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Review Article

The Role of Attention Modulation and Its Neurophysiological Mechanisms in Tinnitus Management: A Review

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Highlights

- Attention plays a crucial role in tinnitus-related distress
- Tinnitus patients show attentional differences in neurophysiological studies
- Attention training interventions can effectively alleviate tinnitus distress

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ABSTRACT

Background and Aim: Tinnitus, characterized by the perception of sound without the presence of an external auditory stimulus, can profoundly affect the quality of life. This review study aims to assess the role of attention modulation in tinnitus management and investigate the neurophysiological mechanism of attention and its interaction with emotional processing in patients with tinnitus.

Recent Findings: The studies revealed differences in the function of attentional networks among individuals with tinnitus. The studies showed the positive impact of various techniques for attention modulation through direct attention training or indirect mechanisms influencing attention. These techniques could modify attentional biases, enhance attention control, and alleviate tinnitus-related distress.

Conclusion: The results of studies suggest the potential role of attention modulation in tinnitus management. By targeting attentional processes, researchers and clinicians can provide more effective interventions for individuals with tinnitus. However, there is a need for further investigation to optimize the intervention protocols by collaboration between researchers, clinicians, and individuals with tinnitus to achieve success in tinnitus management.

Keywords: Tinnitus; attention; tinnitus management; neurophysiological mechanism; attention training

Introduction

Tinnitus, characterized by the perception of sound without the presence of any external auditory stimulus, can cause considerable problems in the well-being and quality of life of affected people [1, 2]. This auditory problem has affected millions worldwide who need effective management interventions to alleviate its distressing impact [3]. One of the factors affecting tinnitus perception and maintenance is attentional processes which need further investigation [4]. Attention, a fundamental cognitive process, plays a pivotal role in enabling individuals to selectively focus on specific stimuli, while ignoring irrelevant stimuli [5]. The neurophysiological mechanisms of attention are related to complex interactions among various brain regions, including the prefrontal cortex, parietal cortex, and sensory processing areas [6, 7]. Through these neural interactions, attentional control is achieved, allowing individuals to pay attention to relevant stimuli and regulate their perception and processing [8].

Understanding the relationship between attention and tinnitus perception can be facilitated by using attentional models that propose distinct mechanisms of attentional control. According to Posner's model of attention, there are three attentional networks: alerting, orienting, and executive [9]. Individuals with tinnitus often experience disruptions in these attentional networks, leading to attentional bias in directing their focus towards or away from tinnitus-related stimuli [10-12]. There are also other attention models that provide valuable information about the complex relationship between attention and tinnitus. For instance, the biased competition model proposes that attentional resources are distributed based on the salience and competition among stimuli [13]. The increased salience of tinnitus-related stimuli and their competition with other auditory inputs may lead to attentional bias towards tinnitus and challenges in disengaging attention from tinnitus sensations [14]. The predictive coding framework suggests that attentional processes involve generating and updating predictions about sensory inputs, with abnormal prediction errors contributing to attentional disturbances in individuals [15]. The attentional control theory is a prominent theoretical framework that provides valuable information about the mechanisms of attentional processes in tinnitus perception and modulation. According to this theory, individuals with tinnitus may face difficulties in the proper regulation of attention, leading to attentional biases towards tinnitus-related stimuli. Consequently, this heightened attention can exacerbate tinnitus perception and distress. The theory suggests that attentional biases away from tinnitus can promote habituation to the phantom sound and potentially reduce distress [16].

A growing body of evidence supports the remarkable influence of attentional processes on subjective experience and modulation of tinnitus sensations [4]. Neuroimaging studies have demonstrated altered attentional networks in individuals with tinnitus, indicating disruptions in the neural mechanisms underlying attention [17, 18]. This suggests the presence of attentional biases and difficulties in redirecting attention away from tinnitus-related stimuli, thereby amplifying the perception and impact of tinnitus on emotional and cognitive functioning. Furthermore, the limbic system and emotional processing regions are involved in the relationship between attention and tinnitus perception [19]. The amygdala is crucial for attentional modulation and emotional processing [20]. Abnormal activation of the amygdala and its functional connectivity with other brain regions have been observed in individuals with tinnitus, suggesting an emotional component involved in attentional processes related to tinnitus perception [19, 21]. This emotional aspect of tinnitus perception and its relationship with attention has received great attention. Recent studies have indicated this relationship and have revealed that individuals with tinnitus tend to show slower reactions during specific attentional tasks compared to controls, where the degree of distress they experience mediates the impact of tinnitus on attention [22]. These findings emphasize the importance of tinnitus-related distress in formulating personalized tinnitus management interventions [23].

