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Promoting Relaxation Using Monaural Beats With Ultralow-Frequency Inaudible Sounds: An Empirical Case Study

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ABSTRACT Given the high pressures of life in modern society, promoting relaxation can improve the quality of daily life. This study proposes a relaxation system that uses monaural beats with ultralow-frequency inaudible sounds to promote relaxation. To effectively promote relaxation, monaural beats in the δ band, θ band, and α band were used and evaluated. To avoid directly influencing people's activities, the frequencies of the stimulation sounds, which were used to generate the target beats, were out of the frequency range of people's hearing sense. To examine the performance of the proposed approaches, a subjective testing procedure was designed, and paired-sample t tests were performed. The p values for the experimental relaxation results with monaural beats in the δ band, θ band, and α band were 0.0001, 0.1195, and 0.0065, respectively. Furthermore, the experimental results revealed specific effects of the proposed relaxation system; for example, the δ band had the greatest effect regardless of whether the average, variance, or p value was assessed. On the basis of our experimental results, the proposed relaxation system model can help promote relaxation.

INDEX TERMS Audio, brain waves, binaural beats, monaural beats, relaxation, resonance.

I. INTRODUCTION

In modern society, the high pressure of life severely affects people's sleep and work efficiency. Generally, life pressures will cause people to feel mentally tight, can result in insomnia, and in the long term, may seriously affect physical health and reduce work performance.

Stress can cause conditions such as asthma, rheumatoid arthritis, bipolar disorder, cardiovascular disease, chronic pain, autoimmune disease, dementia, stroke, and certain types of cancer [1]–[3]. Therefore, promoting relaxation can effectively reduce the consequences resulting from stress.

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Although psychiatric drugs can quickly help people enter a relaxed state or fall and remain asleep, their long-term use can cause serious side effects, such as headaches, memory loss, falls, respiratory depression, the need for increased doses, and dependence [4], [5].

Therefore, nonmedicinal adjuvant therapies have received increasing attention in recent years. For example, aromatherapy is performed by inhalation, massage, and other methods. Many of these nonmedicinal therapies have been used as adjuncts to therapy since ancient times.

In recent studies, the effects of these treatments have been evaluated by comparing physical or mental states before and after their use [6], [7]. Its therapeutic properties are derived from the chemical components, including ketones and esters, in essential oils, but essential oils and medicines are also toxic and may cause allergies and other side effects; thus, they need to be used with caution.

The vibration of sound waves in the air is similar to a massage for the human body, and there is no need to be concerned about the toxicity of drugs. The use of sound waves as a design aid for human health is an effective and worthy direction for further exploration, especially in brainwave-related research. Recent research suggests that a brain-computer interface combined with hearing can help severely paralyzed patients and increase the rate of data transmission [47], recognition accuracy, and potential clinical applications [48]. Using sound waves to cause brain waves to resonate could be an effective way to promote relaxation. However, sound waves affect hearing and cause distraction. Thus, developing a relaxation system that does not affect people's activities would effectively and conveniently promote relaxation.

Recently, many approaches have been proposed to promote relaxation. Regarding these approaches, music therapy is a well-known approach and is a particularly recommended form of sensory stimulation [8], [11], [16]. Listening to music can influence people's thoughts, and, when properly guided, repeated experiences with these thoughts and emotions can have a constructive effect [15]. For example, people recover from physiological stress faster when listening to pleasant sounds rather than unpleasant sounds [17]. It has been shown that music therapy has a significant effect in reducing both physical and psychological stress [8], [11], [16]. Thus, it has been widely used to reduce symptoms of discomfort in patients during medical treatment. However, music therapy greatly influences the listener's attention. Therefore, developing an inaudible stimulation sound would be useful for encouraging relaxation without distraction.

The remainder of this article is organized as follows. Section II introduces and discusses previous research on binaural beats, monaural beats, and the avoidance of auditory consciousness. Section III explains the proposed relaxation system. Section IV performs the system utility test. Section V presents the experimental results, analysis, and discussion. Finally, Section VI summarizes the results and discusses future research directions.

II. PREVIOUS RESEARCH

In the last decade, many researchers have shown that music sounds are a type of vibration. In terms of expanding their application, stimulation with a suitable vibration can effectively promote relaxation [20], [31]. Therefore, binaural beats (BBs) and monaural beats (MBs) [22] have been proposed to promote relaxation [9], [10], [12]–[14], [21], [27].

