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Temporal processing abilities in normal hearing individuals with tinnitus: a systematic review

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Purpose: Tinnitus, characterized by the perception of auditory phantoms, is prevalent worldwide and can lead to a range of hearing-related issues. Understanding its influence on temporal processing helps to delineate the auditory manifestations of tinnitus. This systematic review aimed to identify the patterns of temporal processing difficulties in individuals with tinnitus and normal hearing abilities. Furthermore, this review evaluates the potential of specific measurement techniques as tools for diagnosing temporal processing deficits in tinnitus.

Methods: A comprehensive search was conducted in multiple international databases, followed by rigorous screening of the titles, abstracts, and full-length content. The inclusion and exclusion criteria were formulated using the Population, intervention, compression, Outcome, and Study design (PICOS) format, and the study bias was determined. After excluding irrelevant articles, nine studies were selected for the analysis.

Results: Over 50% of the selected studies demonstrated a significant impact on temporal processing in individuals with tinnitus, especially with gap detection test (GDT) and gaps in noise (GIN) tests, indicating of the deficits in peripheral temporal process in tinnitus individuals with normal hearing. However, the other central auditory tests showed no major changes.

Conclusions: The findings from this review underscore the importance of understanding temporal processing impairments in tinnitus and hold promise for enhancing the diagnostic accuracy and treatment outcomes, ultimately improving the lives of those affected by tinnitus. This review highlights the potential of the GDT and GIN tests as sensitive tools for assessing temporal processing deficits in the peripheral auditory system, which in turn can manifest as central changes in temporal processing.

Systematic review registration: http://www.crd.york.ac.uk/PROSPERO/display_record.asp?ID=CRD42021287194, Prospero [CRD42021287194].

KEYWORDS

tinnitus, temporal processing, hearing, systematic review, gap detection

Introduction

Tinnitus, also known as auditory phantom perception in the absence of external sound, is a well-known multifaceted condition (De Ridder et al., 2021), that is known to affect several auditory processes (Eggerrmont, 2015; Kohansal et al., 2021). It affects 12–30% of the adult population worldwide (Shargorodsky et al., 2010), and can be categorized based on etiologies, clinical characteristics, and therapeutic responsiveness (Langguth et al., 2013).

Common descriptors of tinnitus include ringing, buzzing, and hissing noises (Choi, 2012; Langguth et al., 2013). Tinnitus not only reflects a dysfunction in the auditory system but can impact one's quality of life, albeit it varies significantly from person to person (McCormack et al., 2016). Auditory dysfunction in tinnitus stems from deficits in the inner ear (peripheral) or brain (central) (Gerken, 1996; Eggermont and Roberts, 2004). Therefore, different auditory processing abilities related to the inner ear and central processing, including auditory temporal processing, may be affected. Temporal processing refers to the representation of time-related aspects of an acoustic signal. Precise temporal processing plays a vital role in the auditory function (Chermak and Musiek, 1997). It is essential for various auditory functions including auditory discrimination, binaural interaction, pattern recognition, localization/lateralization, monaural low-redundancy speech recognition, and binaural integration (Schow et al., 2000). In addition, temporal processing plays a crucial role in distinguishing phonemic, lexical, and prosodic elements as well as in tasks related to auditory closure and comprehension of speech in noisy environments (Reed et al., 2009). Four fundamental categories of temporal processing are involved in auditory signal perception, all of which play crucial roles in auditory processing. These categories include temporal ordering or sequencing, temporal resolution or discrimination, temporal integration or summation and temporal masking. The temporal resolution tests used in the selected studies (Sanches et al., 2010; Gilani et al., 2013; An et al., 2014; Jain and Sahoo, 2014; Moon et al., 2015; Jain and Dwarkanath, 2016; Ibraheem and Hassaan, 2017; Zeng et al., 2020; Raj-Koziak et al., 2022) are the gap detection threshold (GDT), gaps in noise (GIN), and temporal modulation detection (TMD) tests. GDT and GIN are primarily considered peripheral auditory tests that evaluate the ability to detect gaps in sound stimuli. It provides insights into the temporal resolution at the auditory peripheral level, including the cochlea and auditory nerve. GDT and GIN evaluate central deficits and their test scores are found to be correlated to neurological deficits in central auditory pathway (Filippini et al., 2020). Although these tests primarily address cortical dysfunction, impairments in the peripheral auditory system can affect the transmission of sound information to the central auditory pathway, potentially affecting the temporal processing abilities at the central level (Eggermont, 2015). The TMD and modulation function test (MFT) results were primarily related to central auditory processing. While peripheral auditory processing may play a role in detecting and encoding temporal modulations, the interpretation and analysis of these modulations occur in the central auditory pathways, including the brainstem and higher-level auditory structures. Therefore, these tests primarily target the ability of the central auditory system to process and interpret temporal modulations of sound stimuli. In addition, temporal ordering tests, such as the frequency pattern test (FPT) and the duration pattern test (DPT), also assess the functioning of the central auditory system. These tests were designed to assess an individual's ability to accurately perceive and order stimulus patterns based on their frequency or duration. Temporal processing deficits may serve as biomarkers of tinnitus.

By systematically reviewing the existing literature, we aimed to determine whether there are consistent patterns of temporal processing impairment in normal hearing individuals with tinnitus. This can help to identify specific temporal processing measure that can be used as an objective indicators or diagnostic tools for tinnitus evaluation. The current systematic review focuses on five temporal processing abilities, which include GDT, GIN, TMD/TMTF, DPT, and FPT. The GDT involves detection of gap embedded in noise segment or tonal segment (Fitzgibbons, 1983). The test contains three intervals out of which one contains a gap of a certain length, which is to be recognized by the listener. The other variant of GDT test i.e., GIN test consists of 0–3 silent intervals ranging from 2 to 20 ms embedded in 6-s segments of white presented continuously (Musiek et al., 2005). The location, number, and duration of the gaps-per-noise segment vary throughout the test for a total of 60 gaps presented in each of four lists. The participant is instructed to press the response button as soon as they hear the gap in the stimuli. The other temporal resolution tests discussed in the review is TMD/TMTF. These tests involve discriminability of the rate of amplitude modulation. Participants are asked to perform a same or different discrimination between two frequencies (f, f + Δf) of sinusoidally amplitude-modulated wide-band noise (Viemeister, 1979). The temporal ordering tests of DPT and PPT involves presentation of a series of sounds that must be identified in the order they were heard. In DPS, 1,000 Hz tones of varying duration (500 ms- long and 250 ms short) duration are intermixed and presented in a particular sequence. The participant labels the order in which these tones were presented. The experimental paradigm followed for PPT is similar, except that the tones vary in terms of pitch (low, high) (Balen et al., 2019).

