
200
250
Time(ms)
5
0
-5
Attended to /da/ vs without attention
Frequency(Hz)
1000
500
0
0
50
100
150
200
250
Time(ms)
5
0
-5

Figure 10.

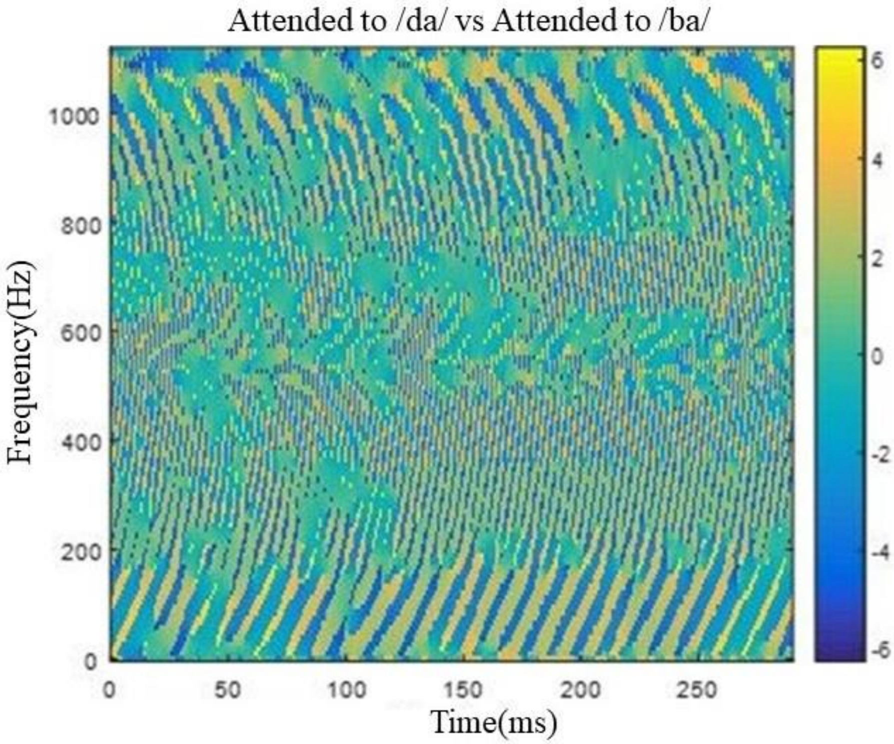

Attended to /da/ vs Attended to /ba/
Frequency(Hz)
1000
800
600
400
200
0
0
50
100
150
200
250
Time(ms)
6
4
2
0
-2
-4
-6

Figure 11.