Regarding binaural beats, two monotones with a slight difference in frequency between the left and right ears are played at the same time. Therefore, if the left ear receives 250 Hz and the right ear receives 256 Hz sounds, then a 6 Hz frequency difference will presumably be created in the medial nucleus of the superior olivary complex [9], [10], [12], [13], [21].

Regular vibrations of a specific frequency can cause neural oscillations of the corresponding frequency in the brain. Through the process of neural entrainment/synchronization with external rhythms, the activity of neurons can be phase-locked with external stimuli [18], [19], [23], [24].

Because resonance allows very small fluctuations to generate a significant influence, fluctuations similar to brain wave frequencies will cause a certain drive for resonance in the brain waves [23]. Finally, the activity patterns of the neurons in the brain are gradually synchronized with this frequency difference and thus achieve a soothing effect [23], [25]. Both binaural and monaural beat stimulation significantly affected the firing rate of most neurons in the medial temporal lobe [28].

Unlike binaural beats, monaural beats play two monotones with a slight difference in frequency through one speaker. Thus, people can hear the beats, which are perceived as a periodic variation in volume whose rate is the difference in the two frequencies of two monotones, which is similar to amplitude modulation (AM). When stimulations with binaural beats and monaural beats exhibited the same frequency, the effects on relaxation were very similar [26].

However, many studies on the influence of auditory beats have shown that the Auditory Steady-State Response (ASSR) or cortex respond more strongly to monaural beats than binaural beats [24], [29], [30], [32], [34]. A recent study even pointed out that binaural beats entrain the cortex more weakly than monaural beats [24]. Thus, developing a monaural beat designed to promote relaxation would be useful and convenient for people in modern society.

To promote relaxation without interfering with the user's attention, delivering stimulation sounds at ultralow frequencies that are out of the frequency range for people's hearing sense is an ideal method. Binaural and monaural stimulation that can generate beats with ultralow frequency are very suitable for promoting relaxation.

However, the difference experienced with binaural sounds can be unpleasant [13], [30], [33]. They may cause auditory rejection and potentially cause dizziness, discomfort, and further anxiety and depression [13], [14]. Thus, delivering comfortable stimulation sounds with ultralow frequency would meet the relaxation needs of modern people.

Since devices for generating ultralow frequencies are very expensive [46], using beats with ultralow frequencies can effectively reduce the cost. However, Pawlaczyk-Łuszczyńska and Dudarewicz [37] showed that low-frequency ultrasounds at 95-130 dB can cause headache, dizziness, and nausea.

Therefore, to prevent such effects, the energy of the stimulation sound should be much lower than 95 dB. In addition, Jurado and Marquardt [38] showed that stimulation sounds with ultralow frequency, which are out of the frequency range

TABLE 1. A comparison between the proposed system and related works.