The present systematic review discusses temporal processing in individuals with tinnitus and normal hearing, to understand the consistency and limitations of findings across studies on the utility of temporal tests as biomarkers in tinnitus sufferers. By addressing the gaps in the literature, we not only seek to deepen the understanding of temporal processing impairments in the tinnitus population, but also use this information to guide the development of targeted interventions or modify existing rehabilitation strategies that can alleviate the consequences of temporal processing deficits.

Methods

The Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) was used to report the methods (Page et al., 2021). The protocol for review was registered in Prospero, with the reference number CRD42021287194 (24/11/2021). Electronic searches of PubMed, Google Scholar, web of science and Scopus were performed to select the articles for this review. The keywords used were, "tinnitus," "psychoacoustic," "temporal processing" "temporal resolution," and "temporal ordering." The terms were then matched to generate a more specific search. Boolean Operators such as AND, OR, NOT or AND NOT were used appropriately to gather more precise search results. The exact keywords and the Boolean operators used to perform the search in the electronic databases is given in Supplementary Table 1. Only studies published between 2006 and 2021 were included. The studies reported in systematic review confined only 2006 to 2021, i.e., a span of 15 years to ensure only recent publications on temporal processing are included. This step was necessary due to the rapid advancements and understanding of both Tinnitus and psychoacoustics (including temporal processing) in the last decade and a half. Restricting the review to this timeframe allowed us to capture studies that would have used recent advancements; thus their findings stay relevant to the context of the study.

Inclusion and exclusion criteria

The current review included studies that were published between 2006 and 2021 and met the following inclusion criteria as determined by the Population, Intervention, Comparison, Outcome, and Study Design (PICOS) framework.

Population

Individuals with normal hearing sensitivity and Tinnitus. The hearing sensitivity is determined based on based on four frequency averages of 0.5, 1, 2, and 4 kHz. The studies which were included in the in study had participants aged between 18 and 63 years, and can be Tinnitus suffers from min of 1–12 years with a mean duration of 19.4 months. Studies with tinnitus participants who were younger than 18 years, older than 63 years, and studies with participants having tinnitus comorbid with any disorders of cochlear pathology and retrocochlear pathology were excluded. Studies that included individuals with hearing loss or cognitive impairment were also excluded. Studies in which participants had hyperacusis were excluded.

Intervention

In the intervention studies, only pre- treatment values for temporal tests were considered. The impact of the tinnitus treatment on the temporal processing was not under the scope of the study.

Comparison

The comparison of interest was the group of participants without Tinnitus.

Outcome

Scores on temporal tests (including GDT, GIN, TMD, TMTF, DPT, PPT). Electrophysiological tests of temporal and speech processing were not considered in this study.

Study designs

The main requirement for article inclusion was the presentation of original research articles that highlighted the association between temporal processing and tinnitus. Regardless of study designs, all peer-reviewed studies published in English were included in the current review. However, resources such as books, reviews, conference papers, newspaper articles, and non-peer-reviewed studies were excluded. The search only included studies published in English. Translated articles and those with other psychoacoustic tests that did not assess temporal processing were excluded. Case-control studies were not included because they were atypical for the sampled population. Systematic reviews were also excluded from the study.

The search yielded 2,671 articles (1,100 excluding duplicates). The reference lists of review papers found during the search were also searched to obtain more related articles. After the search was concluded, all records were inspected in three steps to ensure that they met the eligibility criteria: title, abstract, and full text. Full text was collected for all potentially relevant records that appeared to fit the inclusion criteria or for which there was insufficient information in the title and abstract to conclude. Two review authors independently performed the critical steps for each record. Rayyan, a free web tool, was used for this process (Ouzzani et al., 2016). The first two authors (KVN, MP) reviewed the articles and commented as "included," "excluded" or "maybe" through Rayyan with the option of "blind on." A third author (PP) assessed any differences at each phase, and a decision was reached following discussion, especially for the articles kept as "maybe." All the studies that met the inclusion criteria were included in the analysis. In the case of duplicates (repeated publications from the same study), only one copy of the article was retained.

A quality assessment of the selected articles was performed and a table was created, including selection, comparability, and outcome with subjective ratings. A data extraction table was developed, in which items such as population type, temporal processing tests, testing parameters, outcomes, and discussions were tabulated separately for studies based on temporal resolution tests (GDT and GIN) and those based on temporal ordering and temporal modulation detection.

Results

Experimental questions

This systematic review included several studies that investigated temporal processing in patients with normal hearing, aiming to determine whether tinnitus could result in temporal processing impairments despite the absence of hearing loss. Of the nine studies identified in this systematic review, one recurring research question focused on exploring the impact of tinnitus on temporal resolution in individuals with sensitivity to normal hearing. By recognizing the potential influence of tinnitus on temporal processing abilities, researchers and clinicians can gain further insights into the underlying mechanisms and implications of tinnitus-related auditory difficulties. Addressing this experimental question—"Does the presence of tinnitus affect temporal resolution in individuals with normal hearing sensitivity?"—can help guide the development of targeted interventions and treatments to ameliorate temporal processing impairments and enhance the overall auditory wellbeing of patients with tinnitus and normal hearing.

A systematic keyword search yielded a total of 2,671 studies from PubMed (699), google scholar (12), web of Science (887), Scopus (1,073). No additional studies were obtained after reviewing the reference lists of included studies. After removing duplicates,

