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Original Article

Binaural Processing and Auditory Working Memory in Individuals with Tinnitus Having Normal Hearing Sensitivity

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BACKGROUND: Tinnitus is a sound perceived in the ears or head without any external or internal sound source. It can be hypothesized that the auditory processing at the different levels of the auditory pathway and working memory may get affected due to the additional sound contributed by tinnitus. The objective of our study is to evaluate binaural processes and working memory capacity in individual with tinnitus having normal hearing sensitivity.

METHODS: The binaural interaction process was evaluated using the interaural time difference and interaural level difference. Similarly, the binaural integration process was assessed using the dichotic consonant-vowel test, and the working memory was assessed using the audio descending span test and Audio 2N-Back span test. Mann–Whitney *U* test was done to see the significant difference between the groups.

RESULTS: The Mann–Whitney *U* test showed significantly poorer interaural level difference scores in the tinnitus group. Also, dichotic consonant-vowel test scores and auditory working memory test scores were found to be significantly lower in individuals with tinnitus.

CONCLUSION: The binaural processes, along with the working memory capacity, are found to be affected in an individual with tinnitus, which in turn may affect the speech perception ability of the individual.

KEYWORDS: CAPD, integration, interaction, tinnitus, working memory

INTRODUCTION

Tinnitus is the perception of sound when there are no external acoustic stimuli to correlate to it. Tinnitus sensations are typically of an unformed acoustic nature, such as a buzzing, hissing, or ringing, in contrast to auditory hallucinations, phantom phenomena that mostly affect patients with mental problems and manifest as the perception of voices and musical hallucinations. Patients with tinnitus have described many noises as the perceived sensation, including ringing, buzzing, clicking, pulsations, hissing, and roaring.[1] It may be continuous, intermittent, or pulsating in nature. Tinnitus is caused by the auditory system's signal being processed inappropriately.[2] This abnormal processing occurs before the signal is perceived centrally. This could lead to "feedback," where the annoyance caused by the tinnitus causes the person to concentrate more on the noise, increasing the annoyance, and so a "vicious cycle" develops.

Tinnitus is the most common issue reported by the patient in audiology clinics. The etiology, perceptual qualities, and concomitant symptoms of tinnitus vary clinically. Different symptoms including frustration, annoyance, impatience, anxiety, sadness, hearing problems, hyperacusis, insomnia, and concentration problems are described by the tinnitus sufferers which are crucial for figuring out the severity of the condition. Tinnitus is therefore a very common, potentially upsetting ailment with a wide range of symptoms that can burden patients and significantly lower their quality of life.

The association between hearing loss and tinnitus has been well documented in the literature, and people with hearing loss are more likely to experience tinnitus than those without it.[3] Even though hearing loss is the primary etiology of tinnitus, there are

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other reasons that can also lead to the condition. Health issues such as vascular illness, diabetes, hypertension, autoimmune diseases, and degenerative brain disorders, with or without concurrent hearing loss, are among the risk factors.[4]

The complicated phenomenon of central auditory processing is still not fully understood. Before information reaches the auditory cortex, signals from the ears go down both ipsilateral and contralateral routes and are processed in a number of locations.[5] Central auditory processing dysfunction refers to a difficulty with the central nervous system's ability to perceive and process auditory information. Central auditory processing disorder assessment can be done using verbal and nonverbal tests.[6] The dichotic test, interaural time difference, and interaural level difference can be used to study binaural processing, including binaural integration and interaction.

Dichotic consonant-vowel (CV) tests have provided intriguing data about central auditory processing and the paths involved.[6] Listeners with normal hearing can identify sound sources on the horizontal plane using the information carried by interaural time differences and interaural level differences.[7] It significantly contributes to producing high levels of speech recognition in challenging listening contexts, including cocktail parties.[3] The additional sound that tinnitus contributes could impair auditory processing at many stages of the auditory pathway, which could have a negative impact on auditory function.