Related work	Carrier frequency	Test beat frequency	Binaural (BB) or Monoaural beats (MB)	Healthy subjects (no hearing or neurological related diseases)	Skin contact (i.e., with headphones)	Source sound belongs to the interval of auditory dissonance	Superimposed background sound	Effect of beat frequency on brain waves
[9]	400/405 Hz	5 Hz	BB	Yes	Yes	Yes	No	1. Significant differences observed before and after 2. θ has the possibility of entrainment
[12]	No description	No description	BB	Yes	Yes	Yes	Yes	1. Correlation between the music group and the effect of relaxation 2. The effect of concentration was the most significant with the addition of white noise
[13]	250/256 Hz	6 Hz	BB	Yes	Yes	Yes	Yes	1. Combining BB with ASMR may induce entrainment of brain waves and affect psychological stability. 2.It could also be a way to improve sleep.
[21]	250/253 Hz	3 Hz	BB	Yes	Yes	Yes	No	Increased N3 sleep ratio
[24]	(A) 380/420 Hz (γ) (B) 396.5/403.5 Hz(θ)	γ: 40 Hz θ: 7 Hz	Test: BB Control: MB	Yes	Yes	Yes	No	1. The control MB had higher entrainment 2. May modulate memory and attention
[25]	250/256 Hz	6 Hz	BB	Yes	Yes	Yes	No	6 Hz BB was suggested as a stimulus that induced meditative state
[26]	Center frequency between 110 and 200 Hz and alternate back and forth	6 Hz, 10 Hz, 40 Hz	MB	Yes	Yes	Yes	No	1. Can reduce anxiety 2. MB can be listened to without headphones, providing development potential (in this study headphones were used to isolate external sounds)
[28]	217.5 Hz/222.5 Hz	5 Hz	BB MB	No; preoperative epilepsy patients with microfilament implantation	Yes	Yes	No	Beat frequency was associated with memory performance by altering the level of electrical discharge
[29]	500 Hz/540 Hz	40 Hz	BB MB	Yes	Yes	Yes	No	1. Caused ASSR at 4 Hz 2. MB activates the cortical network five times more than BB
[30]	(A) 380/420 Hz (B) 3180/3220 Hz	40 Hz	BB MB	Yes	Yes	Yes	No	1. Both have ASSR around 400 Hz 2. MB has clear ASSR around 3200 Hz but BB is not obvious 3. Some music students say they are not used to BB and therefore have no ASSR response, but they have ASSR response to MB
[32]	Around 500 Hz, changing with the target beat frequency	3-60 Hz (Change 0-15 Hz per second)	BB MB	Yes	Yes	Yes	No	1. The BB cutoff frequency was as low as described in the previous literature; only 50% remained above 30 Hz 2. The BB response was usually smaller than the MB
[33]	(A) Around 200 (θ) or 259 Hz (β) (B) Around 100, 200, 250, or 300 Hz (θ); or around 500, 650, 750, or 900 Hz (β)	Both (A) and (B): θ: 4 Hz β: 16 Hz	BB	Yes	Yes	Yes	Yes	There was no significant difference. The number of stimulus samples may have been too small (only 6), or it may be due to the addition of background noise (mentioned in the previous literature); a larger sample should be used for further research.
[34]	(A) Around 250 Hz (B) Around 1000 Hz	3 Hz, 6 Hz	BB MB	Yes	Yes	Yes	No	1. Both have effects on the cortex, but the areas involved are different, and both are biased towards the left hemisphere. 2. The excitation degree to source frequency 250 Hz is greater than 1000 Hz, and 3 Hz beat is greater than 6 Hz beat. 3. In general, MB induced greater than BB.
Proposed System	(A) 18000/18002 Hz (B) 18000/18005.5 Hz (C) 18000/18009 Hz	δ 2 Hz θ 5.5 Hz α 9 Hz	MB	**Yes**	No	No	No	1. Without contacting the body or affecting auditory awareness, the use of Delta and Alpha alone has a significant effect on the degree of relaxation 2. The Theta segment alone produced a considerable proportion of responses to stress or inspired thoughts, which may be further explored.

of people's hearing sense, can still be perceived. Thus, selecting a suitable beat with ultralow frequency can effectively promote relaxation.

III. PROPOSED MODEL OF THE RELAXATION SYSTEM

In this study, a relaxation system model using monaural beats with ultralow-frequency inaudible sounds was proposed to promote relaxation, as shown in Fig. 1. To easily promote relaxation, monaural beats with ultralow-frequency inaudible sounds (in the δ, θ, and α bands) were selected as the stimulation sounds. Table 1 lists the comparison of this experimental specification with other related studies.

The frequency of the stimulation sounds used to generate the monaural beats, which were out of the frequency range of people's hearing sense, was chosen to limit the influence on people's activities. To avoid the strange sense associated with hearing a pure tone, reverb effects were adopted. The relaxation test, as assessed and described in the fourth section (results and discussion), uses the mean, variance and ANOVA F statistics to verify the test results.

For the proposed monaural beat-based relaxation system, a stimulation generator (frequency integration unit) was applied to generate the monaural beats. A monaural beat is an interference pattern between two sounds of slightly different frequencies, and it is perceived as a periodic variation in volume whose rate is the difference between the two frequencies.

In this study, the stimulation signal S was generated by using two cosine waves and defined as follows:

$$\begin{aligned} S(f_1, f_2) &= A\cos(2\pi f_1 t) + A\cos(2\pi f_2 t) \\ &= 2A\cos\left(2\pi \frac{f_1 + f_2}{2} t\right)\cos\left(2\pi \frac{f_1 - f_2}{2} t\right) \end{aligned} \tag{1}$$

where A is the amplitude of cosine waves, and f_1 and f_2 are their frequencies, which are very close. Therefore, as shown in (1), the first cosine wave, with the average frequency of the two waves, is the product expression that rapidly fluctuates. The second cosine wave varies more slowly with time and can be considered a time-dependent amplitude of the combined waves. The interference pattern between these two cosine waves can be denoted as a beat with a frequency of $\frac{f_1 - f_2}{2}$. Fig. 2 shows the beat frequency when two similar frequencies are added together, and the waveform is similar to AM. Increasing the frequency does not affect the envelope

