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Article

Three-alternative forced-choice method (3AFC) for tinnitus matching and digital frequency customized relieving sound (DFCRS) generation strategy for tinnitus management

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Abstract: Tinnitus is the perception of sounds without any corresponding external stimulus exists, and it is one of the most common hearing disorders. Currently, there are no objective tests for tinnitus, and thus its detection relies on the subjective reports of patients. Here, we introduce a novel three-alternative forced-choice method (3AFC) for tinnitus pitch and loudness matching. Then, we modulate the soothing music by increasing the sound intensity of two 1/3 octave bands above and below the tinnitus frequency according to a specific algorithm to generate digital frequency customized relieving sound (DFCRS) for tinnitus management. Due to the relatively large frequency interval and more frequency characteristics, the 3AFC method can significantly shorten the time required for psychoacoustic measures of tinnitus and improve the efficiency and satisfaction of subjective tinnitus tests. Based on the matched tinnitus frequency, we created a personalized treatment plan for tinnitus patients using real-time modulation of soft music. We recruited total 32 participants who listened to the modulated music (DFCRS) or the unmodulated music (served as control) for at least 2 h a day for three months, following brief instructions from audiologists. Of these, the participants who received DFCRS experienced more reduced negative impacts of tinnitus and an improved quality of life compared to those in the control group, as measured by various scales. Our patented system seamlessly integrates tinnitus assessment and treatment, offering substantial savings in medical and audiological expenses.

Keywords: tinnitus; pitch matching; loudness matching; three-alternative forced-choice method (3AFC); digital frequency customized relieving sound (DFCRS)

1. Introduction

The human ear can hear sounds in response to external sound stimuli or to internal stimuli. The external ear collects sound, the middle ear transmits and amplifies it, and the inner ear's hair cells transduce the mechanical sound stimulus into electrical nerve signals, which are then transmitted to the cerebral cortex for information processing. Therefore, the perception of sound depends on hair cells, with different sound frequencies corresponding to specific populations of hair cells and neurons [1]. When hair cells associated with a particular frequency are damaged, the auditory center losses signal input for that frequency, resulting in hearing loss at that frequency. A widely accepted hypothesis suggests that in such cases, the auditory nervous system remodels itself to create new neuron connections corresponding to the damaged frequency and nearby frequencies [2,3]. Neighboring neurons to the damaged cells become hyperactive and exhibit synchronous burst firing [4,5], which activates adjacent neurons in turn, thus resulting in tinnitus [6]. The core of tinnitus diagnosis is detection, where the acoustic characteristics of tinnitus are used to create a "characteristic" diagnosis for each tinnitus patient, forming the basis for tinnitus sound therapy [7]. Tinnitus detection mainly involves the following psychoacoustic properties, including pitch (frequency), loudness, minimum masking level, and residual inhibition [7–9]. The key for tinnitus frequency and loudness assessment is to establish a method for fast, efficient, and accurate tinnitus matching.

At present, there are two main methods for tinnitus matching. The first is the "likeness rating method" [10–12], which tests the audiometric frequencies sequentially based on pure tone audiometry. This method rates the similarity of sounds to tinnitus, identifies the frequency closest to tinnitus as the pitch of tinnitus, and adjusts the intensity to match the tinnitus loudness. The second is the "binary method" [13], which involves three steps. The first step is to test the hearing threshold, including every 1/3 octave frequencies from 500 Hz to 16,000 Hz. The second step is to match the loudness of tinnitus [14]. The third step is to match the frequency of tinnitus by presenting two pure tones of simultaneously and asking patients to choose the one closer to their tinnitus frequency [13]. Finally, the patient performs an octave confusion test to confirm their choices. The "likeness rating method "is time-consuming due to continuous attempts to identify the final frequency [15]. According to the Fletcher Munson Curve, also known as the equal-loudness-level contour graph [16], the human ear's perception of pure tones varies across different frequencies. For example, lower frequencies need to be louder to be perceived as equally loud for frequencies below 1 kHz, and the ear's sensitivity to volume is slightly reduced between 1 kHz and 2 kHz. The range between 2 kHz and 5 kHz is where the human ear is most sensitive, especially at lower volumes compared to higher volumes. For frequencies above 6 kHz, sensitivity gradually decreases, but volume has a greater impact on the ear's sensitivity to low frequencies than to those above 5 kHz. It demonstrates that human hearing sensitivity varies across frequencies, further complicating tinnitus matching. This variation impacts the reliability of this method. Meanwhile, the "binary method" selects from the two given frequencies each time, and if a higher frequency is selected, the tinnitus frequency will be limited to the range above the higher frequency, while if the lower frequency is selected the tinnitus frequency will be limited to the range below the lower frequency. In order to reduce the possibility of the tinnitus frequency being out of the range of the tested frequencies, the interval between the two provided frequencies at each test should not be too large, which indirectly limits the change step size resulting in low matching efficiency. In addition, each selection will divide the tinnitus frequency range to 1/2 of the current frequency range, which leads to the potential error of the tinnitus frequency being divided into the wrong frequency range where it cannot be corrected. Therefore, the "binary method" is less fault tolerant than the likeness rating method.