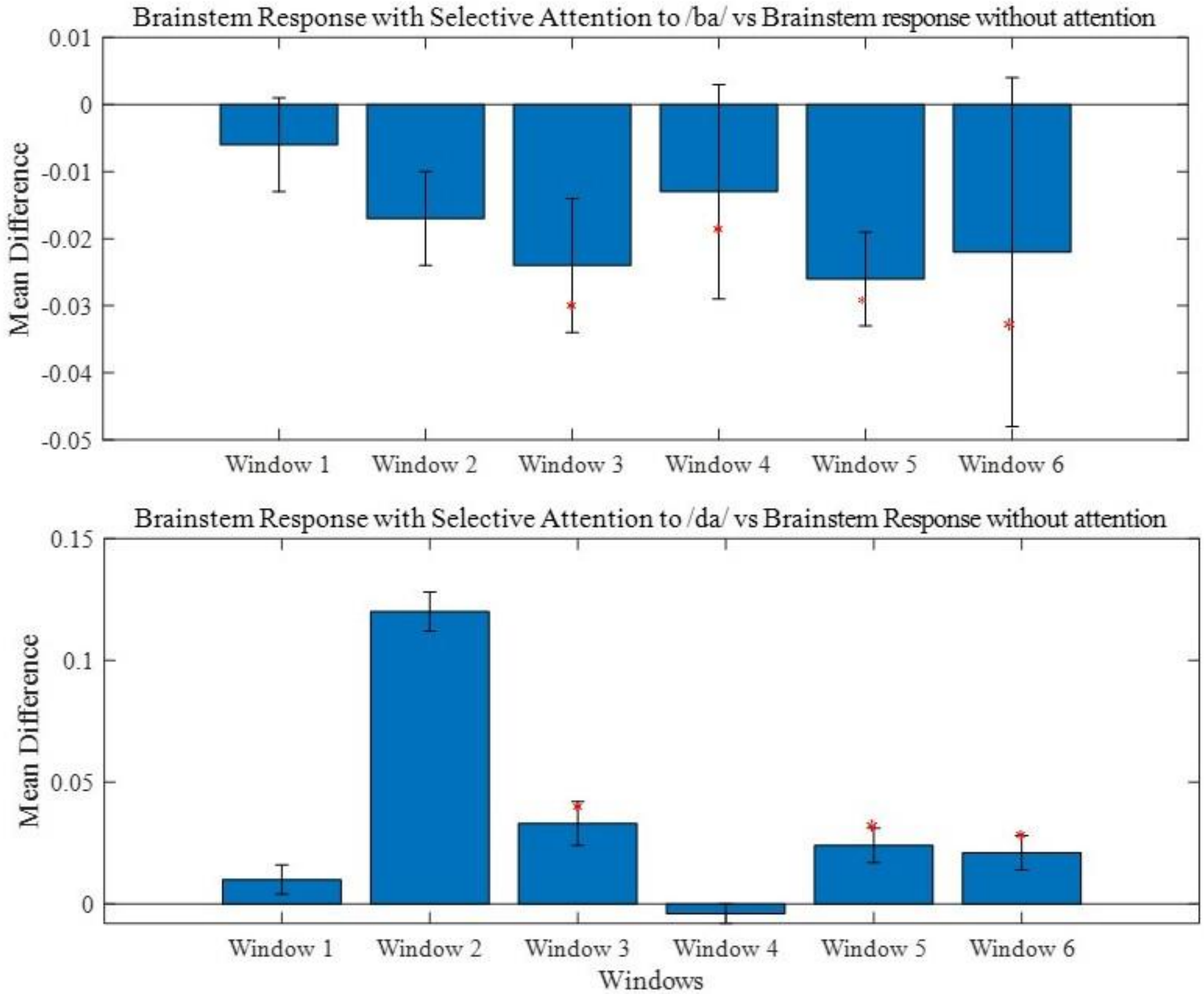

Brainstem Response with Selective Attention to /ba/ vs Brainstem response without attention
Mean Difference
0.01
0
-0.01
-0.02
-0.03
-0.04
-0.05
Window 1
Window 2
Window 3
Window 4
Window 5
Window 6
Brainstem Response with Selective Attention to /da/ vs Brainstem Response without attention
Mean Difference
0.15
0.1
0.05
0
Window 1
Window 2
Window 3
Window 4
Window 5
Window 6
Windows

Figure 12.