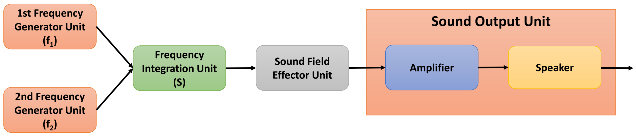


FIGURE 1. The model of the proposed relaxation system.

modulation (Fig. 3). Because the human ear is not phase sensitive, and when two or more sinusoids are added together, the relative phase has a significant impact on the shape of the waveform but no impact on the perceived sound [49]. For audio, the phase angle is just a constant, just translation, it has no effect on the auditory output result. Therefore, the phase is not included in (1).

To effectively promote relaxation, selecting a suitable monaural beat is important. To solve the problem of sound interference, a specific hidden sound wave was designed and hidden in the frequency bands, and humans cannot consciously discriminate this particular sound wave. Moreover, the hidden specific sound waves can be naturally integrated into the environment, and thus, they are effectively transformed into an atmospheric attribute of the natural airflow in the sound field. Monaural beats in the δ, θ, and α bands were used in this study.

Humans can detect sounds in a frequency range from approximately 20 Hz to 20 kHz. With aging or hearing loss, high-frequency hearing tends to gradually decline. Taking middle-aged people as an example, the range of high frequencies drops [50] to 14-17 kHz on average, [51]. Since the higher the high-frequency upper limit and the higher the unit price of the accurate loudspeaker, it is necessary to reduce the cost as much as possible to facilitate the promotion.

Therefore, the selected frequency should be reduced as much as possible in the use of the high frequency that belongs to the air and atmosphere in the range of auditory awareness. In some pretests of this experiment, it was found that the selection of frequencies above 15k is easy for middle-aged people to avoid the effect of conscious recognition due to the improvement in the high-frequency auditory threshold. However, for young people, it is obviously necessary to increase the frequency setting. In the early tests, which gradually increased from 15k, it was found that 18k could still be correctly produced and was close to the upper limit of human hearing. Additionally, because the hearing threshold changed with frequency (see Fig. 4, equal-loudness curve [52]), it can be easily achieved that the effect of avoiding the interference of auditory awareness.

For the reasons above, this study uses high frequencies to make beats; when $f_1 = 18,000$ Hz and $f_2 = 18,009$ Hz, a 9-Hz beat is generated, as shown in Fig. 3(a) to (e). Fig. 3(a) shows a one-second 18,000-Hz sine wave (black) and an 18,009-Hz sine wave (red). Because the high-frequency line density is high, the black 18,009-Hz wave is covered by the red 18,000-Hz wave. Fig. 3(b) shows a small part of Fig. 3(a). The red and black lines gradually separate from the starting point. Fig. 3(c) shows mixed one-second 18,000-Hz and 18,009-Hz waves. Fig. 3(d) shows the peripheral modulation profile formed by a 1-second-length mixed sound file, that is, a 9-Hz beat frequency. Fig. 3(e) is the fast Fourier transform (FFT) of the lowest frequency range of the mixed wave.