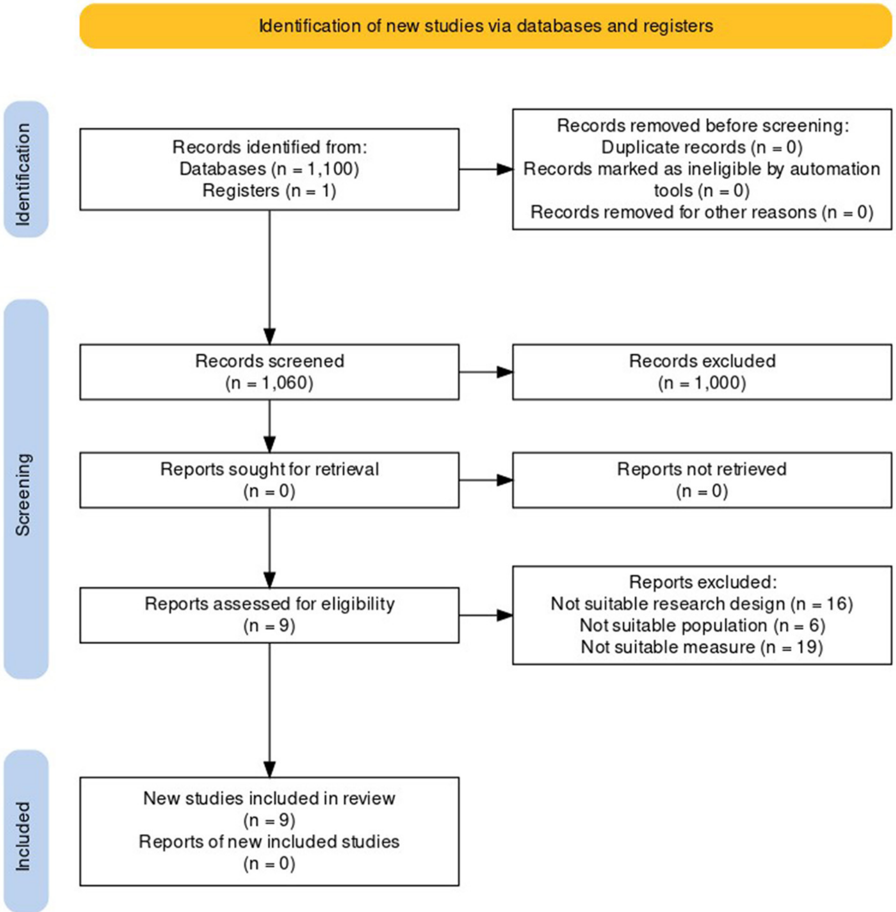

FIGURE 1
PRISMA flowchart of the selection process of articles that were included in the review.

and after the screening of title and abstracts, 1,571 studies were excluded and 1,100 were included. Further 41 studies were removed following the full-length review. Of the 41 studies removed in the full-length review, 16 were rejected due to unsuitable research design, six were removed due to unsuitable population and 19 due to unsuitable measure. At the end of this process, nine studies were included for systematic review. This detailed process is depicted in the PRISMA chart shown in Figure 1.

Participant characteristics

This review included nine studies encompassing a range of participant characteristics, shedding light on the diverse nature of tinnitus and its association with temporal processing. The target population in the selected studies included individuals with normal hearing and tinnitus, aged 18–63 years. Most participants were adults, and both males and females were included in the study. It is worth noting that studies have explicitly mentioned the degree (Jain and Sahoo, 2014; Zeng et al., 2020; Raj-Koziak et al., 2022), duration of tinnitus (Sanches et al., 2010; Gilani et al., 2013; Ibraheem and Hassaan, 2017) and laterality of tinnitus (An et al., 2014; Moon et al., 2015; Jain and Dwarkanath, 2016; Raj-Koziak et al., 2022). The target population was compared with the normal hearing group without tinnitus. The participants considered in the study followed PICOS classification, as shown in Table 1.

Quality assessment

The quality assessment scores provided for the studies were based on the Newcastle–Ottawa Quality Assessment Scale (adapted for cross-sectional studies), and are provided in Table 2. While specific criteria were not provided, the studies generally received high-quality ratings, with most receiving four stars (except Moon et al., 2015 in the selection category). The comparability category received a range of scores, with some studies receiving one star (*) and others receiving two stars (**). Regarding outcome assessment, most studies received one star (*), with a few receiving two stars (**). Overall, the quality assessment suggested that the studies included in the systematic review were generally of good quality with robust selection criteria.

TABLE 1 Data extraction according to PICOS format.

References	Population	Comparison	Outcome	Study Design
Sanches et al. (2010)	Individuals with tinnitus Sample size: 20 adults (three male and 17 female) Age: 33.8 years (range: 21–56 years) Tinnitus laterality: unilateral tinnitus-7 (3 in the left ear and 4 in the right ear) Bilateral tinnitus—13 subjects Tinnitus severity: information not available Duration of tinnitus: at least 1 year Hearing level (HL): normal hearing	Individuals without tinnitus Sample size: 28 adults (10 male and 18 female) Age: 22.8 years (range: 22–40 years) HL: normal hearing	GIN	Standard group comparison
Gilani et al. (2013)	Individuals with tinnitus Sample size: 20 adults (10 male and 10 female) Age: 30.31 ± 9.35 years (range:19–45 years) Tinnitus laterality: unilateral tinnitus- 6 (four in the left ear and two in the right ear) Bilateral tinnitus—14 subjects Tinnitus severity: information not available Duration of Tinnitus: 7 years (2–13 y) HL: normal hearing	Individuals without tinnitus Sample size: 20 adults (10 male and 10 female) Age: 27.80 ± 7.74 years (range: 18–45 years) HL: normal hearing	GIN, DPT	Standard group comparison
Ibraheem and Hassaan (2017)	Individuals with tinnitus Sample size: 15 adults Age: 34.7 ± 7.2 years (20–45 years) Tinnitus laterality: unilateral tinnitus-6 (4 in the left ear and 2 in the right ear) Bilateral tinnitus—9 Tinnitus severity: information not available Duration of tinnitus: 14.8 ± 8.1 months (6–36 months) HL: normal hearing	Individuals without tinnitus Sample size: 15 adults (30.7 ± 8.8 years) HL: normal hearing	GIN	Standard group comparison
Jain and Sahoo (2014)	Individuals with tinnitus Sample size: 20 (12 males and eight females) Age: 38.1 years (18–55) Tinnitus laterality: information not available Tinnitus severity: - Mild tinnitus (score of 18–36 on THI) 10; 6 males and 4 females - Moderate tinnitus (Score of 38–56 on THI) —10; six males and four females HL: normal hearing	Individuals without tinnitus Sample size: 20 (12 males and eight females) HL: normal hearing	GDT, TMD	Standard group comparison
An et al. (2014)	Individuals with tinnitus Sample size: 60 adults (27 males, 33 females) Age: 43.6 ± 17.6 years (22–75 years) Tinnitus laterality: 60 unilateral tinnitus (27 right, 33 left) Tinnitus severity: mean score of 29.6 ± 24.0 (based on THI)—moderate tinnitus Duration of tinnitus: 31.2 ± 43.8 months (1–36 months) HL: normal hearing	Individuals without tinnitus Sample size: 30 (11 males, 19 females) Age: 42.2 ± 13.9 years (23–68) HL: normal hearing	GIN	Standard group comparison
Zeng et al. (2020)	Individuals with tinnitus Sample size: 45 adults (18 females and 27 males) who had chronic tinnitus Age: 44 ± 15 years (20–70 years) 24 old subjects (i.e., >42 years old and 21 young subjects (i.e., >39 years old) Tinnitus laterality: unilateral tinnitus (Right- 4; left—5) Bilateral tinnitus—36 Tinnitus severity: THI scores 38 ± 22 (moderate) Duration of tinnitus: >6 months HL: normal hearing	Individuals without tinnitus Sample size: 27 (11 females and 16 males) Age: 22 ± 2 years (20–70 years)	GDT, TMD	Cross sectional
Raj-Koziak et al. (2022)	Individuals with tinnitus Sample size: 54 adults (19 males, 35 females) Age: 37.1 (19–61) who had chronic tinnitus Unilateral—16 (nine in the left ear and seven in the right ear) B/L—38 Duration of tinnitus: 3.8 years (±2.5 y) (1–12 years) HL: normal hearing Severity: 40.3 (SD = 21.2), chronic tinnitus	Individuals without tinnitus Sample size: 43 adults Age: 35.5 (±11.1) years (20–63 years)	GDT, FPT, TMD	Standard group comparison