The association between cognition and tinnitus has been widely explored in the literature. Cognitive functions require the capacity of attention, use of working memory, concentration, and information processing.[8] A cognitive system called working memory is used to temporarily store information that can later be accessed to complete tasks that are external to the brain.[9] Given the limited brain resources available for working memory and the fact that suppressing tinnitus consumes neuronal resources that could have been used to store information, it is thought that tinnitus negatively affects working memory ability.[10]

There have been reports linking tinnitus to attention issues.[11] This is corroborated by behavioral studies that show adult tinnitus sufferers perform worse on activities requiring attention or working memory.[10] Due to the high prevalence of hearing loss in individuals with tinnitus, it is vital to take this into account while researching the relationship between tinnitus and cognitive function.[12] Studies on central auditory processing in individuals with tinnitus who have normal hearing sensitivity are limited.

The main objective of our study is to analyze cortical processing, mainly binaural interaction, and integration, in the individual with tinnitus having normal hearing. The relationship between working memory capacity and tinnitus is still debated in the literature due to ineffective management of the co-occurring condition. To address this issue, our study also aims to evaluate the working memory capacity of individuals with tinnitus controlling the effect of hearing sensitivity. Such controlled research is required to create evidence-based interventions targeting cognitive challenges in tinnitus individuals.

METHODS

Ethical approval for the study was obtained from the Mysore University Institutional Review Board of All India Institute of Speech and Hearing and the approval number was SH/ERB/2022-22/34. Before including any individuals in the study, their informed consent was obtained. The participants who denied being subjects were excluded from the study.

The patients visiting the tertiary care center with the chief complaint of tinnitus were taken for the study and comparison was made with the healthy control group. The adult participants having tinnitus for at least 6 months without any complaints of hearing problems were included in the study. The patients above 50 years were excluded from the study to minimize the aging effect on auditory processing test results. Similarly, literate participants with minimum qualification of school-level education were included in the study to minimize the effect of task complexity.

The tinnitus group consisted of 20 adult participants with tinnitus either in one ear or both ears. Among 20 participants included in the tinnitus group, 3 (15%) were female, and 17 (85%) were male. The mean age of the participants was 35.7 (SD = 8.9) years. The control group consisted of 20 healthy subjects (mean age = 30, SD = 10.7) with no tinnitus, hearing loss, and ear/health problems. The sample size used in the study was based on the G*power analysis[13] derived from the effect size in the previous study[14] on the 4 psychoacoustic measures in normal hearing individuals with and without tinnitus. For an effect size of 0.32,[14] and power of 0.51 at significance level (*P*) of .05, the sample size required was 42. Thus, the study sample 40 (20 with tinnitus and 20 without tinnitus) was considered appropriate for the study. The test procedure comprised audiological evaluation, tinnitus assessment using tinnitus handicap inventory,[15] central auditory test batteries, and tests for working memory as described below.

Audiological Evaluation

Before recruiting for the study, otoscopic examination was done for all the participants to make sure that the ear is free of any active external and middle ear diseases. Further, audiological evaluation comprises pure tone audiometry and tympanometry. All participants' hearing threshold was determined for all frequencies from 250 Hz to 8000 Hz (air conduction) and from 250 Hz to 4000 Hz (bone conduction) in the sound-treated room using American National Standards Institute guidelines.[16] An average air conduction value of 25 dB HL or less was taken as the criteria for normal hearing. Tympanometry was done using 226 Hz probe tone. The standard criteria were the middle ear pressure ranging from +60 to −100 daPa and compliance from 0.5 to 1.75 mL.[17]

Tinnitus Severity Evaluation

The Kannada version of the Tinnitus Handicap Inventory (THI) developed by Zacharia et al. (2012) was administered to determine tinnitus severity.[18] Patients were asked questions from the questionnaire and given a score of 0 for no response, 2 for sometimes response, and 4 for yes response. The patient with a THI score of 0-16 is classified as slight, 18-36 as mild, 38-56 as moderate, 58-76 as severe, and 78-100 as catastrophic tinnitus.