Current therapies mainly include tinnitus sound therapy [17], tinnitus retraining therapy [18], tinnitus activities treatment [19–21], and a series of new forms of sound stimulation. Traditional tinnitus sound therapy mainly referred to masking, which uses white noise to achieve complete masking of tinnitus. However, some patients find it irritating and intolerable to listen to white noise or narrowband noise played to mask louder tinnitus, making it difficult for all patients to persist with such treatment. Masking is especially challenging for patients with high-frequency tinnitus due to agerelated or noise-induced hearing loss, as higher volumes needed for masking may worsen hearing loss or tinnitus [22]. A recent study has shown that sound therapy alone can benefit some patients without professional counseling [23]. Tinnitus retraining therapy involves the selection of natural sounds such as wind, running water, and bird calls according to the patient's preferences, trying to "replace" the tinnitus with a natural sound so that the patient can adapt or become accustomed to the tinnitus [24]. However, it uses "directive" not collaborative counseling, and focuses on the mixing point, which is often too loud to be pleasant [25], and such treatment will not make the tinnitus lessen or disappear [26]. For marketing purposes people have modified TRT, making it more like strategies that existed before TRT [27,28]. New forms of sound stimulation methods, such as tailor-made notched music therapy [29,30], neuromonics music therapy [31,32], acoustic coordinated reset neuromodulation [33,34], hearing aids [35,36], and cochlear implants [37,38], show promise but require further refinement. Tinnitus activities treatment, which combines CBT, mindfulness and acceptance and is widely used worldwide. Tinnitus activities treatment treats the four primary functions affected by tinnitus: 1) Thoughts and emotions, 2) Hearing, 3) Sleep and 4) concentration. The Psychological Model, proposed by Tyler, Aran and Dauman [39], suggested that the overall annoyance of the tinnitus was a result of the 1) tinnitus characteristics and the 2) psychological make up of each individual patient. Several parts of the brain will be involved in the representation of the tinnitus and of the reactions to the tinnitus. Treatments can be focused on reducing the tinnitus (e.g., pills) or on reducing the reactions to the tinnitus (e.g., Counseling) [40,41]. However, some tinnitus treatments involve detecting the frequency and loudness of tinnitus through a set of instruments and then, based on the test results, treating the tinnitus by other devices, which causes great inconvenience in tinnitus treatment. Thus, the existing tinnitus treatment methods are difficult to perform and do not usually have a satisfactory effect on tinnitus. There are many categories of mechanisms of tinnitus, and Preece et al. had grouped them into 3–4 broad categories: 1) deafferentation and central changes, 2) increase in spontaneous activity, and 3) increase in cross fiber correlation [42]. According to the principle of lateral inhibition, modulating music in specific frequency bands can stimulate neurons adjacent to those in the tinnitus area, suppressing their hyperactivity and thus reducing or even eliminating tinnitus perception.

Given the limitations of existing methods, this study proposes a novel tinnitus matching method and a therapeutic music generation method. Tinnitus patients tend to prioritize the frequency of their tinnitus over loudness. Matching loudness first may lead to rejection of the test sounds, hindering treatment. Therefore, our method begins with matching tinnitus frequencies, and tests for both tinnitus frequency and loudness are performed separately for the left and right ears. This approach aims to address the inefficiencies and error-prone nature of existing techniques while enabling integration of tinnitus detection and treatment.

