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REVIEW ARTICLE

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Central auditory processing abilities in individuals with tinnitus and normal hearing sensitivity: a systematic review

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Abstract

Background Tinnitus is the perception of sound when there is no external sound stimulus. Individuals with tinnitus may have altered neurological system corresponding to the auditory pathway. Therefore, central auditory processing abilities, which rely on the central auditory pathway, may be affected. This study reviewed the published studies regarding the impact of tinnitus on central auditory processing abilities.

Main text A total of 3087 studies were identified, of which 18 fulfilled the eligibility criteria and were included in the review. The included studies scored good or fair in the quality assessment checklist. The review showed that individuals who had tinnitus with normal hearing sensitivity performed poorly on temporal resolution tests, speech perception in noise, localization, and auditory memory. However, temporal patterning and dichotic tests were not shown to be affected by tinnitus.

Conclusion The audiologists involved in tinnitus assessment are recommended to include central auditory processing tests in routine evaluation for the early diagnosis and intervention for subjects with tinnitus.

Keywords Tinnitus, CAPD, Temporal processing, Speech perception, Memory

Background

Tinnitus is the perceived sensation of sound in the absence of a corresponding external acoustic stimulus [1]. Tinnitus sensations are usually acoustic, such as a buzzing, hissing, or ringing sound [2]. Tinnitus can be unilateral or bilateral, sometimes described as emerging within the head. The perceived sensation can be intermittent or have a pulsatile character. In the "neurophysiological model" of tinnitus [3], tinnitus results from the abnormal processing of a signal generated in the auditory system. This abnormal processing occurs before the signal is perceived centrally. This may result in "feedback," whereby the annoyance created by the tinnitus causes the individual to focus increasingly on the noise, exacerbating the annoyance, and so a "vicious cycle" develops.

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Main text

Studies have shown that tinnitus can impair various central auditory processing abilities [4–15]. Central auditory processing is complex and difficult to comprehend in detail. Central auditory processing disorder [(C)APD] is the name given to difficulties in the perceptual processing of auditory information in the central nervous system [16]. (C)APD covers a range of disorders that affect auditory analysis, although, typically, patients have normal auditory threshold sensitivity but difficulty identifying speech in background noise [17]. The deficits can be measured in terms of sound source localization, level discrimination; temporal patterning; temporal aspects (such as temporal integration, temporal discrimination, such as gap detection, temporal ordering/sequencing of rapid events, and temporal masking); and skill in word recognition in the presence of competing acoustic signals (such as dichotic listening) or understanding degraded speech [16]. A detailed assessment of the various processes that may be affected in individuals with (C)APD requires a comprehensive case history along with an appropriate test battery.

The auditory processing is affected by both auditory factor and cognitive factors [18]. Tinnitus is an auditory factor that can affect auditory processing [19]. Studies have shown that tinnitus affects speech perception in noise (SPIN) [6–8, 10, 14], temporal processing [5, 8, 9, 11, 20, 21], localization [22], working memory [5, 8, 9, 11, 20, 21], and even in those with normal hearing. A higher level of central auditory processing is needed for SPIN, temporal processing, auditory discrimination, etc. [4]. Speech comprehension difficulties are among the most common causes of tinnitus-related handicaps in many patients [23].

The cerebral imagery techniques have indicated abnormal activation in cortical structures, abnormal cortical excitation, and evidence for functional reorganization in tinnitus patients with normal hearing sensitivity [24]. This might affect central auditory processing abilities. However, the outcome of the studies is mixed, wherein few studies have shown a negative impact of tinnitus on auditory processing [7, 20, 21, 23], and few studies have shown no impact of tinnitus on auditory processing [15, 25, 26]. Therefore, there is a need to systematically review the studies on tinnitus's effect on central auditory processing, which can help the clinician to modify assessment protocol in tinnitus individuals. Thus, the present study aimed to review the studies on tinnitus's potential impact and interference on central auditory processing skills.

Methods

The study followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [27].

Eligibility criteria

The literature search was done for articles published after 2002. Experimental studies were chosen for systematic review, and the systematic reviews were excluded. The population of interest was individuals with tinnitus with normal hearing sensitivity. Articles that included populations with tinnitus existing with other audiological complaints were excluded. The experimental group should have at least 10 participants, with or without the control group. Articles published in any other language other than English language were not included in the review process.

