Aud Vestib Res (2021);30(4):232-240.
DOI: https://doi.org/10.18502/avr.v30i4.7444

**REVIEW ARTICLE**

# Effect of tinnitus on the performance of central auditory system: a review

**Behieh Kohansal[1*], Mehdi Asghari[2], Sirvan Najafi[3], Fahimeh Hamedi[1]**

[1]- Department of Audiology, School of Rehabilitation, Arak University of Medical Sciences, Arak, Iran

[2]- Department of Occupational Health and Safety Engineering, School of Public Health, Arak University of Medical Sciences, Arak, Iran

[3]- Department of Audiology, University of Social Welfare and Rehabilitation Sciences, Tehran, Iran

Received: 21 Apr 2021, Revised: 24 May 2021, Accepted: 22 Jun 2021, Published: 15 Oct 2021

## Abstract

**Background and Aim:** Tinnitus is one of the most difficult challenges in audiology and otology. Previous studies have been shown that tinnitus may interfere with the function of central auditory system (CAS). Involvement of CAS abilities including speech perception and auditory processing has led to serious problems in people with tinnitus. Due to the lack of enough information about the impact of tinnitus on CAS and its function, and given that there is no standardized protocol for assessment and management of tinnitus, this study aimed to review the studies on the effect of tinnitus on the CAS function.

**Recent Findings:** Sixteen eligible articles were reviewed. Temporal and spectral resolution, frequency differentiation and speech perception deficits were reported in patients with tinnitus, especially in background noise. This was reported even in tinnitus patients with normal hearing.

**Conclusion:** Assessment of central auditory processing and speech perception in noise seems to be useful for proper management of tinnitus in clinical practice.

**Keywords:** Tinnitus; auditory system; central auditory processing; speech in noise performance

[*] **Corresponding author:** Department of Audiology, School of Rehabilitation, Arak University of Medical Sciences, Golestan Blvd., Ghods Town, Arak, 3818146851, Iran. Tel: 009886-33685006, E-mail: kohansal.b@gmail.com

**Citation:** Kohansal B, Asghari M, Najafi S, Hamedi F. Effect of tinnitus on the performance of central auditory system: a review. Aud Vestib Res. 2021;30(4):232-40.

## Introduction

Tinnitus is a conscious perception of sound in the absence of any external acoustic stimulus [1]. Currently, there is no precise and comprehensive definition of tinnitus. Tinnitus has been widely reported as one of the most challenging symptoms in audiology and otology in recent years [2,3]. The sound may be perceived as a high- or low-pitched pure tone or a noise. Tinnitus is classified based on its clinical characteristics such as duration, laterality, or its implications [4]. Growing industrialization and urbanization along with technological advances have contributed to prolonged exposure to high levels of noise. Noise pollution is a serious problem due to its harmful impacts on health such as noise-induced tinnitus (NIT) and noise-induced hearing loss [5,6]. According to a study, over 70 million people in Europe and 50 million in U.S. are affected by tinnitus [7]. Therefore, it can be said that most of people, especially those with exposure to noise are susceptible to tinnitus and its adverse effects. Studies have revealed that approximately 20−40% of industrial workers suffer from persistent tinnitus. The prevalence of tinnitus in workers with high-level noise exposure is four times higher than in non-exposed subjects (20.7−42% vs. 5−7.5%), which highlights the negative effect of noisy workplaces on the workers [5,8].

Given the high prevalence of NIT worldwide and considering the adverse effects of tinnitus on communication and daily living activities, it can be claimed that central auditory impairment can be caused by NIT [2,4,7]. NIT can negatively affect the auditory functions including speech perception which may be impaired in most of people with tinnitus even in those with normal hearing. Speech comprehension difficulty is one of the leading causes of tinnitus-related handicap in many affected patients [9]. Higher level of central auditory processing is needed for speech perception in noise (SPIN) test, frequency analysis, auditory discrimination and etc. [10]. Studies have shown the association of abnormal sound transduction, coding, and processing in the central auditory system (CAS) of people with tinnitus [11-13]. Auditory temporal processing (the ability to process acoustic signals over time) has been considered as one of the important characteristics of CAS function which may be influenced by tinnitus [14]. Proper temporal resolution is involved in other CAS abilities including the identification of speech signals starting with silence gap, spectral and temporal modulation detection ability within the cochlea [15]. Cochlear damage, disruption of the neural encoding by means of temporal desynchronization and/or differentiation in the ascending auditory pathway up to the auditory cortex contribute to subsequent deterioration of auditory perception and SPIN [15-17].