2. Methods

The main flow of our work is shown in **Figure 1**.

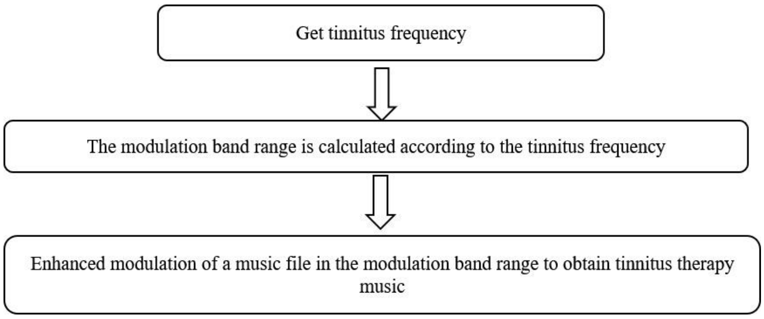

Figure 1. Method flow chart.

2.1. Pure-tone hearing threshold test

Tinnitus is the supra-threshold perception of sound, and its frequency is closely related to the frequency band of hearing threshold elevation [43–45]. Therefore, pure-tone audiometry of both ears is a fundamental measurement that must be conducted prior to all other tests [46,47]. Pure-tone air conduction for both ears will be measured between 0.25 and 8 kHz (0.25, 0.5, 1, 2, 4, and 8 kHz). A standard Hughson-Westlake procedure (steps: 10 dB down, 5 dB up; 2 out of 3) is used to determine hearing thresholds.

2.2. The three-alternative forced-choice method (3AFC) for tinnitus pitch matching

The test sounds during tinnitus matching are delivered to the ear opposite to the tinnitus-perception ear, that is, if the tinnitus is in the left ear, a pure tone is played to the right ear, allowing the patient to compare the pure tone's frequency with the tinnitus perceived in the left ear. If the tinnitus is perceived bilaterally or within the brain, the ear with better hearing is chosen as the test ear. We use a computer-automated 3AFC method for tinnitus pitch matching, and the process of matching tinnitus frequencies is shown in **Figure 2**.

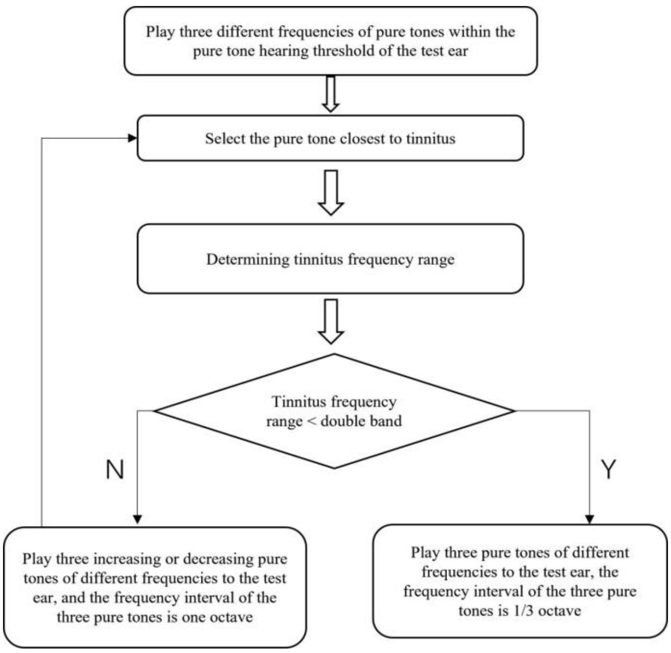

Figure 2. The 3AFC matching process.