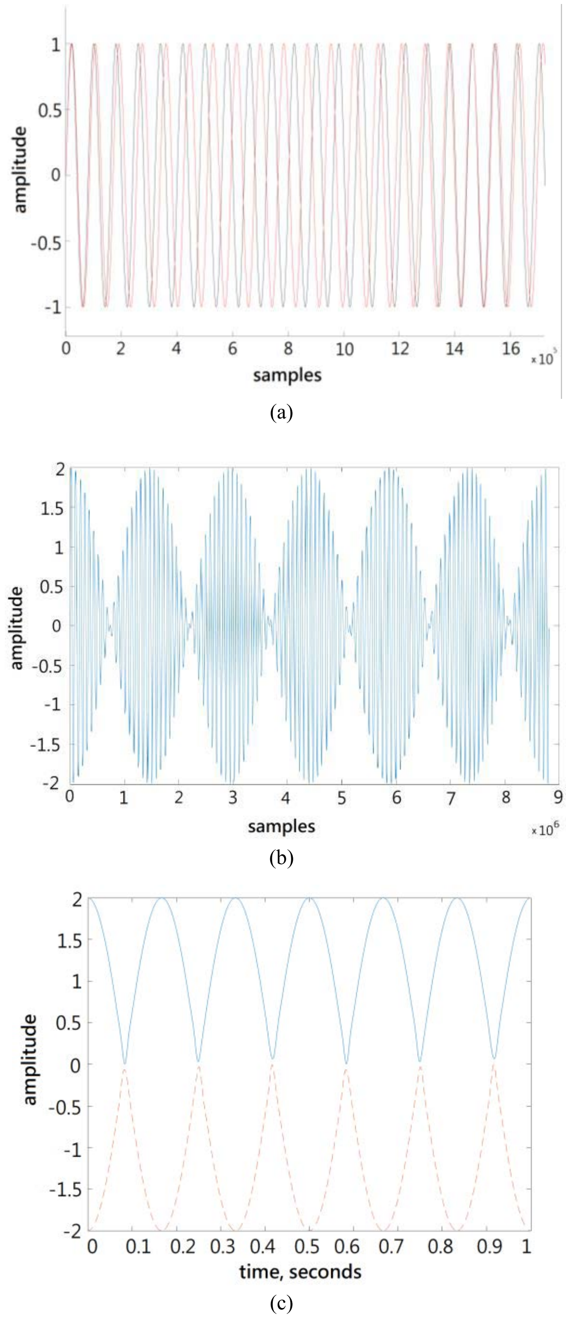


FIGURE 2. (a) A 110-Hz sine wave (black) and a 104-Hz sine wave (red), (b) their sum (blue), and (c) the corresponding envelope.

There is a clear energy value at 9 Hz, which is the correct beat frequency of mixed 18,000- and 18,009-Hz waves. If it is directly and internally calculated by MATLAB without outputting it as a sound file, the FFT of the beat frequency can be displayed only after the calculation is squared because