Psychoacoustic Tests

The pitch and loudness matching of the tinnitus was done in all the subjects using the standardized method. All the subjects were instructed about the test procedure. Using the audiometer as the source, sounds similar to the patient's description were presented over the headphone. Pitch matching was done using the one-third octave rule from the frequency range of 0.25-12.5 kHz at the 10 dBSL. The patients were asked to raise their fingers when they heard a sound similar to their tinnitus. After the pitch matching, loudness matching was done at that particular frequency, raising/lowering the tone level on and above the threshold. The patients were instructed to raise their fingers when the signal's loudness matches their tinnitus loudness level.

Auditory Processing Evaluation

The evaluation of binaural processing, including binaural interaction and binaural integration, was done. The binaural interaction process was evaluated using the Interaural Time Difference (ITD) and Interaural Level Difference (ILD) test, and binaural integration was assessed using the dichotic CV test. Before administering each test, patients were familiar with the test process and material and instructed about the complexity of the test process.

Interaural time difference was done using the MATLAB version R2014a (MathWorks). Noise discrimination was used as the stimuli. Three alternate choice methods were used as the testing method with the three-down one-up staircase option. The starting level used was 3, with a standard level of –30. The number of reversals used was 5 with a factor of 2. The reversal for the threshold was set to 2.

Interaural level difference was done using noise as the stimuli. Three alternate choice methods were used as the testing method with the three-down one-up staircase option. The starting level was set to 0 with a standard level of –30. The number of reversals used was 5 with a factor of 1. The reversal for the threshold was set to 2.

A dichotic CV test was used to assess the binaural integration. The test was administered in a soundproof room using good quality circumaural HDA 200 headphones with stereo presentation features, a laptop, and standardized dichotic CV material developed for the Indian population. Dichotic CV material consists of 30 bisyllabic stimuli presented simultaneously to both ears, with the stimuli presented to both ears being different. Double correct score, right ear single correct score, left ear single correct score, and right ear advantage were calculated for all the participants.

Working Memory Evaluation

Working memory was assessed using Smrithi Shravan software.[19] The 2N-back test and descending span audio test were used in all the participants to assess their working memory. To make familiarization with the testing, a practice stimulus was given, followed by testing stimuli. The testing parameter used for descending span test was the visual stimulus display time of 3000 ms, the interstimulus interval of 1000 ms, and 8 reversals with a response time of 5000 ms. The maximum score, along with the midpoint score, was calculated for all 40 participants.

The testing parameters for the 2N-Back test were the visual stimulus display time of 3000 ms, the interstimulus interval of 1000 ms, 3 numbers of reversal, and 20 trials with a response time of 5000 ms. The maximum number of stimuli correctly memorized was calculated for all the participants.

Statistical Analysis

The Statistical Package for Social Sciences Version 25.0. (IBM SPSS Corp.; Armonk, NY, USA) was used for the data analysis. To confirm the data's normality, the Shapiro–Wilk test was conducted. Nonparametric Mann–Whitney *U* test was done to determine the significant differences between the tinnitus and control groups. As a standard for statistical significance, a *P*-value of .05 or less was used.

RESULTS

Audiological Evaluation

For all the participants included in the study, otoscopic examination showed a normal appearance of the external and middle ear. For the tinnitus group, the average threshold of all the participants for air conduction was 7.97 dB HL (SD = 5.38) and 7.08 dB HL (SD = 4.92) for the right and left ear, respectively. Similarly, for the control group, it was 5.84 dB HL (SD = 2.99) and 4.97 dB HL (SD = 3.2) for the right and left ear, respectively. No statistically significant difference was found in the air conduction threshold between the tinnitus and control group.

Tympanometry results showed the presence of an "A" type tympanogram in both ears in almost all the tinnitus and control group participants except 2 participants who showed "As" tympanogram in both ears. As 2 participants who had "As" tympanogram with low static admittance did not have any symptoms of external and middle ear pathologies with a normal audiogram, all the 40 participants were included in the study.