(Continued)

TABLE 1 (Continued)

References	Population	Comparison	Outcome	Study Design
Moon et al. (2015)	Individuals with tinnitus Sample size: nine unilateral tinnitus subjects (six males and three females) Age: 28.22 ± 9.22 years Laterality: unilateral (information on ear not available) Severity: THI score of 49.00 ± 28.63 (chronic tinnitus) Duration of tinnitus: 10.22 ± 9.46 months HL: normal hearing	Individuals without tinnitus Sample size: 15 adults (six males and nine females) Age: 44.93 ± 9.00 years	TMD	Standard group comparison
Jain and Dwarkanath (2016)	Individuals with tinnitus Sample size: 38 Age: 34.23 ± 6.70 years (range: 24–50 years) Tinnitus laterality: unilateral—22 (9 males, 13 females) Bilateral—16 (eight males, eight females) Tinnitus Severity: THI score of mild tinnitus or more (total score of 18 or more on THI-Kannada) HL: Normal hearing	Individuals without tinnitus Sample size: 38 adults (19 males, 19 females) Age: 33.71 ± 5.48 years (range: 24–50 years)	TMTF, DPT	Standard group comparison

TABLE 2 Quality assessment of the selected articles using Newcastle Ottawa Quality Assessment Scale.

References	Title	Selection	Comparability	Outcome
Sanches et al. (2010)	Influence of cochlear function on auditory temporal resolution in tinnitus patients	****	*	*
Gilani et al. (2013)	Temporal processing evaluation in tinnitus patients: results on analysis of gap in noise and duration pattern test	****	*	*
Jain and Sahoo (2014)	The effect of tinnitus on some psychoacoustical abilities in individuals with normal hearing sensitivity.	****	**	*
An et al. (2014)	The effects of unilateral tinnitus on auditory temporal resolution: gaps-in-noise performance	****	**	*
Moon et al. (2015)	Influence of tinnitus on auditory spectral and temporal resolution and speech perception in tinnitus patients	***	**	*
Jain and Dwarkanath (2016)	Effect of tinnitus location on the psychoacoustic measures of hearing	****	**	*
Ibraheem and Hassaan (2017)	Psychoacoustic characteristics of tinnitus vs. temporal resolution in subjects with normal hearing sensitivity	****	*	*
Zeng et al. (2020)	Tinnitus does not interfere with auditory and speech perception	****	**	*
Raj-Koziak et al. (2022)	Auditory processing in normally hearing individuals with and without tinnitus: assessment with four psychoacoustic tests	****	*	*

Study characteristics are defined on items of the scale using "*" or "–". Higher the stars better is the quality of the article. Max stars for selection - 4; comparability -2; and outcome -3.

Temporal processing tests

Studies have focused on temporal processing tests that assess central and peripheral functions of the auditory system. The studies included in this review employed various methodologies and assessments to investigate the temporal processing abilities of individuals with normal hearing who also experienced tinnitus. These assessments typically involve temporal processing tests that tap into the temporal resolution tests (GDT and GIN) in Table 3 and those based on temporal ordering and temporal modulation detection in Table 4.

Studies assessing temporal resolution in individuals with tinnitus have reported varying findings across the included studies. The studies by Sanches et al. (2010), Gilani et al. (2013) (GIN), Jain and Sahoo (2014), and Raj-Koziak et al. (2022) reported alterations in the temporal resolution among individuals with normal hearing and tinnitus. Specifically, these studies found that tests such as the GDT and GIN indicated poorer temporal resolution in individuals with normal hearing and tinnitus than in those without tinnitus. By contrast, Zeng et al. (2020) study on GDT, and An et al. (2014) study on GIN did not find significant differences in temporal resolution between individuals with normal hearing and tinnitus, and those without tinnitus. These results imply that tinnitus may not substantially affect temporal resolution in individuals with normal hearing sensitivity. Regarding specific temporal resolution tests, Moon et al. (2015) and Zeng et al. (2020) discovered no significant differences in TMD between tinnitus-affected and non- tinnitus ears, indicating that TMD may lack the sensitivity to detect temporal resolution disparities between the two groups. Similarly, Jain and Dwarkanath (2016) did not observe significant differences in Temporal Modulation Transfer Function (TMTF) between individuals with tinnitus and those without tinnitus. Investigating the Duration Pattern Test (DPT) and Frequency Pattern Test (FPT), Gilani et al. (2013) and Raj-Koziak et al. (2022) found no changes in temporal processing among individuals with tinnitus compared with those without tinnitus. Interestingly, Jain and Sahoo (2014) noted that individuals with moderate tinnitus exhibited poorer temporal resolution than

TABLE 3 Studies based on temporal resolution tests (GDT and GIN).