Although several studies have investigated various impacts of tinnitus, a few of them have measured the effect of tinnitus on the function of CAS [4,15,18-21]. Nevertheless, the effect of tinnitus on CAS function remains unclear contributing to the lack of an effective tinnitus management method. In the current study, we aimed to review the possible effect and interference of tinnitus on CAS abilities and find out the contradictions in the results of related studies.

In this review study, a search was first conducted in Web of Science, Google Scholar, Scopus, and PubMed databases using the keywords, "tinnitus" alone or in combination with "auditory central processing", "speech perception "or "speech recognition" and “psychoacoustic”, on the related studies published during 2000−2021. The original papers on tinnitus effects on CAS function in English with available full-text assessing adults (age ≥ 18 years) were included in the review. The abstracts, case reports, non-related studies, letters to the editor, and non-English articles, and those evaluated tinnitus impact on peripheral auditory system were excluded. Initial search yielded 76 articles. After reviewing their title, introduction, and discussion sections, and elimination of duplicates, review articles and irrelevant papers, 16 eligible articles remained. The flowchart of article selection process is shown in Fig. 1.

Of 76 articles, 16 articles with 5537 subjects were reviewed. These studies and their results are briefly presented in Tables 1 and 2.

## Effect of tinnitus on main abilities of central auditory system

### *Central auditory processing*

Eight studies with a total of 406 participants (217 with tinnitus) were found examining the effect of tinnitus on auditory processing. Of 217 tinnitus patients, 112 had normal hearing, while 105 had hearing loss. Only one study reported effect of unilateral tinnitus on central auditory processing. The gap in noise (GIN) and difference limen for intensity (DLI) tests were the most frequently used instruments for the evaluation of central auditory processing in tinnitus patient. GIN test, as a clinically useful tool, measures temporal resolution by determining gap detection threshold in noise. Deficits in gap detection were observed in tinnitus patients in three out of seven studies, while the gaps in the control groups were identified in a shorter time interval. Duration pattern test (DPT) was another test for measuring the temporal processing abilities due to its ease of use, high sensitivity and specificity, and ability