We first play three different pure tones (namely Fa, Fb, Fc) in the patient's test ear. All three tones are within the pure tone hearing threshold of the test ear, and the three pure tones are presented in ascending order of frequency, from low to high. The test frequencies range from 125 Hz to 16,000 Hz, with an interval of one octave between two adjacent pure tones. The test frequency is played at 10–20 dB above the threshold for 500 ms while the adjacent pure tones are played with a 1-second interval between adjacent tones. The subjects are then asked to compare the three pure tones and are forced to select one that is closest to the pitch of their perceived tinnitus after each of the three sounds is played. If Fa is chosen, the range of the next three pure tones is limited below Fb, i.e., the upper limit of the tinnitus frequency is 1/3 octave lower than Fb. If Fb is chosen, the range of the next three pure tones are limited between Fa and Fc, i.e., the upper limit of the tinnitus frequency is 1/3 octave lower than Fc, and the lower limit of the tinnitus frequency is 1/3 octave higher than Fa. If Fc is chosen, the range of the next three pure tones is limited above Fb, i.e., the lower limit of the tinnitus frequency is 1/3 octave above Fb. We repeat the process until the range of the tinnitus frequency is narrowed to no more than two octaves, and we continue to play three pure tones at an interval of 1/3 octave following the 3AFC manner. The final frequency chosen after the octave confusion test is recorded as the tinnitus pitch (**Figure 2**).

An illustration of 3AFC for tinnitus pitch matching is shown in **Figure 3**. In the example, the initial three frequencies are Fa = 2000 Hz, Fb = 4000 Hz, and Fc = 8000 Hz. The 1/3 octave frequency points between 2000 Hz and 4000 Hz are 2520 Hz and 3180 Hz; the 1/3 octave frequency points between 4000 Hz and 8000 Hz are 5040 Hz and 6340 Hz; and so on. If 2000 Hz is selected, the range of the next three pure tones is restricted to below 4000 Hz, i.e., the upper limit of tinnitus frequency is 3180 Hz. If 4000 Hz is chosen, the range of the next three pure tones is limited between 2000 Hz and 8000 Hz, i.e., the upper limit of tinnitus frequency is 6340 Hz, and the lower limit of tinnitus frequency is 2520 Hz. If 8000 Hz is chosen, the range of the next three pure tones is limited above 4000 Hz, i.e., the lower limit of tinnitus frequency is 5040 Hz. We then repeat the above process until the tinnitus frequency range is narrowed to within two octaves.

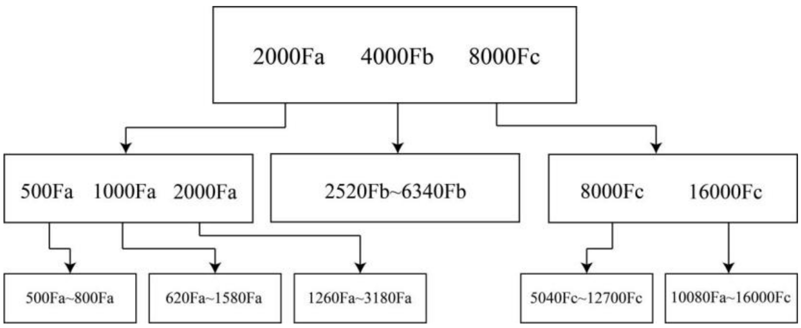

Figure 3. Tinnitus frequency selection flowchart.

2.3. The 3AFC method for tinnitus loudness matching

Tinnitus loudness matching is conducted after tinnitus pitch matching. First, three pure tones at the tinnitus frequency are played to the test ear at different sound intensities. The sound intensity interval between two adjacent pure tones is denoted as

"*D*" ($D \geq 1$ dB), with an initial value of *D* typically set to 5 dB. Each pure tone is played three times to facilitate patient selection, with adjacent pure tones presented in sequence at intervals. The duration of each pure tone is 500 ms, and the interval between tones is 1 s.

Next, patients are asked to select one from the three tones that most closely matches the intensity of their perceived tinnitus. If $D = 1$ dB, the selected tone's intensity is recorded as the loudness matching value of the test ear. However, since individual pure tone hearing threshold vary, the selected intensity cannot be directly used as the test ear's tinnitus intensity for calibration and comparison. The final loudness of tinnitus is recorded as the sensation level, calculated as the loudness matching value of the test ear minus the pure tone hearing threshold at the tinnitus pitch for the same ear. If *D* is greater than 1 dB, the selected pure tone becomes the new middle tone in the next run, and the first and third pure tones are reselected based on a reduced intensity interval of $D-1$. This process is repeated until *D* decreases to 1 dB.