Search strategy

The electronic databases, PubMed, Google Scholar, and the institutional repository of All India Institute of Speech and Hearing, were searched. The keyword used was as follows: 'tinnitus,' 'ringing in the ear,' 'buzzing in the ear,' 'humming in the ear,' 'auditory processing,' 'CAPD,' 'speech perception in noise, 'SPIN,' 'binaural interaction,' 'binaural integration,' 'dichotic listening,' 'temporal processing,' and 'auditory closure.' The keywords were combined with the Boolean search operators to search.

Study selection

After the database search, a three-step process was used to review all studies according to the eligibility criteria: title screening, reading the abstract, and reading the full text. The full text was retrieved for all potentially relevant records meeting the inclusion criteria or for insufficient information in the title and abstract to make a firm decision. Two review authors performed each key step independently for every record. A third author reviewed any discrepancies at each step, and a decision was made after discussion.

Quality assessment

Quality assessment of the included studies was done using the National Institute of Health Quality Assessment Tool for Case–Control Studies for Observational Cohort and Cross-Sectional Studies [28]. Each study was rated to assess the risk of bias. Each study was classified as good, fair, or poor based on the assessment score. Studies with good and fair scores were only included in the review process.

Results

The process of search is represented in Fig. 1. A total of 3087 articles were obtained from the database search. The articles were exported to the Rayyan software [32] to identify and remove the duplicated articles, and 396 duplicates were removed. Title and abstract screening were carried out, and the full texts were screened to select the articles based on eligibility. After the screening process, 18 articles were included in the systematic review. The included studies are cross-sectional studies, prospective controlled studies, and prospective non-randomized clinical studies.

Furthermore, nine out of the eighteen selected studies provided tinnitus pitch and loudness match results on the individuals with tinnitus. Nine studies included participants with both unilateral and bilateral tinnitus, while the remaining had either bilateral or unilateral tinnitus group. All studies except Sanches et al. [4] included