Tinnitus Characteristics

The participants included in the study had chronic tinnitus for 2.7 (SD = 1.3) years with a variation from 1 year to 5 years. Among 20 participants, 4 (20%) had bilateral tinnitus, 4 (20%) had tinnitus in the left ear, and 12 (60%) had tinnitus in the right ear. The result of the THI showed the presence of mild tinnitus with an average score of 28.6 (SD = 4.81) for the 10(50%) participants and a moderate level of tinnitus for the 10 participants (50%) with the mean score of 43.4 (SD = 4.99). During the matching procedure, 16 (80%) patients matched their tinnitus to the tone, 2 (10%) patients matched their tinnitus to the noise, and 2 (10%) patients could not match their tinnitus to the sounds presented through audiometer. The matched frequency of all the patients ranged from 2 kHz to 10 kHz with an overage of 5.5 kHz (SD = 2.46). The matched loudness ranged from 10 dB SL to 30 dB SL with an average of 20.75 dB SL (SD = 6.74). The 4 patients who had bilateral tinnitus matched the same frequency of tinnitus and loudness level in both ears. The detailed audiological evaluation results and tinnitus characteristics of all the subjects are illustrated in Table 1.

Binaural Interaction in Tinnitus and Control Group

The result of the interaural level difference and the interaural time difference was analyzed among the tinnitus and control groups to see the binaural interaction abilities. The mean value of ITD and ILD was found to be higher in the tinnitus group than control group. The

Table 1. Descriptive Characteristics of All the Subjects Included in the Study (n = 40)

Tinnitus Group							Control Group	
S.N	PTA Threshold		Laterality of Tinnitus	THI Score	Matched Frequency (KHz)	Matched Loudness (dB SL)	PTA Threshold	
	Right (dB HL)	Left (dB HL)					Right (dB HL)	Left (dB HL)
1	22.5	8.75	Right	20	3	10	0	0
2	15	11.25	Left	42	6	30	10	6.5
3	6.67	0	Right	34	4	25	6.67	0
4	6.25	10	Right	56	8	10	6.25	10
5	2.5	1.25	Right	44	10	20	2.5	1.25
6	1.25	6.25	Right	36	8	20	1.25	3.25
7	5	7.5	Right	28	6	20	5	7.5
8	7.5	6.67	Bilateral	42	4	30	7.5	6
9	16.25	6	Left	28	3	25	10	6
10	3.75	0	Right	38	3	15	3.75	0
11	5	6.67	Bilateral	44	4	10	5	6.67
12	11.25	20	Right	28	6	20	8.75	10
13	11.25	10	Bilateral	34	4	20	8.75	5
14	7.5	5	Right	26	4	15	7.5	5
15	11.25	0	Left	26	8	25	7.5	0
16	7.5	6	Right	38	10	30	7.5	6
17	6.67	6.75	Bilateral	44	6	30	6.67	6.75
18	6	7.75	Right	42	2	25	6	7.75
19	6.25	15	Left	26	3	15	6.25	5
20	0	6.67	Right	44	8	20	0	6.67

PTA, Pure Tone Audiometry

Mann–Whitney *U* test result showed a significant difference in the ILD among the 2 groups ($U = 49.0$, $P = .00$, $r = -0.65$). However, interaural time difference comparisons between the group did not show any significant difference ($U = 163.0$, $P = .316$, $r = -0.16$). The results of the ITD and ILD test for the tinnitus and control group are shown in Table 2.

Binaural Integration in Tinnitus and Non-tinnitus Group

The result of the dichotic CV test was analyzed to see integration abilities among the tinnitus and control group. The mean value of right ear single correct score, left ear single correct score, and double correct score is found to be lower in the tinnitus group in comparison to control group. The detailed result of dichotic CV tests is illustrated graphically in Figure 1.

Mann–Whitney *U* test showed a significant difference in the right ear single correct score ($U = 41.0$, $P = .00$, $r = -0.68$), left ear single correct score ($U = 103.5$, $P = .009$, $r = -0.41$), and double correct score ($U = 31.0$, $P = .00$, $r = -0.73$) between the 2 groups with the mean score of control group being better than tinnitus group. The detailed result of the Mann–Whitney *U* test is illustrated in Table 3.