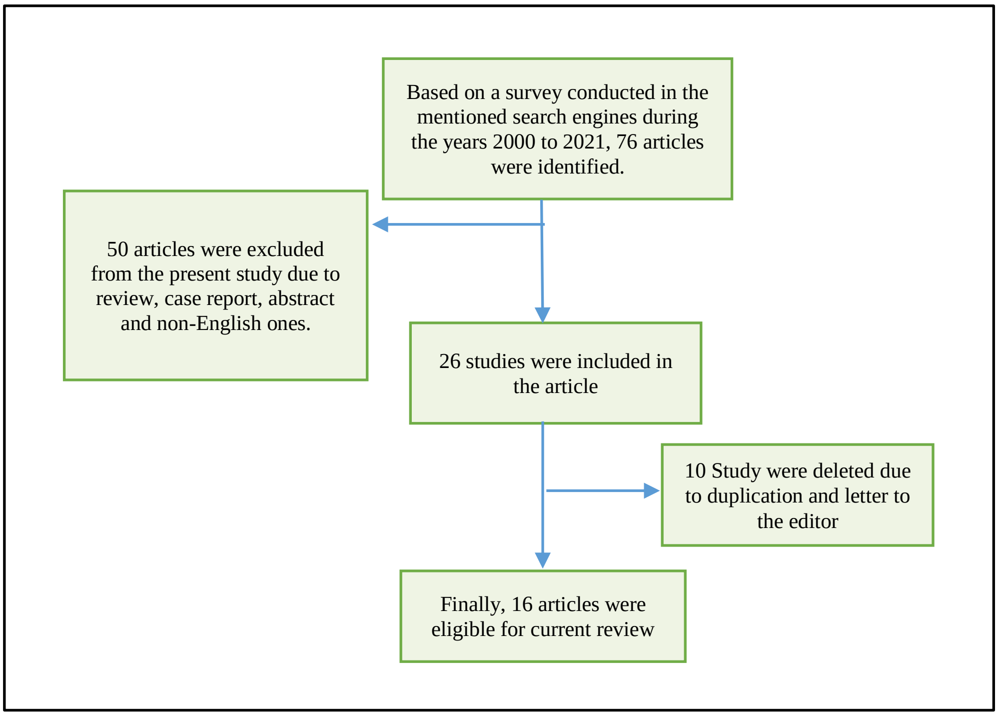


**Fig. 1. Flowchart of selection process of articles included in this review.**

to evaluate each ear separately [14]. One study reported that the frequency discrimination was impaired in subjects with moderate tinnitus but not in those with mild tinnitus [22]. In terms of intensity discrimination, one study found a 1 dB deficit under two of nine test conditions [23]. Jain and Sahoo reported the effect of tinnitus on different aspects of central auditory processing abilities such as temporal resolution, SPIN and frequency discrimination in affected subjects [22]. Regarding the laterality of tinnitus, the only study investigating the effect of unilateral tinnitus using GIN test showed no evidence for the impact of unilateral tinnitus on auditory temporal resolution [24]. Six studies included normal hearing cases with and without tinnitus and two studies included tinnitus patients with hearing loss. Normal-hearing subjects with tinnitus were found to suffer from impaired temporal resolution compared to those without tinnitus [24, 25]. Mismatch negativity (MMN) and auditory brainstem response (ABR) tests were other diagnostic tests used for investigating the impact of tinnitus on CAS [26,27]. The MMN test assesses the temporal integration of auditory perception and its generators [26]. The study used ABR test showed reduced wave I amplitude, indicating different auditory nerve fibers in patients with tinnitus and normal hearing [23]. Findings of Epp et al. and Mahmoudian et al. showed that the MMN latency and amplitude were significantly different in tinnitus patients compared to control group [23,28]. Effect of tinnitus using other processing tests (DPT, DLI, difference limen for frequency, gap detection test, modulation detection thresholds) was also observed [14,23,25] except in Jain and Sahoo's study using DLI [22]. It can be argued that even a small cochlear damage without affecting the auditory threshold under pure-tone audiometry may change the processing of auditory information in the CAS due to the development of tinnitus, and reduce the temporal resolution [15,29]. The main results of eight reviewed studies are summarized in Table 1.

*Speech perception*

A total of eight studies, including 5266 subjects, were found examining the effect of tinnitus on speech perception. Impaired speech perception,

**Table 1. Summary of eight studies on the effect of tinnitus on central auditory processing**

| Authors | Year | Participants | Measures | Main results |
|---|---|---|---|---|
| Sanches et al. [18] | 2010 | 48 subjects with NH, 18 with tinnitus and 23 without tinnitus | HF Audiometry, GIN test | Major difference in HF audiometry and GIN test results between two groups<br>Detecting gaps in shorter time intervals and better hearing thresholds in control group than tinnitus group |
| Epp et al. [23] | 2012 | 11 NH subjects with tinnitus and 14 NH subjects without tinnitus | DLI and ABR tests | Significant increase of intensity-discrimination thresholds during loudness matching in NH subjects with tinnitus<br>Reduction in the amplitude of wave I under the ABR test in NH subjects with tinnitus. |
| Mehdizade Gilani et al. [14] | 2013 | 20 NH subjects with tinnitus and 20 NH subjects without tinnitus | GIN test and DPT | Significant increase in threshold of gap detection in the tinnitus group in both ears under the GIN test<br>No significant differences in correct responses between two groups under DPT. |
| Mahmoudian et al. [28] | 2013 | 28 subjects with chronic subjective idiopathic tinnitus and 33 healthy peers | MMN test | Significant differences in amplitude, duration, and area under the curve in tinnitus subjects compared to controls under MMN test |
| An et al. [24] | 2014 | 60 patients with unilateral tinnitus and symmetric hearing loss and 30 subjects with NH | GIN test | No significant difference in the mean GIN thresholds among tinnitus patients and non-tinnitus NH subjects<br>No relation between GIN threshold and perception level in tinnitus subjects with gender, frequency, tinnitus loudness, and audiometric data. |
| Jain and Sahoo [2] | 2014 | 20 NH subjects with tinnitus and 20 age-matched NH subjects without tinnitus | DLI, DLF, GDT, and MDT tests | Tinnitus group performed poorly under all tests except in DLI test |
| Ibraheem and Hassaan [15] | 2017 | 15 NH adults without tinnitus and 15 NH adults with tinnitus. | GIN test | Significant decrease of correct scores under GIN test in tinnitus group |
| Zeng et al. [25] | 2020 | 45 hearing-impaired subjects with chronic tinnitus and 27 young NH subjects without tinnitus | GIN, DLI, and DLF tests | Tinnitus had no effect on gap detection<br>Hearing loss was associated with frequency discrimination, while tinnitus had no association<br>Tinnitus had level-dependent effects on intensity discrimination and masking |