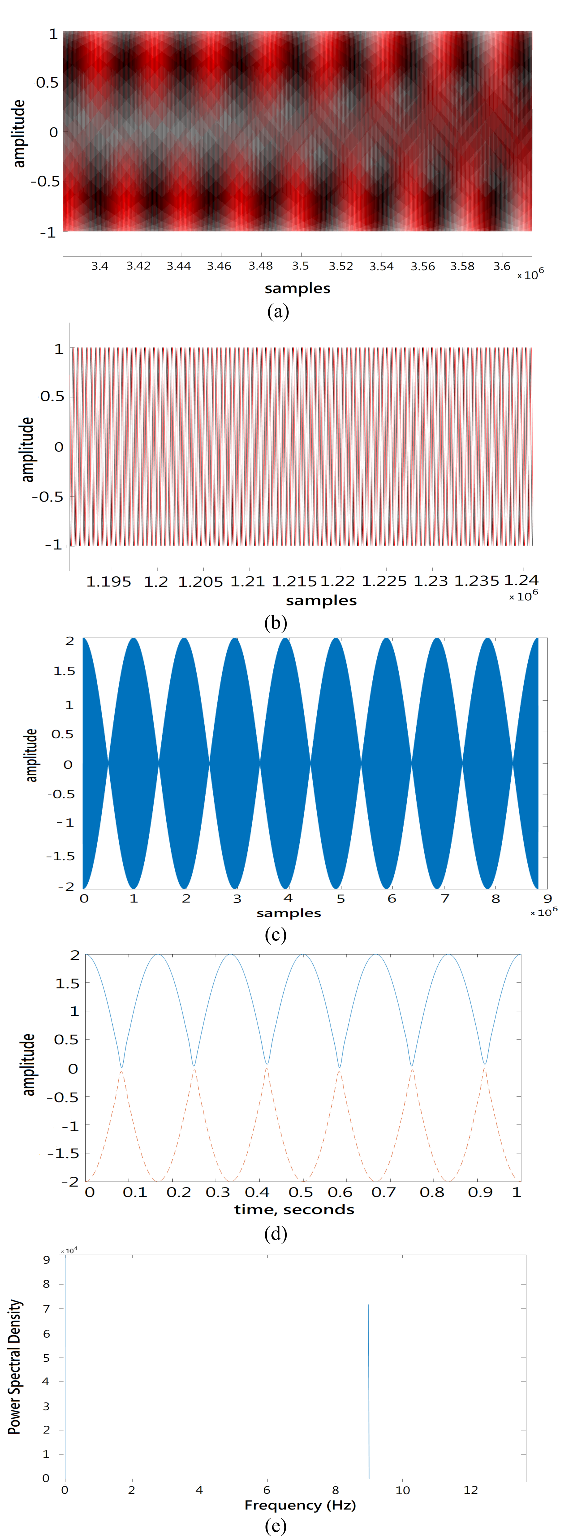


FIGURE 3. **(a) An 18,000-Hz sine wave (black) and an 18,009 Hz sine wave (red) when the resolution is the same as in Fig. 2 (a) and the density of the abscissa is now dozens of times that of 2(a), (b) horizontal zoom of the picture above, (c) sum of 18,000- and 18,009-Hz waves (blue), (d) corresponding envelope, and (e) FFT after using audioread to read the audio file of the mixed 18,000- and 18,009-Hz waves.**

sound is a kind of energy and needs to be analyzed based on an energy spectrum.

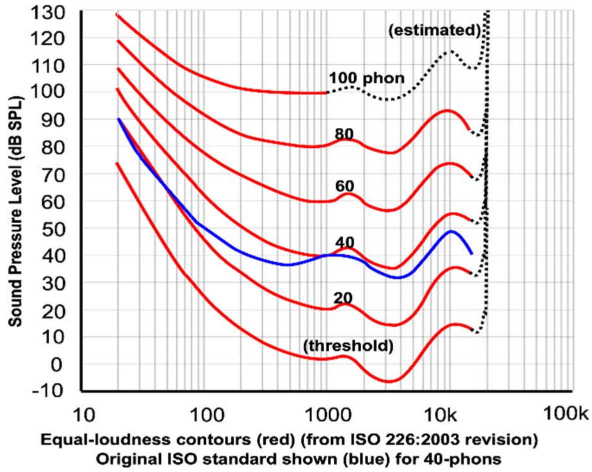


FIGURE 4. **Equal-loudness curve [52].**

In general, the reverb effect was used to produce an artificial spatial sound field of a hall or room. Unlike delay effects, reverb effects use multiple delays within a very short time that are unrecognizable for humans. All repetitions are superimposed to sound continuous. Thus, when the monaural beat was obtained, a universal spatial sound field effector reverberation was used to transform S to S' such that S' blends with the natural space. In this study, the reverb effect was implemented by using the reverberator in MATLAB [40].

Although most studies in the past used BB, an increasing number of studies in recent years have been looking forward to MB because MB does not need to touch the human body. Table 1 shows that in the comparative experiment between BB and MB, the activation obtained by MB is often more significant and applicable to a wider frequency range. In the experiments comparing BB and MB, MB also wore headphones, which may be because of BB. The approach proposed is to take it a step further and look at one of the possible functions of the MB in terms of helping relaxation. In addition, MB has more possibilities for research and development.

IV. SYSTEM UTILITY TEST

To verify the effect of the silent brainwave resonance audio system device on relaxation in silent mode, we compared the differences in the degrees of relaxation across the low α, θ, δ and other frequency bands with and without the use of the silent brain wave resonance audio. Generally, as people sleep, their brainwaves will first go through the low α band (8-10 Hz), where consciousness begins to relax, then gradually fall into the θ band (4-7 Hz), which represents light sleep and dreaming, and finally enter the δ band (1-4 Hz), which is deep sleep and dreamless. In this experiment, the brainwave resonance audio frequency was represented by the middle value in these frequency bands; thus, these values not only represent the characteristics of the frequency band but also accurately indicated that any observed effects were caused by the response to these frequency bands and not to stimuli

FIGURE 5. Testing flowchart.

in other frequency bands [25]. Therefore, we used 9 Hz for the low α band (which is more related to relaxation), 5.5 Hz for the θ band and 2 Hz for the δ band as indicators of the α, θ, and δ bands related to relaxation and sleep, and the monaural audio device was approximately one meter away from the subject.

In this experiment, we used mobile games for emotional stimulation [36], and the stimulation parameters were designed to be in the upper right quadrant of the valence-arousal emotional coordinate system as it relates to mobile games [35], [36], [41]. Additionally, mobile games must create tension and excitement through, for example, online battles, racing, survival, and loss of balls; we chose "Speed Drifters," "Arena of Valor," "Asphalt," "Brawl Stars," and "Crazy Arcade" and let the participants choose the mobile game for themselves.