Table 2. Comparison of ITD and ILD between Tinnitus and Control Group on Mann-Whitney *U* test

	Control Group		Tinnitus Group		Test Result (*Z*-Value)	*P*	*r*
	Mean	SD	Mean	SD			
ILD	4.193	1.34	6.58	1.31	−4.091	.00	−0.65
ITD	1.04	1.15	1.5	1.31	−1.002	.32	−0.16

Right Ear Advantage

The comparison of mean score of the tinnitus group and control group for the right ear and left ear showed the absence of right ear advantage in the tinnitus group. The left ear mean score was found to be higher than the right ear mean score in the tinnitus group. Results of Mann–Whitney *U* test showed the absence of right ear advantage in the tinnitus group with ($U = 110.5$, $P = .015$, $r = -0.38$). The detailed result of the right ear advantage is illustrated in Table 4.

Working Memory in Tinnitus and Control Group

The result of descending audio span test and 2N-Back audio span test were analyzed to compare the working memory capacity of the tinnitus group with the control group. The mean value of tinnitus group subjects was found to be poorer than the control group in all the working memory tests. The comparison of mean values of both groups in working memory tests is graphically illustrated in Figure 2.

The result of the Mann–Whitney *U* test showed poorer working memory capacity comparisons to the non-tinnitus group on the descending audio span test with the score of ($U = 35.0$, $P = .00$, $r = -0.71$) for midpoint score and ($U = 43.5$, $P = .00$, $r = -0.68$) for the maximum

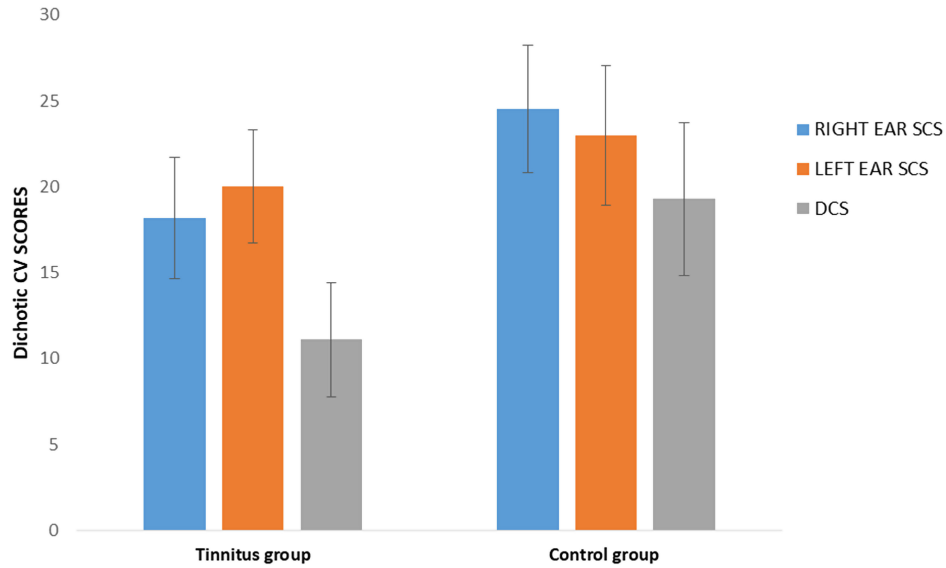

Figure 1. Comparison of dichotic CV test scores between tinnitus and control group.

score. Similarly, the 2N-Back audio span test also showed a statistically significant difference between the 22 groups ($U = 11.5$, $P = .00$, $r = -0.82$). The results of Mann–Whitney tests on the working memory tests are illustrated in Table 5.

DISCUSSION

Our study aimed to assess binaural interaction abilities in an individual with tinnitus and normal hearing using 2 nonverbal psychoacoustic test batteries (ITD and ILD). Our study showed that the binaural interaction abilities of tinnitus subjects are significantly different compared to the control group, even though they had normal hearing sensitivity. Interaural level difference results showed statistically significant differences among the tinnitus group and the control group ($P < .05$). This could be because tinnitus loudness could have masked the slight interaural intensity difference making the tinnitus subjects difficult for loudness judgment. However, there are no studies in the literature to support our findings as this is the first study of this kind, and there is a need to carry out a study in the future taking a larger sample size.