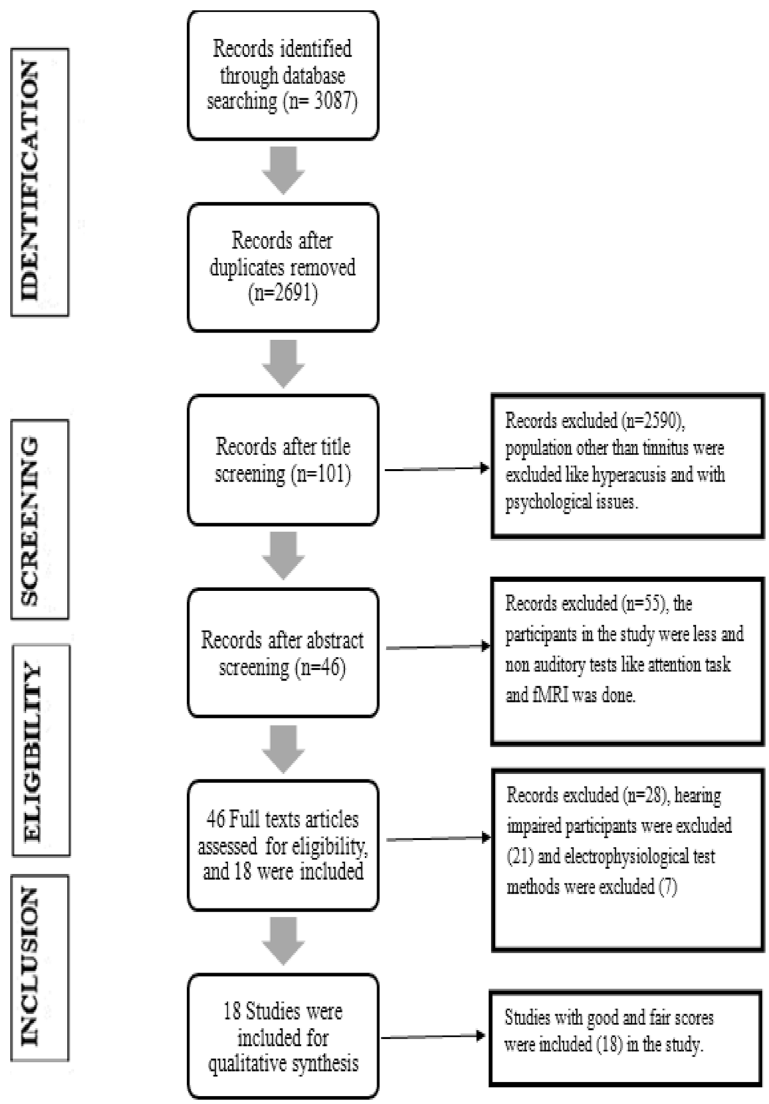

Fig. 1 PRISMA flowchart for the selection process of articles in the review

information on tinnitus duration. The duration of tinnitus among the selected studies ranged from 3 months to 4 years. Ten studies assessed tinnitus severity using the Tinnitus Handicap Inventory (THI). Of the eighteen studies selected, none of the studies had information regarding the previous or ongoing treatment for tinnitus. Table 1 shows the tinnitus characteristics of the patients included in the various studies.

Studies on assessing temporal perception in individuals with tinnitus have used gap in noise (GIN), gap startle paradigm, gap detection test (GDT), temporal modulation transfer function (TMTF), amplitude modulation depth discrimination (AMDD), and amplitude modulation rate discrimination (AMRD). Four studies carried out the GIN test to assess the temporal resolution, and all the studies showed that the tinnitus group required longer gaps than the control group to identify [4, 5, 9, 21]. Similarly, two studies reported differences between the experimental and control group using the GDT [8, 11]. Fournier and Hébert [20] used the gap startle paradigm to assess temporal resolution. Results showed that participants with tinnitus displayed a stronger startle response than controls without tinnitus, as the tinnitus participants could not perceive the gap embedded in the stimulus. Similarly, Mohanapriya [31] reported poor depth discrimination abilities of the tinnitus group in the presence of noise, while the without noise condition did not show any significant difference between the groups. In contrast, Moon et al. [10] reported no significant difference in spectral ripple discrimination (SRD), temporal

Table 1 Tinnitus characteristics of the patients included in the various studies

Sl no	Author	Pitch match	Loudness match	Laterality of tinnitus	Duration of tinnitus	Severity	The scale used to measure tinnitus severity
1	Rossiter and Walker [13]	NM	NM	B/L: 14 U/L: 5	> 3 months	Mild	THI
2	Huang et al. [7]	NM	5.25 on 9-point scale	B/L: 15 U/L: 5	> 2 months	Chronic	THI, TLS
3	Sanches et al. [4]	NM	NM	B/L	NM	NM	NM
4	Gabriela, Sanches, and Ganz [21]	High frequency	NM	B/L	> 1 year	NM	NM
5	An et al. [22]	250 to 8 kHz	20 to 60 dB SPL	B/L: 14 U/L: 25	> 12 months	NM	NM
6	Ryu et al. [14]	250 Hz to 8 kHz	8.3 (*SD* = 6.8) dB SPL	U/L	> 12 months	30.2 plus or minus 16.9 of 100	THI
7	Gilani et al. [5]	NM	NM	U/L	> 12 months	NM	NM
8	Fournier and Hébert [20]	Ranged from 250 Hz to 16 kHz Maximum at 16 kHz	Ranged from 25 to 55 dB SPL	B/L	> 6 months	NM	NM
9	Jain and Sahoo [8]	NM	NM	B/L	> 3 months	Mild to moderate	THI
10	Shakarami et al. [29]	2 klHz to 8 kHz	Slight to severely loud	B/L: 10 U/L: 6	6 to 36 months	Mild to severe	THI
11	Moon et al. [10]	NM	NM	B/L: 9 U/L: 9	> 6 months	NM	NM
12	Gilles et al. [6]	NM	NM	U/L:19	> 3 months	NM	NM
13	Jain and Dwarkanath [9]	NM	NM	B/L: 16 U/L: 22	> 6 months	Mild to severe	THI
14	Tai & Husain [15]	Wide frequency range	48.36 (25.71)/100	B/L: 14	> 3 years	Chronic tinnitus	THI
15	Ravirose, Thanikaiarasu, and Prabhu [12]	250 Hz to 8 kHz	20 to 40 dB HL	B/L:15	62–4 months	NM	NM
16	Kondli, Amruthavarshini, and Prashanth [30]	NM	NM	B/L:9 U/L: 6	6–24 months	Mild to severe	THI
17	Mohanapriya [31]	250 Hz to 8 kHz	20 to 40 dB HL	B/L or U/L: 20	> 3 months	Mild to severe	THI
18	Raj et al. [11]	0.125 to 12.5 kHz	2 to 65 dB	B/L: 70%, U/L: 30%	3.8 (*SD* = 2.5) years	Chronic	THI