References	Population size and tests administered	Testing parameters	Findings	Discussion
Sanches et al. (2010)	With tinnitus ($n = 20$) and without tinnitus ($n = 28$) Extended high frequency pure tone audiometry (HF-PTA) Distortion product otoacoustic emission (DPOAE) **GIN**	Pure tone thresholds were tested from 0.25 Hz to 20 KHz. The DPOAE growth rate (DP growth) and the DPOAE threshold were obtained at the f2 frequencies of 2 and 4 kHz. Stimuli were presented at the intensity of the f2 (L2) stimulus, varying from 20 to 65 dB SPL in steps of 3 dB In GIN, white noise stimuli were presented that lasted 6 s and contained 0–3 silent gaps that varied in length from 2 to 20 milliseconds. Stimuli presented at 50 dBSL (relative to SRT), and the participant's task was to identify the gaps distributed.	Tinnitus subjects showed elevated thresholds above 8 KHz. DP-growth response presented slope values that were significantly lower than controls. Tinnitus subjects exhibited statistically poorer temporal processing (GIN threshold: 7.23 ms) compared to controls (GIN threshold: 5.96 ms)	Tinnitus patients with normal audiograms but exhibiting modifications in extended high frequencies demonstrated poorer performance. These results were associated with subtle cochlear damage, which can trigger the involvement of central auditory processes linked to the perception of tinnitus.
Gilani et al. (2013)	With tinnitus ($n = 20$), and without tinnitus ($n = 20$). **GIN**	In GIN, the test materials were segments of white noise stimuli that lasted 6 s and contained 0–3 silent gaps that varied in length from 2 to 20 milliseconds. Stimuli presented at Presentation level—50 dBSL (relative to SRT), and the participant's task was to identify the gaps distributed.	Statistically significant increase in GIN in the tinnitus group (GIN threshold—6.15 ms) relative to non-tinnitus group (GIN threshold—4.8 ms).	The study found auditory temporal resolution difficulties in patients with tinnitus despite having normal auditory thresholds. The authors stated that there may be some possibility of abnormality in central auditory processing functions.
Ibraheem and Hassaan (2017)	With tinnitus ($n = 15$) and without tinnitus ($n = 15$) Transient evoked otoacoustic emission (TEOAE) HF-PTA **GIN**	Pure tone thresholds were tested from 0.25 Hz to 16 KHz. The TEOAE was elicited using click stimulus with intensity of 80 dBpeSPL. The overall amplitude of the TEOAE was measured. In GIN, the test materials were segments of white noise stimuli that lasted 6 s and contained 0–3 silent gaps that varied in length from 2 to 20 milliseconds. Stimuli presented at 50 dBSL (relative to SRT), and the participant's task was to identify the gaps distributed.	Tinnitus subjects showed elevated thresholds above 8 KHz. Overall TEOAE amplitude higher in tinnitus group. Tinnitus group had higher GIN thresholds ($7 \pm 0.1.1$) and lower response accuracy (58.1 ± 5) than control group (GIN threshold: 5.2 ± 0.8 ms; accuracy—67.6 ± 4.7). Tinnitus duration, scaling, audiological profile, and psychoacoustic measurements were unrelated to GIN test results.	The tinnitus group showed a slight increase in hearing thresholds at high frequency region which could be attributed to subtle cochlear damage that is not detected in the audiogram. Poor auditory temporal resolution in tinnitus patients may be attributed to cochlear impairment and reduced neural firing within the auditory pathway. This reduced neural output from the damaged cochlea may be associated with the occurrence of tinnitus.
Jain and Sahoo (2014)	With tinnitus ($n = 20$), and without tinnitus ($n = 20$) **GDT**	500 ms broadband noise with 0.5 ms cosine ramp at the beginning and end, and the participant's task was to identify the temporal gaps distributed.	Moderate tinnitus individuals exhibited longer gap detection intervals compared to those with mild tinnitus or without tinnitus.	Central auditory system issues, associated with neural structure abnormalities, contribute to tinnitus perception and temporal perception difficulties. Among those with mild tinnitus, GDT were unaffected. Tinnitus can impact temporal resolution, possibly because of subtle alterations within the central auditory system.
An et al. (2014)	Tinnitus group ($n = 60$) and non-tinnitus group ($n = 30$) **GIN**	The test materials were segments of white noise stimuli that lasted 6 s and contained 0–3 silent gaps that varied in length from 2 to 20 milliseconds. Stimuli were presented at 50 dB SL (relative to SRT), and the participant's task was to identify the gaps distributed.	The ear affected by tinnitus did not show a significant effect on GIN performance. GIN thresholds showed no significant differences between tinnitus- affected ears, unaffected ears, and normal ears.	The authors conclude that the cause of central auditory nervous system dysfunction in unilateral tinnitus remains unclear. Limited literature prevents definitive conclusions on the neural generators of unilateral and bilateral tinnitus. Additionally, even minor cochlear damage has minimal impact on tinnitus temporal resolution, especially when standard pure-tone thresholds are normal or near-normal.

(Continued)

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TABLE 3 (Continued)

References	Population size and tests administered	Testing parameters	Findings	Discussion
Zeng et al. (2020)	Tinnitus group ($n = 45$) and non-tinnitus group ($n = 27$) **GDT**	Sinusoids of various frequencies, including subjects' tinnitus pitch were used. In the 400 ms signal, a central gap was flanked by 2 ms cosine-squared ramps. Gap duration was determined at 6 dB down points, with a consistent sinusoidal phase, and signal intensity ranged from 5 to 15 dB SL and the participant's task was to identify the gaps distributed.	There was no significant difference in gap detection between control and tinnitus subjects.	According to the authors, depending on the stimulus, individuals with tinnitus might rely on either amplitude or frequency cues to perceive a resolution.
Raj-Koziak et al. (2022)	Tinnitus group ($n = 54$) and non-tinnitus group ($n = 43$) HF-PTA Distortion product oto-acoustic emission test (a DP-gram) **GDT**	High-frequency pure-tone audiometry was determined for the right and left ears above 8 kHz till 16 kHz. DPOAEs were measured over 1–8 kHz. The intensities of tones f1 and f2 were 65 dB (L1) and 55 dB SPL (L2), and the ratio of f2/f1 was 1.22. DPOAEs at various frequencies, noise levels, and signal-to-noise ratios were recorded Stimulus for GDT encompassed a 500- ms white noise signal, presented at an intensity of 50 dB HL to both ears, and the participant's task was to identify the gaps distributed.	No statistically significant difference in high-frequency thresholds between the two groups. DPOAEs were present in both ears in all tinnitus patients. The tinnitus group showed significantly poorer (GDT thresholds: 3.83 ± 1.21 ms) compared to controls (GDT thresholds: 3.20 ± 0.55 ms), indicative of poorer temporal processing. No correlation was found between tinnitus severity and GDT results.	Tinnitus subjects showed poorer performance despite normal hearing sensitivity, likely due to subtle cochlear damage. Additionally, central auditory processing abnormalities may exist in these patients despite normal auditory thresholds

The temporal resolution test is given in bold text. Temporal resolution thresholds for studies showing significant effect of tinnitus on tests are mentioned. For participant characteristics see Table 1.
GIN, gaps in noise; SRT, speech recognition threshold; THI, tinnitus handicap inventory; GDT, gap detection threshold; MDT, modulation detection threshold.
The mean values from graphs in the selected studies are obtained using webplot digitizer.

those with mild tinnitus, as measured by the GDT. Furthermore, individuals with mild tinnitus demonstrated diminished temporal resolution compared with those without tinnitus. These findings suggest a potential relationship between tinnitus severity and deficits in temporal resolution.