The interaural time difference did not show any significant difference between the tinnitus group and the control group, although there were differences in the mean value. The first reason for this could be phase difference being the cues of the interaural time differences, which did not get impaired due to tinnitus, and tinnitus loudness does not have any role in the ITD judgment. The second reason could be the presence of high-frequency tinnitus in our subjects who were taken for the study. The interaural time difference cues depend on the low frequencies, and ILD cues depend on the high frequencies. As none of the subjects included in our study had low-frequency tinnitus, this could be the reason for not getting a significant difference in the ITD test. However, this is the first study of this kind, and we need to replicate the findings in the future, taking a larger sample size.

Likewise, the study aimed to see integration abilities in individuals with tinnitus and normal hearing using the verbal dichotic CV tests. Dichotic CV assesses the right ear advantage, which describes the condition when linguistic stimuli presented in the right ear are detected better than in the left ear.[5] The result of the dichotic CV test showed a significant difference in the right ear score, left ear score, and double correct score among the tinnitus group and non-tinnitus group. The score of the tinnitus group was lower as compared to the control group in all the scoring ($P < .05$). These results showed impaired integration abilities in the tinnitus group compared to the control group suggesting impaired cortical functioning in the individual with tinnitus. The results of our study are in support of Raj-Koziak et al[14] who reported impaired dichotic listening abilities in an individual with tinnitus having normal hearing.[14]

The right ear advantage result showed an absence of right ear advantage in the tinnitus group with a better score in the left ear. However, the control group showed a significant right ear advantage. There was a significant difference in the mean value of the tinnitus and non-tinnitus groups with a P value less than .05. These results showed poorer cortical integration abilities in individuals with tinnitus supporting the findings of Raj-Koziak et al.[14]

Table 3. Result of Mann–Whitney *U* test for the Dichotic CV Test Score Between Tinnitus and Control Group

Mann–Whitney *U* test	*U*	Test Results (*Z*-Value)	*P*	*r*
Right ear SCS	41.0	−4.31	.00	−0.68
Left ear SCS	103.5	−2.63	.009	−0.41
DCS	31	−4.59	.00	−0.73

DCS, Double correct score; SCS, Single correct score

Table 4. Result of Mann–Whitney *U* Test Comparing Right Ear Advantage for Tinnitus Group and Control Group (n = 40)

	Tinnitus Group (n = 20)		Control Group (n = 20)		Test *z*-Score Value	*P*	*r*
	Mean	SD	Mean	SD			
Right ear advantage	−1.75	5.25	1.55	3.71	−2.430	.015	−0.38

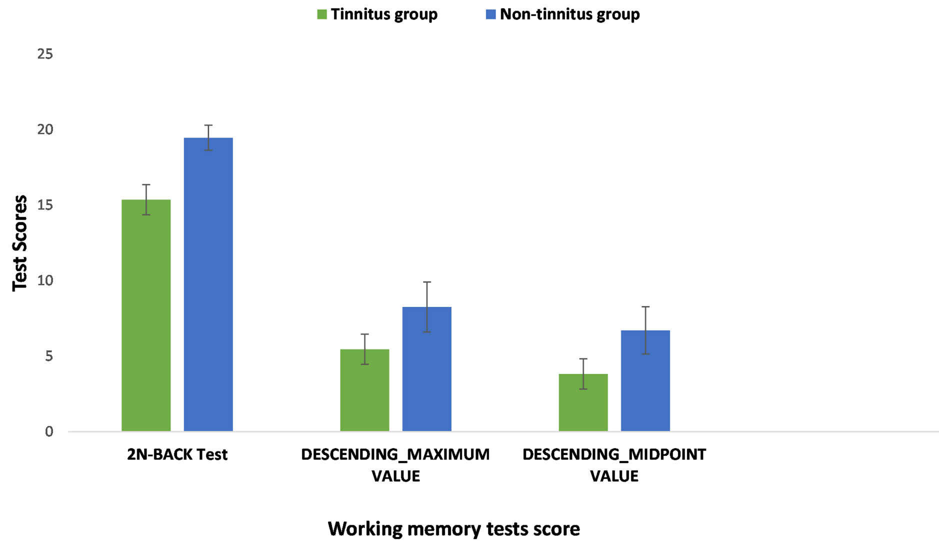

Figure 2. Comparison of working memory tests scores between tinnitus and control group.