NM not mentioned, *THI* Tinnitus Handicap Inventory, *TLS* tinnitus loudness scale. *B/L* bilateral, *U/L* unilateral

modulation detection (TMD), and Schroeder-phase discrimination (SPD) tests among individuals in the tinnitus and no tinnitus groups. For the rate discrimination experiment, the control group performed better than the experimental group in with and without noise conditions at 10- and 100-Hz modulation rates, whereas at 40-Hz modulation rate, there was no significant difference between the groups in the without noise condition [33]. Furthermore, no significant difference was seen between the control and the tinnitus group for temporal sequencing task [5, 9, 11].

Speech perception abilities in tinnitus individuals were assessed using Mandarin speech in noise (MSPIN), Korean version of hearing in noise test (K-HINT), reception threshold for speech (RTS), QuickSIN, speech recognition threshold (SRT), and speech in noise testing Leuven Intelligibility Sentence Test (LIST). In a study where SPIN was assessed using MSPIN, it was noted that the control group had significantly higher scores than the experimental group in high and low predictability list scores [7]. Ryu et al. [14] assessed speech perception using K-HINT, RTS (quiet) and signal-to-noise ratio (SNR) RTS in a quiet environment, and SNR in various noise conditions. Results showed that the scores were significantly poorer in the tinnitus group than in the control group, regardless of whether the noise came from the front, right, or left. QuickSIN results revealed that tinnitus participants had significantly poorer speech-in-noise performance (5 dB SNR) in the left ear than in the right ear, and at 10–25 dB SNR conditions, there was no significant between-group difference [8, 15]. Speech-in-noise testing using LIST was done by Gilles et al. [6], where the tinnitus subjects had significantly worse SRT scores compared to non-tinnitus subjects for sentences embedded in steady-state noise and for sentences embedded in 15-Hz AM noise. Similar results were reported by Moon et al. [10], where the tinnitus-affected ears (TEs) showed poorer SRTs than the non-tinnitus ears (NTEs). Overall, all the studies showed that the tinnitus group either required high SNR or the speech perception was affected compared to the control group.

In this review, three studies tested auditory memory using the reading span test, digit forward span, digit backward span, ascending span test, and descending span test. Kondli, Amruthavarshini, and Prashanth [30] reported that individuals with tinnitus had poor backward span, ascending span, and descending span tasks but not the forward digit span. Furthermore, the reading span test revealed that the reading span of the tinnitus group was significantly shorter than that of the control group [13]. Scores on dichotic auditory verbal memory test (DAVMT), and randomized dichotic digit test (RDDT), showed no significant differences between the tinnitus and control group [29].

Ravirose, Thanikaiarasu, and Prabhu [12] assessed discrimination abilities through duration discrimination test (DDT), difference limen for intensity (DLI), and difference limen for frequency (DLF). Results showed a significant increase in DDT, DLI, and DLF thresholds at the tinnitus frequency compared to half an octave above and below the matched frequency in individuals with tinnitus.

An et al. [22] studied localization through sound localization test (SLT) at 30-degree resolution for a total of 180° on the horizontal plane in front of the listener at a distance of 1 m. The results showed that the mean total error score (TES) was significantly greater in the tinnitus group than in the control group. Regarding stimulus frequency, no significant difference was seen for the tinnitus group. In the control group, mean TES values were significantly higher for 4 and 8 kHz than for 0.25 and 1 kHz. There was no significant difference in the scores between the right tinnitus group, the left tinnitus group, and the bilateral tinnitus group. Also, TES was higher for stimulus presented from the side of the tinnitus than the opposite side. There was no correlation between tinnitus pitch and TES and between tinnitus loudness and TES. A summary table of the selected articles is given in Table 2.