Study characteristics

Tables 3, 4 provide information about the temporal processing tests performed, test protocol used, results obtained, and study outcomes of all nine articles selected for review. Table 3 provides a compilation of studies examining how tinnitus affects temporal processing tests that specifically evaluate the peripheral aspects. Table 4 includes studies that show the effects of central tests on behavioral measures.

Discussion

The primary aim of this study was to thoroughly analyze and interpret the cumulative findings of multiple studies that have investigated the relationship between tinnitus and temporal processing abilities in individuals with normal hearing. Through a comprehensive review of the literature, these studies provided valuable insights into the intricate nature of tinnitus and its underlying mechanisms.

Complex interplay of factors

A review of the reviewed studies revealed a complex interplay between factors influencing temporal processing abilities in individuals with tinnitus. This complexity arises from multiple contributing factors including cochlear damage, central auditory nervous system involvement, tinnitus severity, and laterality. Importantly, these studies have proposed diverse explanations for temporal processing phenomena observed in individuals with tinnitus.

Cochlear damage and temporal processing

The status of outer hair cells and cochlear function play potential roles in temporal resolution and tinnitus generation (Kaltenbach, 2009; Jain and Dwarkanath, 2016). The impaired temporal resolution observed in patients with tinnitus may stem from cochlear damage and the disruption of the auditory pathway (Moore and Oxenham, 1998). Studies have shown significant differences in the temporal resolution and extended high-frequency hearing thresholds in individuals with tinnitus (Sanches et al., 2010; Ibraheem and Hassaan, 2017). Damage to OHCs can lead to reduced compression and broadening of auditory filters, negatively affecting the frequency selectivity and temporal resolution (Moon et al., 2015). The relationship between tinnitus and extended high-frequency hearing loss remains controversial with varying findings (Barnea et al., 1990; Yildirim et al., 2010; Fabijańska et al., 2012; Vielsmeier et al., 2015; Raj-Koziak et al., 2022). In

TABLE 4 Studies based on temporal ordering and temporal modulation detection.

References	Subject size and tests administered	Testing parameters	Outcome	Discussion
Gilani et al. (2013)	With tinnitus ($n = 20$) without tinnitus ($n = 20$) 14 subjects with B/L tinnitus and 6 subjects with U/L tinnitus (two subjects had in right ear and four had in left ear). **DPT**	The DPT utilized 40 sets of binaural 3-tone sequences at 1,000 Hz with varying durations (short: 250 ms, long: 500 ms) and a 300 ms separation. Subjects were tasked with recalling the order of tones (e.g., long–long–short) presented at 60 dB HL, with each tone having a rise/decay time of 10 ms.	No change in DPT between tinnitus and control.	The study found that tinnitus patients might have potential impairment in their central auditory processing despite having normal auditory thresholds. The reason for the normal outcome of the DPT in tinnitus patients was attributed to the test's inability to detect abnormalities in structures located beneath the auditory cortex.
Jain and Sahoo (2014)	Tinnitus group ($n = 20$) Control (without tinnitus) group ($n = 20$). **TMD**	500 ms Gaussian noise, modulated at 8, 20, 60, and 200 Hz, measured modulation detection threshold. 10 ms increasing cosine ramps at start and offset. Total root mean square power compared modulated and unmodulated noise. The subjects were asked to say which block had the modulated noise.	Moderate tinnitus individuals had the poorest modulation detection threshold (TMD) values (−5.5 to −14 dB), followed by Mild tinnitus group (−5.5 to −13.6 dB) to who showed poor TMD. Both the groups showed statistically poorer TMD than control group (−9.5 to −17 dB).	Impairments in the central auditory nervous system, related to neural structure defects, contribute to tinnitus perception and temporal perception difficulties. Modulation detection thresholds were impaired in mild tinnitus patients. This suggests that MDT tests may offer a more sensitive measure for assessing tinnitus-related temporal resolution issues. Tinnitus affects temporal resolution, potentially due to subtle changes in the central auditory system that are not reflected in the audiogram.
Moon et al. (2015)	Tinnitus group: Nine unilateral tinnitus subjects (six males and three females, Non-tinnitus group: 15 adults (six males and nine females) **TMD**	In TMD test, Wideband noise was amplitude modulated at 10 and 100 Hz; each signal lasting 1 s. These signals had 10 ms linear ramps at their start and end and were combined without gaps. TMD thresholds were determined using a 2-interval, 2-AFC paradigm, where participants identified the interval with modulated noise. The subjects were asked to say which block had the modulated noise.	There were no significant differences in TMD between the tinnitus-affected ears (TEs) and non-tinnitus ears (NTEs).	Hypothesized that if the spectral and temporal resolution in ears affected by tinnitus (TEs) matches that in unaffected ears (NTEs), it suggests minimal damage to the outer hair cells (OHCs) on the tinnitus side. This hypothesis is particularly relevant for individuals with unilateral tinnitus and normal hearing, including in extended high frequencies. This leads us to propose that the cochlear hair cells' condition remains intact and comparable on both sides.
Jain and Dwarkanath (2016)	With tinnitus ($n = 38$) Without tinnitus ($n =$ 38). **TMTF** **DPT**	MTF—three modulation rates (8, 60, and 200 Hz) with a 500-ms Gaussian noise stimulus. The participant's task was to identify the stimulus that was different from the other two in each trial on a specific parameter. DPT—using variable duration white noise stimuli. Duration pattern perception used 1,000-Hz pure tones with short and long durations.	The tinnitus group demonstrated statistically poorer performance on DPT (unilateral tinnitus—56.51%; unilateral tinnitus 56.9%) compared to those without Tinnitus (58.50%). Similar results were obtained for TMTF too	The authors were unable to draw definitive conclusions regarding the neural generators of unilateral and bilateral tinnitus due to limited available literature. However, they suggest that these generators may be distinct and located within the higher auditory system, potentially near the regions responsible for temporal processing of auditory stimuli.
Zeng et al. (2020)	Tinnitus group ($n = 45$) and non-tinnitus group ($n = 27$) **TMD**	Temporal modulation detection was evaluated at different carrier frequencies (250, 2,000, and 8,000 Hz) using modulation frequencies of 4, 41, and 80 Hz.	There was no significant difference in temporal modulation detection between control and tinnitus subjects	Depending on the stimulus, individuals with tinnitus might rely on either amplitude or frequency cues to perceive a resolution.
Raj-Koziak et al. (2022)	Tinnitus group ($n = 54$) and non-tinnitus group ($n = 43$) **FPT** **DPT**	FPT: 40 binaural stimuli at 60 dB HL, triplets of 200 ms tones (880 or 1,122 Hz), repeating tone order. DPT: 40 binaural 3-element sequences at 60 dB HL, 1,000 Hz tones (250 or 500 ms), repeating tone order.	No difference in the FPT and DPT tests was found between the tinnitus and control groups.	Tinnitus sufferers show poorer performance despite normal hearing sensitivity, likely due to subtle cochlear damage. Additionally, central auditory processing abnormalities may exist in these patients despite normal auditory thresholds.