Neurophysiological evidence reveals significant differences in attentional networks among individuals with tinnitus, with functional Magnetic Resonance İmaging (fMRI) studies highlighting heightened activity in the Dorsal Attention Network (DAN) and the frontoparietal control network. [24-28]. The DAN, as the "top-down" attention, guides selective attention on specific objects or locations and is notably more engaged in tinnitus patients, potentially reflecting

the heightened cognitive effort required to cope with tinnitus. The disruptions in connectivity between these attentional networks and the limbic system (responsible for emotional processing) have been reported [29]. These disruptions highlight the complex relationship between attention and emotional processing in tinnitus patients, indicating the need for further exploration of their implications for the emotional distress experienced often by people with tinnitus [30]. The VAN, as the "bottom-up" attention, has a role in involuntarily orienting of attention towards salient environmental stimuli. The VAN is crucial for redirecting attention when unexpected or emotionally significant events occur [31]. Together with the DAN, it forms the neural basis for attention allocation [32]. In tinnitus, the high DAN activity may indicate increased cognitive demand due to persistent auditory disturbances, while disruptions in connectivity between these networks and the limbic system may highlight the neural underpinnings of emotional responses in tinnitus patients [33, 34]. Having knwoledge of the interactions between these attentional networks and the limbic system is essential for understanding the impact of tinnitus on attention and emotional well-being [21, 35].

Attention training is a promising approach for tinnitus management, focusing on principles of neural plasticity and sensory retraining [36]. These interventions aim to modify attentional biases and enhance attentional control over tinnitus-related stimuli, thereby reducing distress and improving functional outcomes [37]. Various attention training methods, including multisensory stimulation program, have shown positive results in redirecting attention away from tinnitus and promoting habituation processes [38]. However, further investigation is necessary to enhance the protocol of these interventions, by assessing the influence of individual factors on treatment outcomes, and establish the enduring efficacy over an long period [39]. In addition, gaining a comprehensive knowledge of the neurophysiological mechanisms underlying attention training and its specific effects on attentional processes in individuals with tinnitus is of utmost importance for the development of personalized interventions [40]. Future studies should delve into the neural mechanisms underlying attention modulation and explore effective methods to modify attentional biases. Moreover, investigation of the effects of factors, such as tinnitus severity, duration, and comorbidities, on attentional processes and treatment outcomes can facilitate the development of personalized interventions. This can empower us to effectively manage tinnitus and improve the quality of life of affected people. In this regard, this study aimed to review attentional processes in individuals with tinnitus and the tinnitus management approaches.

Methods

In this systematic review study, the search was condcuted to find the related studies published in English language assessing the role of attention and its neurophysiological mechanisms for tinnitus management, in online databases, including PubMed, Scopus, and Google Scholar, using the keywords, "tinnitus", "attention modulation", "neurophysiological mechanisms", "cognitive training", "management strategies", and "intervention protocols".

The search yielded 882 articles published between 2003 to 2023. They were subjected to inclusion and exclusion criteria. The inclusion criteria were: assessing the relationship between attention modulation and its application in tinnitus management, exploring the neurophysiological underpinnings associated with these interactions, investigating strategies for managing tinnitus by targeting attention modulation mechanisms, focusing on unraveling their neurological foundations within the context of tinnitus management. The studies solely on pharmacological interventions or other tangential aspects of tinnitus management were excluded from our review.

To ensure a refined selection process, we examined the titles and abstracts, followed by a reading the full-texts.

For data extraction, the information of the selected articles, including the study design, sample size, participants, intervention, outcome measures, and key findings were collected. The extracted data were organized and synthesized to provide a comprehensive overview of attentional interventions for tinnitus management. Then, a narrative synthesis approach was employed to summarize the findings derived from the selected articles. Attention training techniques, such as auditory, visual, and multisensory stimulation, were elucidated, along with their underlying theoretical

frameworks and mechanisms of action. The efficacy of these interventions in ameliorating attentional control, mitigating tinnitus-related distress, and enhancing functional outcomes was comprehensively discussed.