Discussion

The present review aims to study tinnitus' effect on central auditory processing abilities. Eighteen articles were shortlisted after extensive review. The majority of the articles showed that individuals with tinnitus had affected central auditory processing, which was seen in terms of poor temporal processing [4, 5, 8, 9, 11, 20], poor auditory memory [13, 30], and reduced SPIN [7, 8, 10, 14]. The anatomical and physiological defects in the central auditory nervous system's neural structures result in tinnitus perception and impair central auditory processing abilities.

Studies reported that temporal resolution was affected in individuals with tinnitus, assessed using the GIN test and TMTF [4, 5, 8, 9, 11, 20]. Boyen et al. [34] postulated that the reason for poor gap detection could be that ongoing tinnitus masks the gap, resulting in impaired gap detection and modulation function. Also, physiologically, detecting silence gaps in noise requires precise processing of the temporal structure of the sound stimulus [33]. The difference in the GIN test performance between patients with and without tinnitus shows dysfunction in the central auditory system in patients with tinnitus [35].

It has also been reported that there is hyperactivity in cortical and thalamic structures in tinnitus patients [36]. This can lead to neural changes at the higher auditory structures, reorganizing the tonotopic map. These neural changes are thought to alter the temporal processing abilities of individuals with tinnitus. Good performance in auditory temporal resolution requires precise neuronal firing, which can be impaired in individuals with tinnitus [5, 9]. However, studies on temporal sequencing using duration pattern test (DPT) and frequency pattern test (FPT) found no difference between the clinical and control groups [9]. This could be attributed to the insensitivity of the tests used to assess temporal ordering (sequencing) to the abnormalities of structures below the auditory cortex [1].

Studies also report tinnitus interferes with SPIN [7, 8, 10, 14]. Studies have shown that tinnitus patients had aberrant links between the limbic and auditory systems, suggesting that tinnitus might originate in the central auditory system rather than the cochlea. Changes in cortical plasticity might account for tinnitus and associated symptoms which affect speech perception [24, 37]. Studies have also reported that tinnitus may affect the central auditory system as "a central masker" that interrupts speech perception [10].

The present systematic review also showed that auditory memory was affected in individuals with tinnitus [13, 30]. Attention resources may be disrupted or depleted due to negative thoughts due to tinnitus,

Table 2 Summary of eighteen articles on the effect of tinnitus on CAP

Author and year	Objectives of the study	Population type	Tests used	Results
Rossiter and Walker [13]	To investigate the relationship between tinnitus and cognition	Clinical group: 19 adult patients with tinnitus, with 34 to 3 years old (mean = 48.9 years, *SD* = 8.2) Control group: 19 normal hearing adults without tinnitus, with 34 to 63 years old (mean = 48.8 years, *SD* = 8.8)	Reading span test	Reading span affected in tinnitus group
Huang et al. [7]	To investigate the following: • The effect of tinnitus on speech perception	Clinical group: 20 adults (13 M and 7 F) with tinnitus, mean age — 40.75 years old (range 22–62 years) Control group: 20 healthy adults (12 M and 8 F) without tinnitus, mean age — 38.35 years old (range — 29–56 years)	MSPIN, tinnitus loudness scale, THI	• MSPIN-tinnitus group had less scores in high and low predictability list scores
Sanches et al. [4]	• To compare the results of the GIN test in normal listeners with and without tinnitus	Clinical group: 18 tinnitus patients with normal hearing (3 M, 15 F) aged between 21 and 45 years, mean age — 31.3 years Control group: 23 normal hearing participants (8 M, 15 F) aged between 21 and 45 years, mean age — 29.7 years	GIN test	GIN is affected in tinnitus group
Gabriela, Sanches, and Ganz [21]	To analyze auditory temporal resolution in tinnitus patients using GIN	Clinical group: 20 adults with tinnitus, mean age: 33.5 years Control group: 28 participants with no tinnitus Mean age: 28.8 years	GIN	GIN is affected in tinnitus group
An et al. [22]	Effect of tinnitus on localization	Clinical group: 40 adults (15 M and 25 F) with tinnitus Mean age — 36.7 years (range — 14–63 years) Control group: 40 adults (14 males and 26 females) Mean age — 39.3 years (range = 16–62 years)	SLT at 30-degree resolution for a total of 180° on the horizontal plane in front of the listener Distance 1 m	• Mean TES significantly greater in the tinnitus group than in the control group
Ryu et al. [14]	To evaluate the effects of masking noise on speech perception ability in patients with normal hearing but unilateral chronic tinnitus	Clinical group: 20 adult patients with unilateral tinnitus, with 20 to 35 years old tinnitus Control group: 20 normally hearing adults without tinnitus, with 20 to 35 years old	K-HINT RTS (quiet) SNR	Tinnitus group had reduced values than the control group