NH; normal hearing, HF; high frequency, GIN; gap in noise, DLI; difference limen for intensity, ABR; auditory brainstem response, DPT; duration pattern test, MMN; mismatch negativity, DLF; difference limen for frequency, GDT; gap detection test, MDT; modulation detection thresholds

especially in noise, was reported in tinnitus patients in 7 out of 8 studies [4,9,19-21,30-32]. However, a study found low or no impairment when age and hearing loss were controlled, and showed impaired SPIN in young people with normal hearing and NIT [31]. Of three studies that investigated the SPIN of participants, two studies showed higher difficulty in SPIN [4,31, 32]. Different tests were used for assessing the SPIN. In most studies, speech perception was evaluated with the speech-in-noise (SIN) [19,31, 32] and speech reception threshold in noise (SRTn) tests [20,21,30]. SRTn was measured using open-set spondee recognition in steady-state speech-shaped noise started with a signal-to-noise ratio (SNR) of 6 dB. The final SRTn for each subject was calculated by averaging the results of three adaptive -runs [21]. Moon et al.

**Table 2. Summary of eight studies investigated the impact of tinnitus on speech perception**

| Authors | Year | Participants | Measures | Main results |
|---|---|---|---|---|
| Huang et al. [19] | 2006 | 20 tinnitus subjects and NH subjects | MSPIN test | Significantly lower MSPIN test score in tinnitus group than control group |
| Soalheiro et al. [4] | 2012 | 495 workers exposed to environmental or occupational noise with hearing complaints | SRI test | Greater difficulty in speech recognition in noise-exposed workers |
| Mertens et al. [20] | 2013 | 15 CI users with ipsilateral unilateral tinnitus under two conditions of CI on and CI off | SRTn test | Unilateral tinnitus interfered with SRTn in non-affected ear<br>SRTn was significantly poorer in subjects with high tinnitus loudness |
| Moon et al. [30] | 2015 | 30 tinnitus subjects and 15 NH subjects divided into 4 groups | SRTn test | Significant decrease in SRTn scores in tinnitus subjects<br>Tinnitus can constrain patients' SRTn regardless of their hearing sensitivity |
| Gilles et al. [31] | 2016 | 87 young adults with a history of recreational noise exposure (19 with tinnitus and 68 without tinnitus) | HF Audiometry, TEOAE, DPOAE, SIN, and ABR tests | No significant differences between tinnitus and non-tinnitus subjects in terms of hearing thresholds, and TEOAE, DPOAE, and ABR test results<br>Significant decrease in SRTn in tinnitus subjects compared to non-tinnitus subjects. |
| Vielsmeier et al. [9] | 2016 | 361 patients with chronic tinnitus | Göttingen sentence test | Speech perception deficits were prevalent among tinnitus patients especially in noisy environments<br>Deficits in CAS function cause SPIN difficulties. |
| Van Eynde et al. [32] | 2016 | 37 patients with mild noise-induced hearing loss and tinnitus complaints | SRT test and DTT | Significant correlation between the averaged HF PTA and the averaged SRT across ears on the DTT<br>Slight influence of tinnitus onset on the SRT score |
| Oosterloo et al. [21] | 2020 | 4211 participants with and without tinnitus | SRTn test | Higher SRTn in tinnitus subjects with hearing loss was associated with speech intelligibility in noise<br>More severe tinnitus increases the SRTn. |