Results

Table 1 provides a summary of the reviewed studies, detailing their participants, study designs, intervention methods, outcome measures, and key findings. Boecking et al. conducted a randomized controlled trial involving 177 adults to explore the effects of auditory stimulation on tinnitus-related distress, assessed by the Tinnitus Questionnaire (TQ), Tinnitus Handicap Inventory (THI), and Tinnitus Functional Index (TFI). The results revealed a significant reduction in TFI scores, indicating a notable alleviation of tinnitus-related distress following auditory stimulation [41]. This study highlights the potential of auditory-based approaches in addressing tinnitus-related distress. Spiegel et al. conducted a quasi-experimental study on 18 participants to assess the effectiveness of multisensory stimulation program in mitigating the functional impact of tinnitus. The TFI was used as the primary outcome measure, and the results demonstrated a statistically significant improvement in TFI scores after intervention [38]. This study indicates the advantages of integrating multiple sensory modalities in attention modulation for tinnitus management. McKenna et al. investigated the efficacy of Mindfulness-Based Cognitive Therapy (MBCT) in 182 adults with chronic and distressing tinnitus. The TQ and the Clinical Outcomes in Routine Evaluation-Outcome Measure (CORE-OM) were used as primary outcome measures. The results indicated significant reduction in tinnitus-related distress and psychological distress, and imrovment in tinnitus acceptance and mindfulness after intervention [42]. These findings emphasize the potential of mindfulness-based interventions in alleviating tinnitus impact and enhancing overall cognitive wellness. Zimmerman et al. conducted a pilot study on 12 participants with chronic tinnitus, using task-based and resting-state fMRI measures, along with the TFI to assess tinnitus severity. The results demonstrated significant decreases in functional connectivity among specific brain regions throughout the intervention, suggesting that mindfulness-based interventions may have a beneficial effect on tinnitus severity by influencing brain function [43]. This study provides neurophysiological evidence of a difference in attentional networks of individuals with tinnitus and highlights the potential of mindfulness-based interventions in modulating these networks to reduce tinnitus severity.

Wise et al. conducted a randomized controlled trial on 31 tinnitus patients, randomly assigned to attention training (Terrain game) and control (Tetris game). The training was perfromed for 20 consecutive days. Significant reduction in tinnitus severity and improvment in attentional capacities were observed in the Terrain group, suggesting the potential of perceptual training games as non-invasive therapeutic options for managing tinnitus symptoms [44]. In another randomized clinical trial, Kallogjeri et al. evaluated the impact of the Brain Fitness Program-Tinnitus (BFP-T) on tinnitus of 40 patients with bothersome tinnitus and 20 age-matched healthy controls. The BFP-T, designed by Posit Science, was employed as the cognitive training intervention and included 11 interactive training exercises (simple acoustic stimuli, continuous speech, and visual stimuli). These exercises were designed to specifically address the attentional aspects of tinnitus. The primary outcome measure was the THI. Over the 8-week intervention period, both BFP-T and healthy groups showed a reduction in THI scores, with median scores of 7 and 11, respectively. However, this reduction was not statitically significant (median difference=0; 95% CI: -10-8). Notably, functional connectivity in the regions involved in cognitive control showed a significant difference between baseline and follow-up scores in the BFP-T group, but not in healthy individuals. Moreover, 50% of the participants in the BFP-T group reported improvement after intervention, of whom 30% reported more improvements in domains of tinnitus, memory, attention, and concentration [45].

In a study by Busse et al., the effect of neurofeedback by neural correlates of auditory selective attention for tinnitus therapies was investigated on 8 healthy volunteers, who participated in a single session of feedback intervention, during which they were able to control the highness of bars on a computer monitor by varying their attention levels, without prior training. Four distinct patterns were described, and most subjects could perform the task for pattern 1 in the first part of the session. After a 15-minute rest interval, significant improvement was observed in all subjects during the second part. By the end of the session, six out of eight

Table 1. Summary of studies investigating attention modulation in tinnitus management