Table 2 (continued)

Author and year	Objectives of the study	Population type	Tests used	Results
Gilani et al. [5]	To assess temporal processing in individuals with tinnitus	Clinical group: 20 individuals with tinnitus Mean age: 30.31 ± 9.35 years Control group: 20 individuals without tinnitus, mean age: 27.80 ± 7.74 years	GIN, DPT	GIN is affected in tinnitus group
Fournier and Hébert [20]	To investigate the gap paradigm in high-frequency tinnitus	Clinical group: 15 adult patients, 19 to 61 years old (mean age = 28.5 years, *SD* = 6), with tinnitus Control group: 17 normally hearing adults without tinnitus; mean age = 23 years (*SD* = 3)	Gap startle paradigm	Impaired perception of gap in tinnitus group
Jain and Sahoo [8]	To investigate the effect of tinnitus on the temporal perception, frequency, and intensity discrimination and speech perception ability in noise in persons with normal hearing sensitivity	Clinical group: 20 normal hearing individuals with tinnitus Age range: 18–55 years (mean age: 38.1 years) The clinical group was further subdivided into mild tinnitus group (10 subjects; 6 M, 4 F) and moderate tinnitus group (10 subjects; 6 M,4 F) Control group: 20 normal hearing participants without tinnitus Age range: 18–55 years (mean age: 38.1 years)	GDT, MDT, DLF, DLI, Kannada QuickSIN	GDT, MDT, DLF, and Kannada QuickSIN were affected in tinnitus group, and no difference was seen in DLI
Shakarami et al. [29]	To compare the verbal auditory memory between individuals with normal hearing with and without tinnitus	Clinical group: 16 adults (6 males and 10 females) with tinnitus Mean age — 36.44 years (range — 23–53 years) Control group: 20 adults (3 males and 17 females) without tinnitus Mean age — 33.65 years (range — 21–49 years)	DAVMT, RDDT	• No significant differences seen

Table 2 (continued)

Author and year	Objectives of the study	Population type	Tests used	Results
Moon et al. [10]	To investigate the pathophysiology of tinnitus using psychoacoustic assessments of auditory spectral and temporal resolution and speech perception in noise	Clinical group: 9 unilateral tinnitus subjects with normal hearing thresholds (group 1 mean age — 28.22 + − 9.22 years), 12 unilateral tinnitus subjects with hearing loss (group 2 mean age — 56.08 + − 12.92 years), 9 bilateral tinnitus subjects with symmetrical hearing loss (group 3 mean age — 60.67 + − 10.98 years) Control group: 15 normally hearing adults without tinnitus, with less than 30 years old (mean age − 44.93 + − 9 years)	SRD, TMD SPD, and SRT	• No significant differences in SRD, TMD, and SPD • The TEs showed poorer SRTs than the NTEs
Gilles et al. [6]	To assess differences in audiological characteristics between noise-exposed adolescents with and without NIT	Clinical group: 19 adult patients with unilateral tinnitus, participants age was less than 30 years old Control group: 68 normally hearing adults without tinnitus, with less than 30 years old	Speech-in-noise testing list	Scores were affected in tinnitus group
Jain and Dwarkanath [9]	To assess psychoacoustic abilities in individuals with tinnitus	Control group: 38 participants (19 M & 19 F) Mean age — 33.7 years UTG — 22 participants (9 M and 13 F) Mean age — 34.7 years BTG — 16 participants (8 M and 8 F) Mean age — 38.3 years All participants were in the age range of 24–50 years	GIN, TMTF, DDT, backward masking, DPT	DPT — no difference was observed GIN, TMTF, DDT, and backward masking affected in tinnitus
Tai & Husain [15]	To investigate how tinnitus interferes with speech recognition ability in noise, and to examine the impact of tinnitus (severity or loudness) on speech recognition	Clinical group: 14 adults with chronic bilateral tinnitus, mean age — 43.86 years Control group: 14 adults with no history of tinnitus, mean age — 44 years	QuickSIN	Tinnitus group required more SNR than the control group • At 10–25-dB SNR conditions, there was no significant between-group difference • No significant correlation
Ravirose, Thanikaiarasu, and Prabhu [12]	To determine the DDT, DLI, and DLF thresholds in patients with tinnitus	Fifteen participants with tinnitus in the age range of 18 to 40 years (mean age = 29.47 and *SD* = 7.20) with their hearing thresholds at normal limits	DDT, DLI, and DLF	DDT, DLI, and DLF are affected in tinnitus