NH; normal hearing, MSPIN; Mandarin speech perception in noise, SRI; speech recognition index, CI; cochlear implant, SRTn; speech reception threshold in noise, HF; high frequency, TEOAE; transient evoked otoacoustic emissions, DPOAE; distortion product otoacoustic emissions; SIN; speech-in-noise, ABR; auditory brainstem response, CAS; central auditory system, SPIN; speech perception in noise, DTT; digit triplet test; PTA; Pure-tone average

also found a significant decrease in SRTn score in tinnitus patients compared to controls using open-set spondees [30]. SIN test was reported as a reliable and feasible clinical technique to evaluate noise-induced damage in patients with normal peripheral function complaining of NIT. It was hypothesized that patients with tinnitus have difficulties in SPIN due to changes in their central auditory processing and mechanism [31]. A study on 20 patients with tinnitus revealed their impaired speech perception, especially in noisy environments, compared to the control group [19]. In two other studies, tinnitus patients with normal hearing also reported difficulties in speech perception [9,31]. Van Eynde et al. reported a little negative effect of tinnitus on the speech perception in normal-hearing subjects with tinnitus [32]. This effect could be higher if subjects would talk simultaneously, known as cocktail party effect [9]. There was high prevalence of speech perception impairment in workers with tinnitus and a history of noise exposure. One study showed that about 40% of tinnitus patients report speech perception difficulties in a subjective manner while about 80% reported difficulties with speech perception in noisy environments, such as cocktail parties [4]. Gilles et al. showed SPIN difficulties in subjects with tinnitus. These results confirm the results of previous studies that noise exposure may develop tinnitus in the absence of measurable peripheral damage [31]. Other measurement methods including high frequency audiometry, otoacoustic emissions and ABR tests showed no significant differences between tinnitus and non-tinnitus subjects [31]. Only in one study using speech perception test without presenting competing noise, findings revealed more difficulties in speech perception for noise-exposed subjects compared to normal subjects [4]. Findings of Vielsmeier et al. indicated the impairment of SPIN using SRTn and Göttingen Sentence tests, may be due to the mechanism of the central auditory nervous system in noisy environments [9]. Table 2 summarizes the main results of eight reviewed articles in this section.

**Discussion**

In this study, 16 articles examining the effect of tinnitus on central auditory processing (n = 8) and speech perception (n = 8) were reviewed. According to these articles, the CAS is affected in the majority of patients with tinnitus in the form of worsened gap detection, reduced temporal resolution, and impaired SPIN [9,15,19,21-23]. The GIN test was shown to be highly sensitive to cortical and brainstem lesions. It was postulated that the reason for poor gap detection is that ongoing tinnitus masks the gap [22]. Poor GIN test scores in subjects with tinnitus suggested that, whether tinnitus originates in the CAS or not, it affects the auditory processing abilities in the CAS [33]. Tinnitus fills the silent gaps in noise and causes difficulties in gap detection. Consequently, it affects the modulation detection and frequency discrimination, all of which can result in poor auditory temporal resolution [24]. It seems that neural changes occurring more at CAS reorganize the cortical tonotopic map and make alterations in the temporal processing ability of people with tinnitus [30,34,35]. Auditory temporal resolution is another CAS ability which encodes and detects subtle changes in acoustic stimuli. Neurological structures are involved in auditory temporal processing of simple or complex stimuli. Auditory temporal processing is critical for phonological awareness, lexical knowledge, and SPIN. Electrophysiological evidence also showed that pre-attentive and automatic auditory processing are impaired in subjects with chronic tinnitus [28]. Epp et al. indicated that deafferentation of auditory nerve fibers can underlie tinnitus in normal hearing people. Apart from peripheral damage, changes in central auditory processing can affect the intensity discrimination thresholds and increase gain in the tinnitus frequency range in tinnitus patients [23]. Magnetic resonance imaging and functional magnetic resonance imaging results have demonstrated an increased responses to sound at the midbrain level in subjects with tinnitus compared to controls [28,36]. Consequently, it can be claimed that tinnitus plays an important role in reducing auditory temporal resolution and gap detection, creating difficulties in speech perception.