Study	Year	Design	Participants	Intervention	Outcome Measure	Results
Boecking et al. [41]	2022	Randomized controlled trial	177 adults with tinnitus	Auditory stimulation intervention	TQ, THI, TFI	Significant TFI reduction ($p<0.001$), indicating alleviated tinnitus distress.
Spiegel et al. [38]	2015	Quasi-experimental study	18 participants	Multisensory stimulation	TFI	Statistically significant TFI improvement, suggesting reduced functional tinnitus impact.
McKenna et al. [42]	2018	Pre-post design study	182 adults with chronic tinnitus	Mindfulness-based cognitive therapy	TQ, CORE-OM	Significant improvements in tinnitus distress, psychological distress, acceptance, and mindfulness. 50% had reliable distress reduction; 41.2% lowered psychological distress post-intervention.
Zimmerman et al. [43]	2019	Pilot study	12 participants with chronic tinnitus	Mindfulness-based interventions	Task-based and resting-state fMRI, TFI	Significant decreases in functional connectivity, suggesting beneficial effect on tinnitus severity through brain function.
Wise et al. [44]	2016	Randomized controlled trial	31 tinnitus patients	Auditory attention training game (Terrain)	TFI, attentional abilities	Significant TFI reduction and improved attentional capacities in "Terrain" group, potential non-invasive tinnitus management.
Kallogjeri et al. [45]	2017	Randomized Clinical Trial	40 adults with bothersome tinnitus; 20 age-matched healthy controls	BFP-T vs. non–BFP-T control	THI; cognitive tests; functional connectivity	THI score reduced in both groups, but no significant difference; significant improvement in functional connectivity in BFP-T group; self-reported improvements in attention, memory, and tinnitus perception in BFP-T group.

Study	Year	Design	Participants	Intervention	Outcome Measure	Results
Busse et al. [46]	2008	Exploratory study	8 volunteers with chronic tinnitus	Neurofeedback based on ALRs and attention control	Phase synchronization stability and attention control improvement	Participants were able to control attention levels, improve task performance, and increase phase synchronization stability, indicating potential effectiveness in tinnitus treatment.
Smith et al. [47]	2007	Single-blind, randomized pilot design	14 participants with chronic tinnitus	rTMS	Change in tinnitus loudness (VAS)	Significant reduction in tinnitus loudness in active rTMS group compared to sham. rTMS might influence tinnitus via modulating attention.
Kan et al. [48]	2019	pre- and post-treatment design	11 patients with idiopathic tinnitus	rTMS targeting left temporoparietal region cortex	THI, VAS	No significant tinnitus alleviation with left temporoparietal rTMS; observed changes in neural activity in tinnitus-associated brain regions.
Leaver et al. [49]	2023	Randomized controlled mechanistic trial	Individuals with chronic tinnitus	tDCS	Changes in cerebral blood flow and functional connectivity in the auditory cortex	tDCS induced significant changes in brain function in individuals with chronic tinnitus.

TQ; tinnitus questionnaire, THI; tinnitus handicap inventory, TFI; tinnitus functional index, CORE-OM; clinical outcomes in routine evaluation-outcome measure, fMRI; functional magnetic resonance imaging, BFP-T; brain fitness program–tinnitus, ALR; auditory late responses, rTMS; repetitive transcranial magnetic stimulation, VAS; visual analogue score, tDCS; transcranial direct current stimulation

subjects were even capable of reducing the size of a right triangle, indicating an enhancement in their attention. Moreover, their study demonstrated an increase in phase synchronization stability, suggesting that subjects were better able to focus on signals other than tinnitus noises. These promising results indicate the potential of the proposed neurofeedback system in improving attention control, which is important for tinnitus management [46]. Smith et al. in a single-blind, randomized, placebo-controlled clinical trial investigated the effectiveness of repetitive Transcranial Magnetic Stimulation (rTMS) in 14 participants with chronic tinnitus. The primary outcome measure was the Visual Analog Scale (VAS) measuring change in tinnitus loudness. Their results revealed a significant reduction in tinnitus loudness in the active rTMS group compared to the sham group [47]. Kan et al. also investigated the effects of rTMS on individuals with idiopathic tinnitus. Although the

results of measures (THI, and VAS) were not show a statistically significant reduction in tinnitus symptoms after rTMS over the left temporoparietal cortex, the study revealed noteworthy changes in neural activity in the specific brain regions. Their findings suggest that rTMS can induce broad changes in functionally connected brain networks responsible for regulating the emotional, attentional, and perceptual aspects of tinnitus [48]. Leaver et al conducted a study to investigate the effects of focal transcranial Direct Current Stimulation (tDCS) on brain function in chronic tinnitus subjects using MRI. The study involved 20 people with chronic tinnitus who were randomly assigned to receive either active or sham tDCS for five consecutive days. The results showed that the first active tDCS session led to acute increases in cerebral blood flow and functional connectivity in the auditory cortex. Additionally, the final tDCS session was associated with reduced tinnitus loudness ratings, which correlated with acute changes in functional connectivity between an auditory network and mediodorsal thalamus and prefrontal cortex. Furthermore, reduced tinnitus intrusiveness also correlated with acute changes in connectivity between precuneus and an auditory network [49].