2.4. Calculation of the modulated frequency range

The modulation band range refers to one or more frequency bands adjacent to the tinnitus frequency. To determine this range, the 1-octave upper and lower endpoints of the frequency centered on the tinnitus frequency are first identified. As shown in **Figure 4**, where *A* denotes the energy value of the music file before the enhancement modulation, the energy of the tinnitus treatment music is increased to $A + 10$ dB within the first and second frequency bands. This enhancement allows the treatment music to effectively inhibit the activity of adjacent neurons in the tinnitus region. The frequency of tinnitus is recorded as F_t, while the lower and upper endpoints of the 1-octave range centered on F_t are denoted as F_l and F_u, respectively. The formula transformation between F_t, F_l, and F_u is as follows.

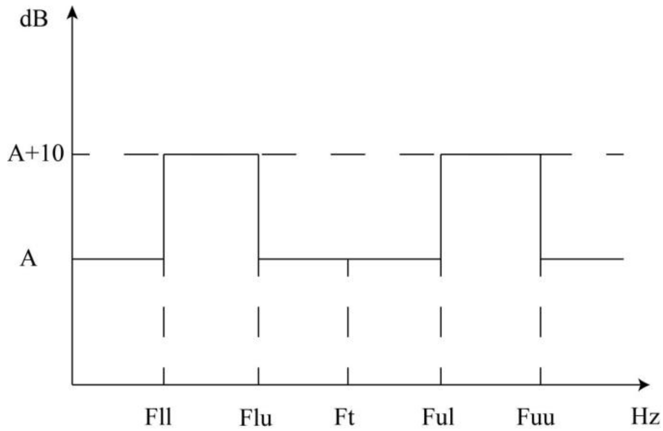

Figure 4. Intensities corresponding to different frequencies of the acoustic therapy modulation methods.

$$F_u = 2F_l \tag{1}$$

$$F_u \times F_l = F_t^2 \tag{2}$$

These can be solved to give $F_u = \sqrt{2}F_t$ and $F_l = \frac{F_t}{\sqrt{2}}$. Next, we determine the upper end and the lower end of the 1/*N* octave with F_u as the center frequency in order to obtain the first modulated frequency band, where *N* is a positive integer.

According to the definition of the 1/*N* octave, the upper (F_{uu}) and lower (F_{ul}) end points of the 1/*N* octave centered at F_u are:

$$F_{uu} = (2^{\frac{1}{N}})^{\frac{1}{2}} \times F_u \tag{3}$$

$$F_{ul} = (2^{\frac{1}{N}})^{-\frac{1}{2}} \times Fu \tag{4}$$

The first modulated frequency range is therefore $[F_{ul},\ F_{uu}]$.

Similarly, we determine the upper end and the lower end of the 1/*N* octave with F_l as the center frequency in order to obtain the second modulated frequency band, where *N* is a positive integer. The upper (F_{lu}) and lower (F_{ll}) end points of the 1/*N* octave centered at F_l are:

$$F_{lu} = (2^{\frac{1}{N}})^{\frac{1}{2}} \times F_l \tag{5}$$

$$F_{ll} = (2^{\frac{1}{N}})^{-\frac{1}{2}} \times F_l \tag{6}$$

The second modulated frequency range is therefore $[F_{ll},\ F_{lu}]$.

If we take *N* = 3, then the first frequency band range is about [1.26 × F_t, 1.59 × F_t] and the second frequency band range is about [0.63 × F_t, 0.79 × F_t]. Considering the human ear's ability to discriminate sound, using 1/3 of an octave as the first and second frequency bands can accurately determine the adjacent frequency bands of the tinnitus band.

2.5. Generation of the digital frequency customized relieving sound

The dynamically enhanced intensity of music is generated as follows. First, the frequency components of the music file that lie within the modulation band range are enhanced, while those outside this range remain unchanged. Priority is given to enhancing the frequency components within the modulation band by 5~10 dB, as shown in **Figure 4**, which depicts the correspondence between the energy and frequency of the tinnitus treatment music. Next, the sound channel of the music file is enhanced and modulated according to the patients' tinnitus frequency. The volume of the tinnitus treatment music is then adjusted based on the tinnitus loudness matching, ensuring it is set to match or slightly exceed the patients' tinnitus loudness. This approach allows the tinnitus treatment music to suppress the tinnitus perception without damaging the patient's hearing. Because the frequency and intensity of pure music naturally fluctuate over time, the enhanced and modulated tinnitus treatment music also constantly changes in frequency and intensity, staying centered around the tinnitus frequency and its adjacent areas. To maximize therapeutic effect, soothing and peaceful pure music files are selected. The rhythmic variability and pleasing melodies of the music not only enhance its effectiveness but also help alleviate negative emotions such as irritability and anxiety commonly experienced by tinnitus patients.