The brainwave excitation associated with tense states was used as the baseline to compare with the relaxation segments. Because voice guidance is an effective way to affect brainwave states [42], [43], the choice of the voice-guided relaxation method was tested in the pilot test. Compared with the 7-minute relaxation guidance audio file released by the Tainan City Clinical Psychologist Association 2016, a simple form of guidance using gentle language that encouraged relaxation over approximately 10 seconds was more suitable for this experiment because the 7-minute guided content would actually affect emotions of the participants and subsequently interfere with effectiveness measures. At the beginning of the experiment, the relaxation guidelines were repeated for 3 minutes before the initial relaxation phase and 10 minutes after each phase where participants engaged with the mobile game.

A. TESTING PROCEDURE

In this experiment, the testing procedure was divided into 9 segments presented in sequence, which included five relaxation segments (including the prerelaxation segment) and four stimulation segments, as shown in Fig. 5.

B. GUIDANCE

The beginning of each segment was orally guided by the experimenter. The introductory text during the relaxation segment included the oral prompts: "sit with eyes closed and rest," "turn off the phone and mute the phone," "lean on the pillow," and "relax as much as possible." The emotional arousal segment prompt was "start mobile game."

C. EMOTIONAL STIMULATION

The aim of the emotional stimulation segment was to play a mobile game to stimulate brain tension. Due to differences in the progress of each game and individual skill levels, the experiment needed to be stopped after the subject entered the high point of the game, which was designed to trigger emotional tension. Therefore, the testing time was slightly different across participants and was controlled to be between 10 and 15 minutes.

TABLE 2. Testing schedule in the four relaxation segments.

	Subject 1	Subject 2	Subject 3	Subject 4	Subject 5	Subject 6
I	ABCD	BCAD	CADB	DBCA	ADBC	BADC
II	BCDA	CDBA	DBAC	ACDB	BACD	CBAD
III	CDAB	DACB	ACBD	BDAC	CBDA	DCBA
IV	DABC	ABDC	BDCA	CABD	DCAB	ADCB

Note: A: none; B: low α (9 Hz); C: θ (5.5 Hz); D: δ (2 Hz)

D. RELAXATION SEGMENT SETTINGS

With the exception of the prerelaxation period, which was 3 minutes in duration, the other relaxation segment times were all 10 minutes in length. Table 2 shows the test schedule list from the four relaxation segments, and we presented the silent brainwave resonance audio in the indicated sequence.

E. SEQUENCE OF TEST PHASES

Because the original recruiting tester was 12, there were a total of 24 permutations and combinations of the four conditions (three monaural audio conditions with δ, θ, and low α and the no stimulation condition) and every subject tested four times, the subjects were formed into groups of six people. Additionally, the subjects themselves do not know the playback order of each resonance band in each experiment. The actual playback order for each frequency band in the experiment was as follows. First, the 24 permutations and combinations were arranged in order, and then the list was adjusted such that each tester had a more evenly distributed order. Every six testers used the 24 sorted sequences shown in Table 2. After the first round of experiments, due to the small number of people, the eight new subjects were added in one round according to the table below, and the last two were ranked by Subjects 1 and 2. In the future, when planning and designing, we will pay more attention to the design of the number of people.

F. RELAXATION SCALE

After the end of every test, each tester completed a ten-point scale of relaxation with one question:

"What is your degree of relaxation in this segment of the relaxation activity (fill in after the segment; please note: "1" is the least relaxed and "10" is the most relaxed. Please directly select by circling the number)? 1 2 3 4 5 6 7 8 9 10."

The ten-point relaxation scale can be seen in Table 3. Finally, the user could write a qualitative description of each relaxation segment in the remarks column, where they could describe how relaxed he or she felt in each segment. This assessment will be discussed in the next section.

TABLE 3. Ten-point relaxation scale.

The following is a survey on the degree of relaxation, where 1 is the least relaxed and 10 is the most relaxed. Please directly select by circling a number:
What is your current level of relaxation?
1 2 3 4 5 6 7 8 9 10
What is the degree of relaxation in the first segment of the relaxation activity (fill in after the segment)?
1 2 3 4 5 6 7 8 9 10
What is the degree of relaxation in the second segment of the relaxation activity (fill in after the segment)?
1 2 3 4 5 6 7 8 9 10
What is the degree of relaxation in the third segment of the relaxation activity (fill in after the segment)?
1 2 3 4 5 6 7 8 9 10
What is the degree of relaxation in the fourth segment of the relaxation activity (fill in after the segment)?
1 2 3 4 5 6 7 8 9 10
Remarks:

V. EXPERIMENTAL RESULTS AND ANALYSIS AND DISCUSSION

In this section, the experimental results, analysis, and discussion, including hardware verification, relaxation test results, and comparative analyses, are presented.