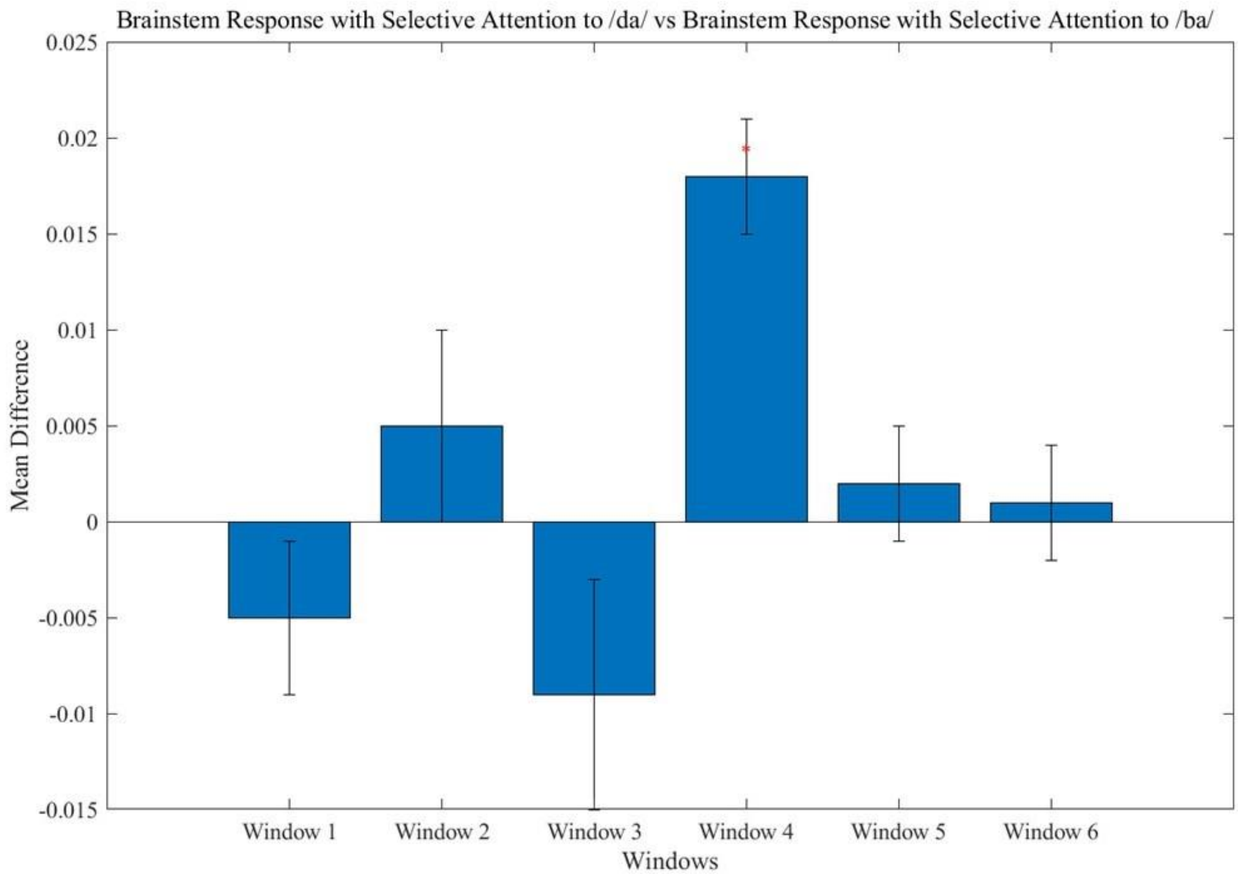


Figure 13.

Table 1.

	F0	F1		F2		F3		F4	F5	F6
	Flat	Onset	Steady-State	Onset	Steady-State	Onset	Steady-State	Flat	Flat	Flat
/da/	100	400	720	1700	1240	2580	2500	3300	3750	4900
/ba/	100	400	720	900	1240	2400	2500	3300	3750	4900

Table 2.

Parameters	The average value of the parameters (%) $\pm SD$
Accuracy	$99 \pm 1.97 * 10^{-3}$
Sensitivity	86 ± 0.2
Precision	92 ± 0.21
Specificity	$98.9 \pm 1.01 * 10^{-3}$

Dr. Amir Homayoon Jafari

Dr Amir Homayoon Jafari is an associate professor at the Tehran University of Medical Sciences, specializing in bioengineering, control systems engineering, and artificial intelligence. With a focus on biomedical signal processing and intelligent systems, his research aims to advance rehabilitation technologies and innovate solutions in healthcare. Amir's diverse expertise extends to fields such as cancer research, reflecting his dedication to pioneering transformative advancements in biomedical engineering.

Dr Azadeh Ghalyanchi-Langeroudi

Dr. Azadeh Ghalyanchi-Langeroudi is a Ph.D. candidate in biomedical engineering at the Tehran University of Medical Sciences, specializing in auditory selective attention, medical signal processing, and deep learning. Her research focuses on medical engineering and biosignal and brain signal processing expertise, Azadeh is committed to driving advancements in neurorehabilitation strategies for patients with brain damages.

Dr. Zahra Shirzhiyan

Dr Zahra Shirzhiyan, PhD, holds a postdoctoral position at the Brandenburg University of Technology Cottbus-Senftenberg, where she researches auditory neuroscience and biomedical signal processing. With a background in psychology and a focus on auditory processing, Zahra's work significantly contributes to our understanding of the human auditory system and its implications for biomedical engineering.

Dr. Morteza Farahi

Dr. Morteza Farahi, a Tehran University of Medical Sciences researcher, specializes in electronic engineering and rehabilitation medicine. His expertise in surface electromyography (sEMG) and medical imaging underscores his commitment to improving patient outcomes through technological innovation in biomedical engineering.

Dr. Amin Asgharzadeh Alvar

Dr. Amin Asgharzadeh Alvar, with a background in biomedical engineering and expertise in data mining and artificial intelligence, is dedicated to leveraging technology to address complex healthcare challenges. His research in artificial neural networks and signal processing has the potential to revolutionize healthcare delivery and patient care.

Dr. Ahmadreza Keihani

Dr. Ahmadreza Keihani, a PostDoc researcher at the University of Pittsburgh, focuses on neuroimaging, nonlinear dynamics, and brain-computer interface (BCI) technology. His expertise in biomedical signal processing and musculoskeletal modelling contributes to advancements in understanding the human brain and its complexities.

Dr. Akram Pourbakht

Dr. Akram Pourbakht, Head of Department at Iran University of Medical Sciences, is a leading expert in audiology and otology. His research in otoacoustic emissions and auditory brainstem response (ABR) enhances our understanding of hearing and auditory function, with implications for clinical diagnostics and patient care.

Dr. Elham Shamsi

Dr. Elham Shamsi is a Ph.D. candidate at Amirkabir University of Technology, researching EEG and EMG processing, neuroscience, and human motor control and rehabilitation. Her interdisciplinary approach and proficiency in engineering tools contribute to innovative solutions in biomedical engineering and healthcare delivery.