2.6. Outcome measures

The outcome measures were the change scores of Tinnitus Handicap Inventory (THI), Hospital Anxiety and Depression Scale (HADS) consisting subscale for anxiety and depress (HADS-A and HADS-D, respectively), Athens Insomnia Scale (AIS), and Visual Analog Scale (VAS).

2.7. Statistical analysis

Data were statistically analyzed based on the scores from various scales at baseline and after 3 months of treatment. For data with homogeneity of variance, two-sample *t*-test was used, whereas Welch's *t*-test was applied for data without homogeneity of variance. A *p*-value of < 0.05 was considered statistically significant. All statistical analyses were performed using GraphPad Prism (version 8.0.2) software.

3. Results

The tinnitus treatment music generated by the method described in this paper was applied to the tinnitus patients in the experimental group, while the unmodulated music file was used for the control group. We recruited a total of 32 participants, including 17 females and 15 males, with ages ranging from 11 to 67 years old. The duration of tinnitus ranged from 1 month to 120 months. Among the participants, 14 were randomly assigned to the control group, while 18 were assigned to the experimental group.

As shown in **Figure 5**, T0 represented the baseline score before treatment, T1 represented the score after 3 months of treatment, and T1–T0 denoted the change in the scale score, calculated as the score after 3 months of treatment minus the baseline score. A *p*-value of < 0.05 was considered statistically significant.

The results for the THI scale, shown in **Figure 5a**, showed the impact of the tinnitus treatment on the patient's emotional and psychological well-being, as well as their quality of life. Higher THI scores indicated a greater negative impact of tinnitus on the patient. A great reduction in the THI score indicated a significant improvement in the patients' condition.

The results for the AIS scale, shown in **Figure 5b**, demonstrated the effect of the tinnitus treatment on the patient's sleep. Higher AIS scores indicated a greater impact on the patient's sleep, and the significant reduction of T1-T0 score proved an enhancement of patients' sleep quality.

The VAS scale was used to reflect the subjective assessment of tinnitus loudness, with scores ranging from 0 to 10. A score of 0 indicated the absence of tinnitus, while a score of 10 indicating extremely loud and unbearable tinnitus. As shown in **Figure 5c**, the change in the VAS score for tinnitus loudness decreased after treatment, which indicated significant efficacy in reducing tinnitus loudness.

The results for the HADS-A and HADS-D, shown in **Figure 5d** and **Figure 5e** respectively, reflected the improvement of anxiety and depression related to tinnitus. Higher scale values indicated greater perceived negative emotions associated with tinnitus, while lower values were the opposite. A greater change in the value indicating better efficacy against tinnitus.