The temporal processing test is given in bold text. Test thresholds for studies showing significant effect of tinnitus on temporal processing are mentioned. For participant characteristics see Table 1.
DPT, duration pattern test; MDT, modulation detection threshold; TMD, temporal modulation detection; TMTF; Temporal Modulation Transfer Function, FPT, frequency pattern test.
The mean values from graphs in the selected studies are obtained using webplot digitizer.

contrast, Raj-Koziak et al. (2022) did not observe statistically significant differences in hearing thresholds between the tinnitus and non-tinnitus groups in high-frequency audiometry. Regarding the relationship between tinnitus and extended high- frequency hearing loss, a study by Jain and Dwarkanath (2016) found no role for high-frequency hearing sensitivity in tinnitus generation, which aligns with the findings of Barnea et al. (1990) and Vielsmeier et al. (2015) reported normal extended high-frequency energy hearing sensitivity in individuals with tinnitus. In contrast, Yildirim et al. (2010) and Fabijańska et al. (2012) reported high-frequency hearing loss in individuals with tinnitus, which suggests cochlear involvement. Additionally, the traditional energy-based tinnitus model has been challenged, suggesting separate processing pathways for tinnitus and external sound (Zeng et al., 2020). Their study provided evidence against this hypothesis as they assessed gap detection using stimuli matched to the loudness and pitch of tinnitus. Hearing loss at a particular frequency lead to loss of energy at the frequency of loss. However, their study showed an improved performance at the tinnitus frequency which matched to the frequency of hearing loss (Zeng et al., 2020). Thus, they suggested that tinnitus frequency is processed more centrally and the peripheral hearing loss at the tinnitus frequency does not affect the temporal processing.

Central auditory nervous system and temporal processing

Several studies have explored the involvement of the central auditory nervous system (CANS) in tinnitus perception and its effect on temporal resolution. Sanches et al. (2010) highlighted the connection between tinnitus and reduced auditory input in patients with CANS, even those with normal hearing thresholds. This aligns with existing theories that suggest cochlear damage triggers changes in the central auditory system, leading to tinnitus.

Weisz et al. (2006) also supported this notion by demonstrating a link between tinnitus and reduced auditory input in patients with CANS. Jain and Sahoo (2014) reported that defects in the neural structures within the CANS associated with tinnitus perception may also impair temporal perception. Altered afferent inputs to the auditory pathway may initiate a complex sequence of events, leading to tinnitus at the central level of the auditory nervous system. This implies that changes in auditory function may contribute to the development and perception of tinnitus (Bartels et al., 2007; Gilani et al., 2013; An et al., 2014). An et al. (2014) examined central auditory processing disorder (CAPD) in individuals with unilateral tinnitus and found no difference in GIN test performance between tinnitus and non-tinnitus groups, indicating no clear dysfunction in the CANS. The research also pointed out that individuals with tinnitus and/or hearing loss might experience difficulties in auditory temporal resolution owing to disruptions in the precise firing of neurons, which requires a proper balance between excitatory and inhibitory synapses (An et al., 2014). In contrast, Raj-Koziak et al. (2022) found no confirmed impact of tinnitus on the gap detection ability, suggesting that tinnitus may not sufficiently disrupt gap detection. Moon et al. (2015) concluded that tinnitus had no influence on the auditory spectral and temporal resolution. However, they suggested that tinnitus may act as a central masker in CANS, particularly during speech perception in the presence of background noise. Musiek et al. (2005) and Fournier and Hébert (2013) investigated gap detection in individuals with confirmed CANS involvement and found a significantly increased GDT. This suggests that the Gaps-In-Noise (GIN) test is a promising and clinically useful tool for assessing temporal resolution in individuals with tinnitus and CANS. They proposed that ongoing tinnitus might mask gaps and impair gap detection. Although some studies have supported the involvement of CANS in tinnitus perception and its impact on temporal resolution, other studies have presented conflicting findings. The relationship between tinnitus and CANS involvement is complex and requires further research to fully understand its underlying mechanisms.

Potential biomarkers of temporal processing deficits in tinnitus sufferers

Upon examining the studies conducted on peripheral (GDT, GIN, TMD) and central (FDT, DPT) temporal processing tests, several significant observations emerged in relation to temporal processing tests and their outcomes in individuals with tinnitus. Gilani et al. (2013) found no significant increase in DPT between the experimental and control groups.

According to Musiek et al. (2005), DPT is resistant to lower-level pathologies such as cochlear involvement and hearing loss. This test was unaffected by minor losses in the system resolution. Therefore, the normal DPT results for patients with tinnitus could be attributed to the insensitivity of the test to abnormalities occurring below the auditory cortex (Gilani et al., 2013). Raj-Koziak et al. (2022) conducted a study on FPT and found no significant difference between tinnitus and control groups. Their study appears to be the only one that utilized FPT in individuals with tinnitus. They suggested that the lack of significant differences between the tinnitus and control groups in the FPT and DPT may be because these tests assess temporal ordering abilities, whereas the GDT assesses temporal resolution. They also found a strong positive correlation between the FPT and DPT results in subjects with and without tinnitus, indicating that these tests measure similar abilities. Additionally, Raj-Koziak et al. (2022) found that tinnitus influenced pitch discrimination ability, with a reduction in performance observed regardless of tinnitus severity. This suggests that subtle cochlear changes that are not evident in pure-tone thresholds may underlie the poor pitch discrimination observed in individuals with tinnitus. This study emphasizes the importance of considering the temporal and speech perception abilities in tinnitus evaluation and management. In contrast, Zeng et al. (2020) observed no significant differences in the gap detection and temporal modulation detection abilities between individuals with tinnitus and a control group. They attributed this lack of difference to the possibility that subjects with tinnitus may rely on amplitude or frequency cues, depending on the stimulus, for detecting resolution.

Tinnitus severity and temporal processing

Examining the impact of tinnitus severity on temporal processing abilities, Jain and Sahoo (2014) found that individuals with moderate tinnitus needed longer periods of silence in noisy environments to detect gaps than those with mild tinnitus or no tinnitus. However, the ability to detect sound modulation was similar across all the tinnitus levels. Interestingly, the mild tinnitus group did not show a deficit in the GDT test but performed poorly in the TMD test. This suggests that TMD may be a more sensitive measure for assessing the impact of tinnitus on the temporal resolution. In contrast, Raj-Koziak et al. (2022) found that as tinnitus severity increased, scores on the FPT and GDT tests decreased. However, the correlation between tinnitus severity and the outcomes of GDT was not statistically significant, yielding different results compared with the study by Jain and Sahoo (2014).