Table 2 (continued)

Author and year	Objectives of the study	Population type	Tests used	Results
Kondli, Amruthavarshini, and Prashanth [30]	• To evaluate the performance of auditory working memory tasks in adults with tinnitus	Clinical group: 15 individuals with tinnitus Mean age: 32.7 years (*SD* = 6.25) Control group: 15 individuals without tinnitus Mean age: 33.4 years (*SD* = 9.7)	Digit forward span, backward span, ascending span, and descending span tasks	• Poor backward span, ascending span, and descending span tasks but not the forward digit span
Mohanapriya [31]	To evaluate the amplitude modulation discrimination function in terms of depth and rate discrimination in individuals with normal hearing sensitivity having tinnitus	Clinical group: 20 individuals with normal hearing sensitivity with tinnitus Age rage — 18–45 years Control group: 20 individuals with normal hearing sensitivity without tinnitus	PTA, immittance audiometry, tinnitus evaluation, AMDD, AMRD	Depth discrimination was comparable, but the rate discrimination was affected in tinnitus group
Raj et al. [11]	To compare the auditory processing abilities of two groups: those with normal hearing and tinnitus and a similar group who did not have tinnitus	Clinical group: 54 adult patients, 19 to 61 years old (mean age 37.1 years, *SD* = 10.7) Tinnitus for 3.8 (*SD* = 2.5) years Control group: 43 normally hearing adults without tinnitus. The mean age was 35.5 years (*SD* = 11.1)	FPT, DPT, GDT, and DLT	GDT and DLT were affected in tinnitus group, and no difference was seen in FPT and DPT. And right ear advantage was absent

GIN Gap in noise, *PTA* Pure-tone audiometry, *M* Males, *F* Females, *GDT* Gap detection test, *MDT* Modulation detection test, *DLF* Difference limen for frequency, *DLI* Difference limen for intensity, *SPIN* Speech perception in noise, *THI* Tinnitus Handicap Inventory, *SD* Standard deviation, *DPT* Duration pattern test, *MSPIN* Mandarin speech in noise, *TLS* Tinnitus loudness scale, *UTG* Unilateral tinnitus group, *BTG* Bilateral tinnitus group, *TMTF* Temporal modulation transfer function, *DDT* Duration discrimination test, *FPT* Frequency pattern test, *DLT* Dichotic listening test, *REA* Right ear advantage, *DPOAE* Distortion product otoacoustic emissions, *DAVMT* Dichotic auditory verbal memory test, *RDDT* Randomized dichotic digit test, *SLT* Sound localization test, *TES* Total error score, *ES* Error score, *K-HINT* Korean version of hearing in noise test, *RTS* Reception threshold for speech, *SNR* Signal-to-noise ratio, *SRD* Spectral ripple discrimination test, *TMD* Temporal modulation detection test, *SPD* Schroeder-phase discrimination test, *SRT* Speech recognition threshold, *TE* Tinnitus-affected ears, *NTE* Non-tinnitus ears, *NIT* Noise-induced tinnitus, *LIST* Leuven intelligibility sentence test, *AMRD* Amplitude modulation rate discrimination, *AMDD* Amplitude modulation depth discrimination continual orienting to tinnitus [13], and increased self-focused and somatic attention [38], which can cause poor auditory memory. Individuals with tinnitus, for whom annoyance is generally linked with tinnitus, have been shown to perform poorly compared to others for whom tinnitus is not annoying. Hence, the attention toward the auditory stimulus would be reduced [39]. Few studies reported no difference between the mild tinnitus and the control groups in individuals with normal hearing in the divided auditory attention and verbal auditory memory [29]. This indicates that the severity of tinnitus has a differential effect on auditory memory.