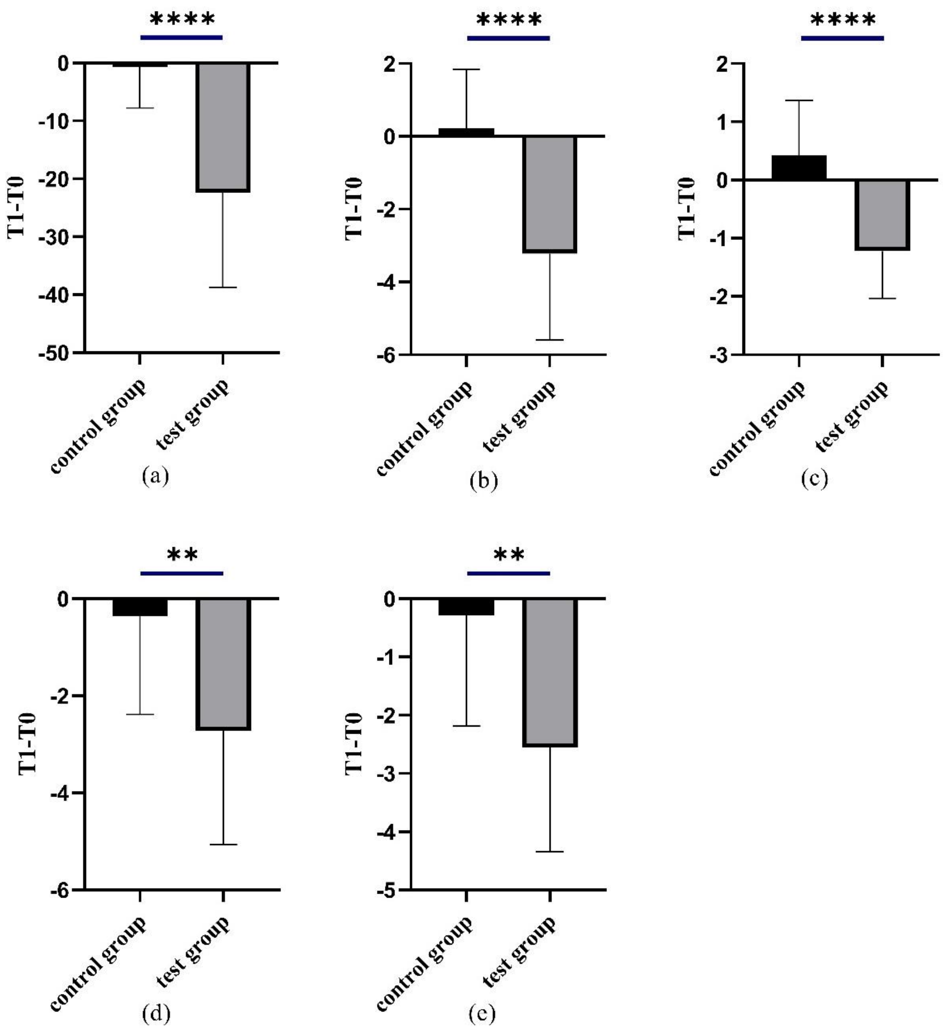

Figure 5. (a) Changes in the THI scale; **(b)** Changes in the AIS; **(c)** Tinnitus loudness changes according to the VAS; **(d)** Changes in the HADS-A; **(e)** Changes in the HADS-D.

Note: *, $p < 0.05$; **, $p < 0.01$; and ****, $p < 0.0001$.

Comparisons of the corresponding scales between the control and experimental groups revealed that the tinnitus treatment music generated using the method described in this paper was effective in reducing tinnitus loudness, alleviating negative emotions, and improving sleep quality in tinnitus patients.

4. Discussion and conclusion

Some tinnitus detection techniques prioritize matching tinnitus loudness before attempting to match the tinnitus frequency [7,48,49]. However, this approach does not align well with the patient's psychology behind seeking treatment. A recent article provided a new perspective on how tinnitus affects someone's life through a new quality-of-life scale that emphasizing the consequences of tinnitus and hearing loss [50].

The 3AFC method improves the frequency interval between the pure tones selected for playback, increases the testing range to two octaves, and significantly reduces the test time. Moreover, as shown in **Figure 3**, this method offers two paths to identify the 1/3 octave point between the frequencies of each two pure tones. This dual-path approach improves fault tolerance and minimizes the risk of missing the tinnitus frequency, which may occur with the binary method if the tinnitus frequency falls between two test tones.

The tinnitus detection method described here greatly reduces the tinnitus matching time, increases fault tolerance, and reduces the possibility of missing the tinnitus frequency compared to existing techniques. The modulated frequency bands correspond to adjacent brain areas in the tinnitus region, thus enabling the tinnitus treatment music to target abnormally overactive neurons in these areas caused by auditory deprivation. Our acoustic therapy strategy generates personalized tinnitus treatment music customized to each patient's specific tinnitus frequencies, thus enabling personalized treatment for patients. The use of soothing pure music not only helps to suppress tinnitus but also provides emotional relief to the patient. The volume of the treatment music is adjusted to match or slightly exceed the loudness of the tinnitus, effectively suppressing the tinnitus sound without causing hearing damage. In summary, our method addresses the limitations of the prior art and is likely to be highly useful in the clinic.

Author contributions: Conceptualization, DT and SS; methodology, DT, KW and SS; writing—original draft preparation, DT, KW and SS; writing—review and editing, SS and DT; funding acquisition, SS and DT. All authors have read and agreed to the published version of the manuscript.

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Availability of data and materials: The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Conflict of interest: The authors declare no conflict of interest.

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