Several studies have reported SPIN problems in tinnitus patients with different languages [4,19, 20,30.31]; however, we found that SPIN ability is not associated with tinnitus severity. In contrast, Oosterloo et al. showed that higher tinnitus loudness can increase SRTn [21]. The reviewed studies suggested that tinnitus and impaired SPIN have common pathophysiologic mechanism in the central auditory pathways. They found poor SPIN in most cases. Impaired SPIN is one of the leading causes of tinnitus-related handicap in many patients with tinnitus and, therefore, is clinically crucial for quantifying the impact of tinnitus on daily life [19,37]. Schaette and McAlpine proposed that reduced auditory nerve input can result in increased neuronal gain in the auditory brainstem. On other hand, tinnitus can be associated with the increased spontaneous activity of auditory neurons [29]. In contrast, a study showed the lack of tinnitus effect on auditory perception as a result of two independent pathways between the tinnitus and external sounds [25]. Speech perception test scores were poor in reviewed studies even if audiologic findings were not conspicuous [19,31]. In other words, speech perception impairment was reported in subjects with no peripheral damage in most of these studies. This indicates that impaired speech perception is not merely related to hearing loss. However, the exact effect of tinnitus on speech perception and the underlying mechanism remains unclear. Some researchers mentioned different reasons such as noise exposure and relevant mechanical changes throughout the auditory system [34,38]. Most of studies confirmed that peripheral damage followed by neuroplasticity in the CAS plays a role in developing chronic tinnitus [35,39]. Majority of tinnitus patients have concentration difficulties. The presence of tinnitus could confuse the patients during the process of threshold detection [37,40]. Decreased SRT scores in the absence of temporal/spectral resolution deficits in subjects with tinnitus imply that tinnitus can occur without cochlear damage (sensorineural hearing loss). This creates a serious challenge to the model of cortical hyperactivity [30,36]. Therefore, we can claim that difficulties in speech perception arise from the interference of tinnitus with CAS function. In unilateral tinnitus, the presence of noise in the affected ear can increase speech perception due to reduced masking effect. However, studies suggest that tinnitus may affect the CAS, as a central masker, when patients are involved in listening to speech in the presence of background noise [4,30]. The reviewed articles showed that tinnitus affects the CAS function including temporal resolution, frequency discrimination, and speech perception especially in the presence of background noise, regardless of its origin. The use of small and heterogeneous study samples can be the possible reason for the contradictory results of reviewed studies.

## Conclusion

Central auditory system function is affected in most of patients with tinnitus in terms of central auditory processing and speech in noise, even in normal-hearing people. High-frequency audiometry is more likely to be affected in patients with tinnitus than normal audiometry. More complex tasks such as speech in noise recognition may be valuable in the standard audiometry, especially in hearing conservation programs. There is a high prevalence of difficulties in speech perception in patients with tinnitus. Speech in noise test should be routinely used in clinical practice. We recommend further studies with larger sample size for assessing speech perception in both quiet and noise to improve future interventions. Furthermore, further studies are recommended to investigate the impact of tinnitus on other auditory abilities (e.g. spatial localization, lateralization, etc.), listening effort, and non-auditory functions such as memory and attention.

## Conflict of interest

The authors state that there was no conflict of interest

**References**


1. Najafi S, Rouzbahani M. Auditory evoked potential P300 characteristics in adults with and without idiopathic bilateral tinnitus. Aud Vestib Res. 2020. 29(4):220-6. doi: 10.18502/avr.v29i4.4641
2. Bhatt JM, Lin HW, Bhattacharyya N. Prevalence, severity, exposures, and treatment patterns of tinnitus in the United States. JAMA Otolaryngol Head Neck Surg. 2016;142(10):959-65. doi: 10.1001/jamaoto.2016.1700
3. Haider HF, Hoare DJ, Costa RFP, Potgieter I, Kikidis D, Lapira A, et al. Pathophysiology, diagnosis and treatment of somatosensory tinnitus: a scoping review. Front Neurosci. 2017;11:207. doi: 10.3389/fnins.2017.00207
4. Soalheiro M, Rocha L, do Vale DF, Fontes V, Valente D, Teixeira LR. Speech recognition index of workers with tinnitus exposed to environmental or occupational noise: a comparative study. J Occup Med Toxicol. 2012;7(1):26. doi: 10.1186/1745-6673-7-26
5. Masterson EA, Themann CL, Luckhaupt SE, Li J, Calvert GM. Hearing difficulty and tinnitus among U.S. workers and non-workers in 2007. Am J Ind Med. 2016;59(4):290-300. doi: 10.1002/ajim.22565
6. Jafari A, Badiei R, yarmohammad tooski M, Kohansal B. [The effect of N-Acetylcysteine on the reduction of permanent noise-induced hearing loss in workers at Hepco Company]. Journal of Arak University of Medical Sciences. 2011;14(5):11-7. Persian.
7. Haider HF, Bojić T, Ribeiro SF, Paço J, Hall DA, Szczepek AJ. Pathophysiology of subjective tinnitus: triggers and maintenance. Front Neurosci. 2018;12:866. doi: 10.3389/fnins.2018.00866
8. Jafari Z. Toufan R, Aghamollaei M. Ebrahimzadeh SH. Esmaili M. [Impact of industrial noise-induced hearing disorders on workers cognition and auditory memory]. J Sabzevar Univ Med Sci. 2013;20(3):259-69. Persian.
9. Vielsmeier V, Kreuzer PM, Haubner F, Steffens T,