Studies on the effect of tinnitus on dichotic listening are sparse [11]. These studies have shown no difference in dichotic listening among tinnitus and no tinnitus groups. However, Cuny et al. [40] reported that tinnitus modifies the normal left-hemisphere specialization in the dichotic listening test. The reason could be that tinnitus modifies the organization of cerebral function. Tinnitus has also been shown to interfere with sound localization ability [22]. The interference is worse when the sound originates from the same side as the tinnitus because the tinnitus reduces interaural level difference [22].

Furthermore, it was noted that THI was used predominantly to measure tinnitus severity across studies. In addition, most studies have not reported tinnitus characteristics such as pitch and loudness ($n = 9$). It is felt that standardization of assessment protocols and reporting of results could overcome these problems. The details of the tinnitus rehabilitation are missing, as these would have affected the auditory processing test results; hence, a detailed pre- and post-assessment report are needed. The sample size of the individual studies included in the review ranged from 9 to 40 participants per group.

Furthermore, most of the studies did not perform a power analysis. With a low sample size, the generalizability of the individual study results to the tinnitus population becomes debatable. Hence, the results of this review could stand as preliminary evidence for an auditory processing deficit in individuals with tinnitus. Thus, the present systematic review concludes that temporal resolution, speech perception in noise, and working memory are the most affected skills in individuals with tinnitus and normal hearing.

Conclusion

Central auditory processing is affected in individuals with tinnitus in terms of difficulty in understanding speech in noise, temporal processing, localization, and auditory memory. The assessment of central auditory processing abilities should be routinely included for individuals with tinnitus. Further studies are needed with large sample size and various degrees of tinnitus severity to assess various central auditory processing abilities.

Abbreviations

(C)APD	Central auditory processing disorder
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
GIN	Gap in noise
PTA	Pure-tone audiometry
M	Males
F	Females
GDT	Gap detection test
MDT	Modulation detection test
DLF	Difference limen for frequency
DLI	Difference limen for intensity
SPIN	Speech perception in noise
THI	Tinnitus Handicap Inventory
SD	Standard deviation
DPT	Duration pattern test
MSPIN	Mandarin speech in noise
TLS	Tinnitus loudness scale
UTG	Unilateral tinnitus group
BTG	Bilateral tinnitus group
TMTF	Temporal modulation transfer function
DDT	Duration discrimination test
FPT	Frequency pattern test
DLT	Dichotic listening test
REA	Right ear advantage
DPOAE	Distortion product otoacoustic emissions
DAVMT	Dichotic auditory verbal memory test
RDDT	Randomized dichotic digit test
SLT	Sound localization test
TES	Total error score
ES	Error score
K-HINT	Korean version of hearing in noise test
RTS	Reception threshold for speech
SNR	Signal-to-noise ratio
SRD	Spectral ripple discrimination test
TMD	Temporal modulation detection test
SPD	Schroeder-phase discrimination test
SRT	Speech recognition threshold
TE	Tinnitus-affected ears
NTE	Non-tinnitus ears
NIT	Noise-induced tinnitus
LIST	Leuven intelligibility sentence test
AMRD	Amplitude modulation rate discrimination
AMDD	Amplitude modulation depth discrimination

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Authors' contributions
SS was involved in concept development, study selection, analysis of the results, interpretation, and writing the manuscript; VV was involved in concept development, study selection, analysis of the results, interpretation, and writing the manuscript; CJ was involved in concept development, study selection, analysis of the results, interpretation, and writing the manuscript; and all authors read and approved the final manuscript.

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Consent for publication
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The authors declare that they have no competing interests.

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