The study of the neurophysiology of tinnitus unveiled significant changes within both auditory and non-auditory brain regions, indicating the multifaceted nature of tinnitus perception and its emotional and attentional dimensions. Auditory brain regions show more changes marked by increased neural activity and synchronization. These changes are often due to peripheral hearing loss and the subsequent compensatory hyperactivity observed in the central auditory pathways. This suggests that neural activity contributes to the generation and amplification of tinnitus perception [50-55]. In addition to the auditory brain regions, non-auditory brain regions are involved in the emotional and attentional aspects of tinnitus. The limbic system is responsible for processing emotions, and the prefrontal cortex has a role in executive functions and attentional processes. These areas are related to tinnitus-related distress, affecting emotional responses and attention allocation, thereby amplifying the perceived impact of tinnitus [56, 57]. Several review studies confirmed our understanding of attention and tinnitus management. Vasudevan et al. conducted a systematic review and meta-analysis and reported impairments in selective attention in individuals with tinnitus [58]. Tegg-Quinn highlighted the link between tinnitus and impaired cognitive function, particularly in executive control [59]. The positive outcomes of different attention modulation methods, along with evidence from review articles, support the claim that attention training is effective to alleviate tinnitus-related distress and functional limitations. Future studies should explore factors affecting the responses to attention training (e.g., tinnitus severity and duration) while considering the complex interaction between attentional processes and tinnitus perception.

Discussion

This review study provides valuable insights into the potential therapeutic benefits of attention training interventions for tinnitus management. We recommend a comprehensive evaluation of the efficacy of attention modulation. The use of various outcome measures and intervention approaches in different studies indicates the importance of attentional interventions for tinnitus management. Boecking et al. [41] demonstrates the potential of auditory-based approaches in tinnitus management, while Spiegel et al. [38] emphasized the advantages of multisensory stimulation. McKenna et al. [42] highlighted the potential of mindfulness-based interventions, and Zimmerman et al. [43] reported the beneficial impact of mindfulness-based interventions on tinnitus severity through brain function modulation. Wise et al. [44] and Kallogjeri et al. [45] provided insights into th efficacy of perceptual training games and cognitive training, respectively, for tinnitus. Busse et al. [46] showed promising results in improving attention control for tinnitus managment after using neurofeedback method. Smith et al. [47] found that rTMS could affect attentional processes in tinnitus management. Leaver et al. [49] showed that focal tDCS targeting auditory cortex can lead to acute changes in functional connectivity and cerebral blood flow, which can reduce tinnitus loudness ratings and intrusiveness.

The study of tinnitus neurophysiology provides a comprehensive perspective on the emotional distress and attentional modulation experienced by individuals with tinnitus. The significant changes observed in both auditory and non-auditory brain regions confrim our understanding of tinnitus perception and emotional processing. Review studies by Vasudevan et al. [58] and Tegg-Quinn [59] further showed attentional impairments and cognitive dysfunction in individuals with tinnitus.

The consistent positive outcomes of different attention modulation methods and the evidence from review studies suggest the potential of attention training in tinnitus management. However, the relationship between attention modulation and tinnitus management is not clear [38], and requires further investigation. Individual differences in treatment responses and the factors contributed to these differences should be investigated for further interventions.

Conclusion

In conclusion, the studies show the potential of attentional training by auditory intervention, multisensory stimulation, mindfulness-based cognitive therapy, and repetitive transcranial magnetic stimulation interventions in tinnitus management, indicating their role in alleviating tinnitus-related distress and functional limitations. Future studies should focus on optimizing direct attention training methods, finding factors affecting treatment responses, and further exploring the complex interaction between attentional processes and tinnitus perception. Attention modulation can be an essential part of future comprehensive approaches to tinnitus management, enhancing the overall well-being of people with tinnitus.

Ethical Considerations

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Authors' contributions

HNA: Study design, literature research, and drafting the manuscript; FJ and SMM: Supervisory roles that included interpreting the results and revision of the manuscript; SJ: Revision of the manuscript and statistical guidance.

Conflict of interest

There is no conflict of interest.

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