Effect of unilateral and bilateral tinnitus on temporal processing

Studies have explored the impact of tinnitus on temporal processing considering its laterality. The origin of unilateral and bilateral tinnitus in the auditory nervous system is distinct. Findings from a range of temporal processing assessments, such as TMTF, GIN, and DDT, revealed a significant contrast between unilateral and bilateral tinnitus. Participants with bilateral tinnitus showed notably lower scores these tests than those with unilateral tinnitus did (Sanches et al., 2010). Jain and Dwarkanath (2016) found that individuals with bilateral tinnitus had poorer scores on the temporal processing tests than those with unilateral tinnitus. This finding implies that the impact on the temporal processing ability is more pronounced in cases of bilateral tinnitus. Nonetheless, it is plausible that bilateral tinnitus is an intensified form of unilateral tinnitus.

Moon et al. (2015) showed no significant effect of tinnitus on outer hair cell (OHC) function in participants with unilateral tinnitus. They noted a lack of reduced spectral and temporal resolution in tinnitus ears (TEs) compared with non-tinnitus ears (NTEs). This finding ruled out the possibility of additional damage to the OHCs on the side were tinnitus was perceived. Similar effects of unilateral tinnitus were observed on the GIN thresholds (An et al., 2014). When the effect of TE on auditory temporal resolution in patients with unilateral tinnitus was investigated, An et al. (2014) did not find any significant difference in GIN thresholds between TE and NTE.

Discrepancies and methodological variations

Several studies have explored auditory temporal processing deficits in individuals with tinnitus and the factors that influence these outcomes. This review identified inconsistencies and variations among these studies. Moon et al. (2015) identified a discrepancy compared to Sanches et al. (2010), which was potentially attributed to variations in subjects with hearing impairment at extended high frequencies or differences in test modalities for assessing temporal resolution. By contrast, Moon et al. (2015) had limitations, focusing on individuals with relatively low hearing thresholds and tinnitus handicap, and unilateral tinnitus with symmetric hearing thresholds, which may not fully represent tinnitus mechanisms after cochlear damage. In contrast, Jain and Dwarkanath (2016) found discrepancies with An et al. (2014) in the GDT, owing to methodological differences in stimulus presentation and psychometric function criteria. Raj-Koziak et al. (2022) acknowledged the limitations related to potential hidden pathologies and unclear connections between peripheral damage and central auditory system adaptation in tinnitus patients.

Ibraheem and Hassaan (2017) discussed the lack of correlation between psychoacoustic tinnitus measures, subjective impact, and GIN test parameters, suggesting that tinnitus impact and temporal resolution are not solely dependent on pitch or loudness. Additionally, Jain and Sahoo (2014) proposed that MDT may be a more sensitive measure for assessing the impact of tinnitus on temporal resolution, as individuals with mild tinnitus showed no GDT deficits, but had poor MDT. Overall, these studies highlight the complexity of auditory temporal processing deficits in tinnitus, and the importance of considering various factors and measures when investigating this condition.

Future research and implications

A meta-analysis was originally intended to provide insight into temporal processing at both peripheral and central auditory levels, which proved unfeasible owing to significant variations among studies. Nevertheless, this review reveals an important observation: more than 50% of the studies in the literature report impairments in GDT and GIN tests, which assess the higher peripheral auditory system and indirectly reflect the central auditory system, in individuals with tinnitus, even those with normal hearing. In contrast, most of the studies discussed did not show significant effects on tests, such as the MDT, TMD, FPT, and DPT, which primarily assess the central auditory system. This implies that evaluating temporal resolution using tests, such as GDT/GIN, may be a sensitive tool for assessing temporal processing in individuals with tinnitus. By integrating these insights into clinical practice, more comprehensive approaches can be developed to address temporal processing deficits associated with tinnitus.

Limitations of the study

The study considered only temporal processing abilities in tinnitus. Further studies are essential on other auditory process as well. We considered articles only till 2021 and hence more recent articles were not included in the study. The study did not consider children and older adults and hence the results can be generalized only for the considered population. Thus, further research delineating the reasons behind the complex interplay between various factors in the temporal sensitivity of patients with tinnitus is imperative. For e.g., this review highlights the differences between unilateral and bilateral tinnitus, with more evident temporal processing deficits observed in individuals with bilateral tinnitus. However, this topic is complex because the degree of severity and test sensitivity in measuring temporal changes in laterality could have affected the results. Further research is required to elucidate the underlying mechanisms. In addition, only a limited number of studies have focused on different temporal processing tests, emphasizing the necessity for comprehensive investigations in this field. Future research should aim to overcome these limitations by studying larger and more diverse tinnitus samples, employing standardized methods, exploring the impact of comorbid conditions on temporal processing and speech perception, and investigating unilateral vs. bilateral tinnitus generators. By addressing these research gaps, we can deepen our understanding of the effects of tinnitus on temporal processing, thereby leading to improved diagnostic and therapeutic approaches for individuals with tinnitus.

Conclusions

Exploration of temporal processing tests within the context of tinnitus has yielded valuable insights into the intricacies of auditory perception in affected individuals. Diverse findings from various studies have shed light on the potential of these tests as biomarkers for understanding and assessing tinnitus-related temporal processing impairments. Central tests such as DPT have emerged as less sensitive indicators for tinnitus- related temporal processing deficits, while the use of peripheral tests such as GDT seems more likely to identify temporal deficits in patients with tinnitus. In conclusion, the studies reviewed in this review shed light on the complex relationship between tinnitus and temporal processing. Although some studies have indicated a potential association between tinnitus and impaired temporal processing, there are discrepancies and limitations in the findings, which are likely due to variations in methodologies and subject characteristics. The impact of tinnitus on speech perception, particularly in noisy environments, is evident, suggesting possible changes in the auditory system function (Jain and Sahoo, 2014; Moon et al., 2015). Comorbid conditions and secondary effects of tinnitus may also contribute to hearing difficulties reported by individuals with tinnitus (Zeng et al., 2020). In addition, tinnitus laterality, whether unilateral or bilateral, may influence temporal processing abilities and speech perception. Further research is needed to explore this aspect (Moon et al., 2015; Jain and Dwarkanath, 2016).

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

MP: Data curation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. PP: Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing. GK: Data curation, Methodology, Formal analysis, Investigation, Resources, Visualization, Software, Writing – original draft. KN: Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fauot.2024.1388252/full#supplementary-material

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