In our study, 60% of participants have tinnitus in the right ear. Hence, we can hypothesize that the absence of the right ear advantage could be due to tinnitus in the right ear. However, we could not see the difference in the right ear advantage between the right ear tinnitus group and left ear tinnitus group due to our study's smaller sample with left ear tinnitus. These findings need to be validated in the future by comparing the subjects with right ear and left ear tinnitus.

The effect of tinnitus on working memory was assessed using the descending audio span test and 2N-back test and compared with the control group. The results showed that the scores of both tests significantly ($P < .05$) reduced in the tinnitus group compared to the control group. The possible reason for having reduced working memory in the tinnitus group could be the poor use of top-down processing skills. The main reason behind the poorer score is the attention and concentration to do the task effectively. Emotional distress, lack of motivation, hearing problems, listening problems, and fatigue are the possible reasons for concentration problems in an individual with tinnitus.[10] Also, in the tinnitus group, there might be an underlining high-frequency hearing loss that was not assessed in our study with conventional pure tone audiometry.

Various theories are presented by broader research on hearing loss and cognitive decline.[20] The cognitive load hypothesis is one of the most well known and contends that hearing loss results in a larger need of brain resources for speech understanding, leaving less available for performing other cognitive activities. Several authors have proposed that attention factors play a crucial role in moderating the adverse effects of tinnitus.[12,20] Andersson[21] (2009) performed a Stroop test on tinnitus subjects and reported poorer results in comparison to control group. The findings imply that any tinnitus-related effects on cognition are probably more selective and will show up in tasks requiring attention. When compared to people without annoyance, those with tinnitus, which is more frequently associated with annoyance, would score badly on the working memory task.[22] We can speculate that when tinnitus is unpleasant, the person may focus more on it, which ultimately impairs cognitive abilities. Tinnitus is a very diverse phenomenon; hence, this statement cannot be used broadly. Future research must compare the quality of tinnitus with cognitive function.

Limitations of the Study and Future Directions

Binaural processing ability in an individual with tinnitus may vary according to its severity. Our study could not see the binaural processing abilities according to tinnitus severity. Hence, there is a need to carry out research studies in the future, taking a larger sample size to compare the effect of tinnitus severity on binaural processing capabilities. In addition, our study could not assess high-frequency threshold of all the participants. Hence, in future, we need to assess for the presence of high-frequency hearing loss as well, which could be the additional factor impacting the score on the psychoacoustic tests.

The result of the working memory evaluation showed degraded working memory capacity in tinnitus sufferers. The effect of tinnitus severity on working memory capacity needs to be evaluated in the future.

Table 5. Result of the Mann–Whitney *U* Test Comparing the Descending Span Audio Test and 2N-Back Test Scores Between the Tinnitus and the Control Group

	Tinnitus Group		Control Group		Test Results (*Z*-Value)	*P*	*r*
	Mean	SD	Mean	SD			
Descending span audio test (midpoint score)	3.82	1.53	6.71	1.56	−4.47	.00	−0.71
Descending span audio test (maximum score)	5.45	1.54	8.25	1.65	−4.31	.00	−0.68
2N-Back test	15.35	2.35	19.45	0.83	−5.22	.00	−0.82

CONCLUSION

The result of the binaural processing test showed that tinnitus suffers a deficit in both the brainstem and cortical auditory processing. This type of processing deficit may affect speech perception abilities. This study will serve as the baseline to explore the cortical functioning of tinnitus sufferers clinically. In addition, the result of our study motivates the clinician to develop assessment protocols including binaural processing and working memory measures for the individual with tinnitus.

Data Availability Statement: The datasets analyzed during the current study are available from the corresponding author on reasonable request.

Ethics Committee Approval: This study was approved by Ethics Committee of Mysore University (Approval No: SH/ERB/2022-22/34, Date: 03/03/2022).

Informed Consent: Written informed consent was obtained from the patients who agreed to take part in the study.

Peer-review: Externally peer-reviewed.

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