Semmler PRO, Kleinjung T, et al. Speech comprehension difficulties in chronic tinnitus and its relation to hyperacusis. Front Aging Neurosci. 2016;8:293. doi: 10.3389/fnagi.2016.00293
10. Musiek RE, Shinn JB, Jirsa R, Bamiou DE, Baran JA, Zaida E. GIN (gaps-in-noise) test performance in subjects with confirmed central auditory nervous system involvement. Ear Hear. 2005;26(6):608-18. doi: 10.1097/01.aud.0000188069.80699.41
11. Diges I, Simón F, Cobo P. Assessing auditory processing deficits in tinnitus and hearing impaired patients with the auditory behavior questionnaire. Front Neurosci. 2017; 11:187. doi: 10.3389/fnins.2017.00187
12. Lanting CP, de Kleine E, Bartels H, Van Dijk P. Functional imaging of unilateral tinnitus using fMRI. Acta Otolaryngol. 2008;128(4):415-21. doi: 10.1080/00016480701793743
13. Moossavi A, Najafi S. Transcranial direct current stimulation in treatment of tinnitus. Aud Vestib Res. 2021;30(1):1-8. doi: 10.18502/avr.v30i1.5305
14. Mehdizade Gilani V, Ruzbahani M, Mahdi P, Amali A, Nilforush Khoshk MH, Sameni J, et al. Temporal processing evaluation in tinnitus patients: results on analysis of gap in noise and duration pattern test. Iran J Otorhinolaryngol. 2013;25(4):221-6. doi: 10.22038/IJORL.2013.1951
15. Ibraheem OA, Hassan MR. Psychoacoustic characteristics of tinnitus versus temporal resolution in subjects with normal hearing sensitivity. Int Arch Otorhinolaryngol. 2017;21(2):144-50. doi: 10.1055/s-0036-1583526
16. Lopez-Poveda EA, Barrios P. Perception of stochastically undersampled sound waveforms: a model of auditory deafferentation. Front Neurosci. 2013;7:124. doi: 10.3389/fnins.2013.00124
17. Pichora-Fuller MK, Schneider BA, Macdonald E, Pass HE, Brown S. Temporal jitter disrupts speech intelligibility: a simulation of auditory aging. Hear Res. 2007; 223(1-2):114-21. doi: 10.1016/j.heares.2006.10.009
18. Sanches SGG, Sanches TG, Carvallo RMM. Influence of cochlear function on auditory temporal resolution in tinnitus patients. Audiol Neurootol. 2010;15(5):273-81. doi: 10.1159/000272939
19. Huang CY, Lee HH, Chung KC, Chen HC, Shen YJ, Wu JL. Relationships among speech perception, self-rated tinnitus loudness and disability in tinnitus patients with normal pure-tone thresholds of hearing. ORL J Otorhinolaryngol Relat Spec. 2007;69(1):25-9. doi: 10.1159/000096713
20. Mertens G, Punte AK, De Ridder D, Van de Heyning P. Tinnitus in a single-sided deaf ear reduces speech reception in the non-tinnitus ear. Otol Neurotol. 2013; 34(4):662-6. doi: 10.1097/MAO.0b013e31828779f0
21. Oosterloo BC, Homans NC, Goedegebure A. Tinnitus affects speech in noise comprehension in individuals with hearing loss. Otol Neurotol. 2020;41(9):e1074-81. doi: 10.1097/MAO.0000000000002733
22. Jain C, Sahoo JP. The effect of tinnitus on some psychoacoustical abilities in individuals with normal hearing sensitivity. Int Tinnitus J. 2014;19(1):28-35. doi: 10.5935/0946-5448.20140004
23. Epp B, Hots J, Verhey JL, Schaette R. Increased intensity discrimination thresholds in tinnitus subjects with a normal audiogram. J Acoust Soc Am. 2012;132(3):EL196-201. doi: 10.1121/1.4740462
24. An YH, Jin YS, Yoon SW, Shim HJ. The effects of unilateral tinnitus on auditory temporal resolution: gaps-in-noise performance. Korean J Audiol. 2014;18(3):119-25. doi: 10.7874/kja.2014.18.3.119
25. Zeng FG, Richardson M, Turner K. Tinnitus does not interfere with auditory and speech perception. J Neurosci. 2020;40(31):6007-17. doi: 10.1523/JNEUROSCI.0396-20.2020
26. Holdefer L, Oliveira CA, Venosa AR. The mismatch negativity test in ears with and without tinnitus-a path to the objectification of tinnitus. Int Tinnitus J. 2013; 18(2):168-74. doi: 10.5935/0946-5448.20130022
27 Milloy V, Fournier P, Benoit D, Noreña A, Koravand A. Auditory brainstem responses in tinnitus: a review of who, how, and what? Aging Neurosci. 2017;9:1-18. doi: 10.3389/fnagi.2017.00237
28 Mahmoudian S, Farhadi M, Najafi-Koopaiec M, Darestani-Farahani E, Mohebbib M, Denglere R, et al. Central auditory processing during chronic tinnitus as indexed by topographical maps of the mismatch negativity obtained with the multi-feature paradigm. Brain Res. 2013;1527:161-73. doi: 10.1016/j.brainres.2013.06.019
29 Schaette R, McAlpine D. Tinnitus with a normal audiogram: physiological evidence for hidden hearing loss and computational model. J Neurosci. 2011;31(38):13452-7. doi: 10.1523/JNEUROSCI.2156-11.2011
30 Moon IJ, Won JH, Kang HW, Kim DH, An YH, Shim HJ. Influence of tinnitus on auditory spectral and temporal resolution and speech perception in tinnitus patients. J Neurosci. 2015;35(42):14260-9. doi: 10.1523/JNEUROSCI.5091-14.2015
31 Gilles A, Schlee W, Rabau S, Wouters K, Fransen E, Van de Heyning P. Decreased speech-in-noise understanding in young adults with tinnitus. Front Neurosci. 2016;10:288. doi: 10.3389/fnins.2016.00288
32 Van Eynde C, Denys S, Desloovere C, Wouters J, Verhaert N. Speech-in-noise testing as a marker for noise-induced hearing loss and tinnitus. B-ENT. 2016;Suppl 26(1):185-91.
33 Jain S, Dwarkanath VM. Effect of tinnitus location on the psychoacoustic measures of hearing. Hear Balance Commun. 2016;14(1):8-19. doi: 10.3109/21695717.2016.1099885
34 Yamashita D. Oxidative stress in noise-induced hearing loss. In Miller J, Le Prell C, Rybak L, editors. Free radicals in ENT pathology. Oxidative stress in applied basic research and clinical practice. Cham: Humana Press; 2015. p.147-61. :doi: 10.1007/978-3-319-13473-4_8
35 Cuny C, Chéry-Croze S, Bougeant JC, Koenig O. Investigation of functional hemispheric asymmetry of language in tinnitus sufferers. Neuropsychology. 2004;18(2): 384-92. doi: 10.1037/0894-4105.18.2.384
36 Melcher JR, Levine RA, Bergevin C, Norris B. The auditory midbrain of people with tinnitus: abnormal sound-evoked activity revisited. Hear Res. 2009;257(1-2):63-74. doi: 10.1016/j.heares.2009.08.005
37 Watts EJ, Fackrell K, Smith S, Sheldrake J, Haider H, Hoare DJ. Why is tinnitus a problem? a qualitative analysis of problems reported by tinnitus patients. Trends Hear. 2018;22:2331216518812250. doi: 10.1177/2331216518812250
38 Henderson D, Bielefeld EC, Harris KC, Hu BH.

The role of oxidative stress in noise-induced hearing loss. Ear Hear. 2006;27(1):1-19. doi: 10.1097/01.aud.0000191942.36672.f3

39 Paglialonga A, Fiocchi S, Del Bo L, Ravazzani P, Tognola G. Quantitative analysis of cochlear active mechanisms in tinnitus subjects with normal hearing sensitivity: Time-frequency analysis of transient evoked otoacoustic emissions and contralateral suppression. Auris Nasus Larynx. 2011;38(1):33-40. doi: 10.1016/j.anl.2010.04.006

40 Hébert S, Lupien SJ. Salivary cortisol levels, subjective stress, and tinnitus intensity in tinnitus sufferers during noise exposure in the laboratory. Int J Hyg Environ Health. 2009;212(1):37-44. doi: 10.1016/j.ijheh.2007.11.005