A. HARDWARE VERIFICATION

The verification of brainwave resonance audio signal physical playback equipment and hardware is divided into electrical signal output tests and sound wave vibration tests. Since the resonance audio frequency bands δ and θ and low α are ultralow frequencies, there is almost no appropriate room for testing given the acoustic conditions of buildings in Taiwan. Therefore, in this experiment, accelerometer testing and spectrum analyses were used for sonic vibration testing.

1) ELECTRICAL SIGNAL OUTPUT TEST RESULTS

The electrical signal output values of low α (9 Hz), θ (5.5 Hz) and δ (2 Hz) monaural beats were recorded and tested with an Agilent DSO-X 2012A oscilloscope. The electrical signal testing results with low α, θ, and δ are shown in Fig. 6(a), (b), and (c), respectively. The unit along the ordinate is dB, and the abscissa shows frequencies. The horizontal display range is set from 0 to 10 Hz, divided into ten equally spaced intervals.

A main frequency can be clearly seen in these three figure panels: 9 Hz, 5.5 Hz and 2 Hz. Because of the window width, multiple harmonics (4, 6, and 8 Hz) can be seen only with 2 Hz. The results showed that the machine generated the correct target frequency for low α (9 Hz), θ (5.5 Hz) and δ (2 Hz) signal output.

2) VIBRATION SIGNAL OUTPUT TEST RESULTS

In this study, the Brüel & Kjær accelerometer model 4507-002, Brüel & Kjær 3050-A-060 PULSE signal analyzer and Pulse Labshop were applied to demonstrate that brainwave resonance audio stimulation was transmitted from the

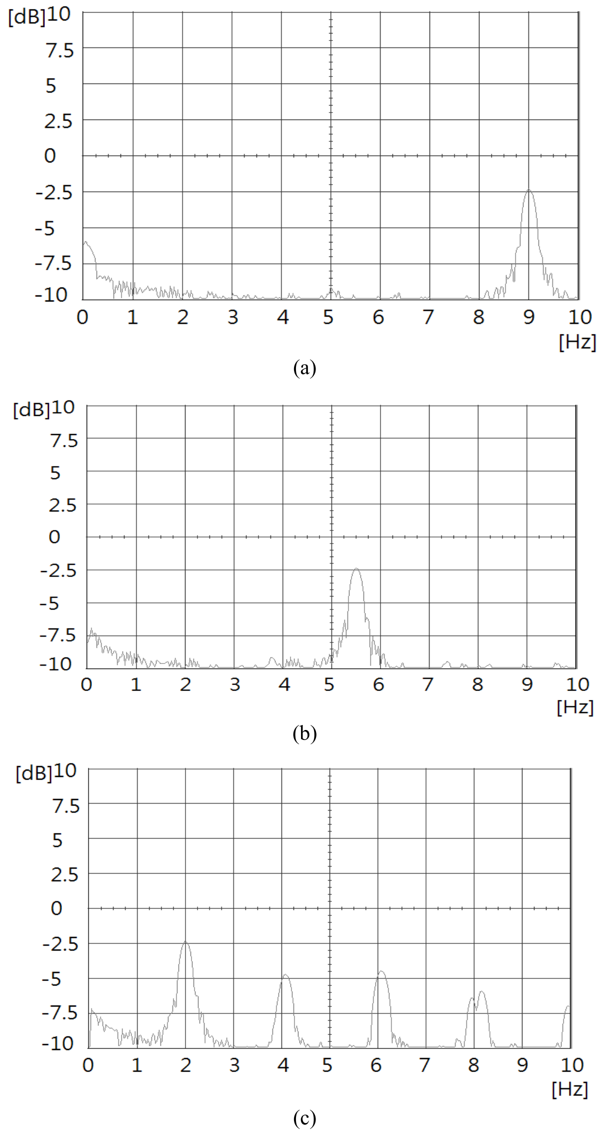


FIGURE 6. Electrical signal test results for the (a) low α (9 Hz), (b) θ (5.5 Hz), and (c) δ (2 Hz) electrical signals.

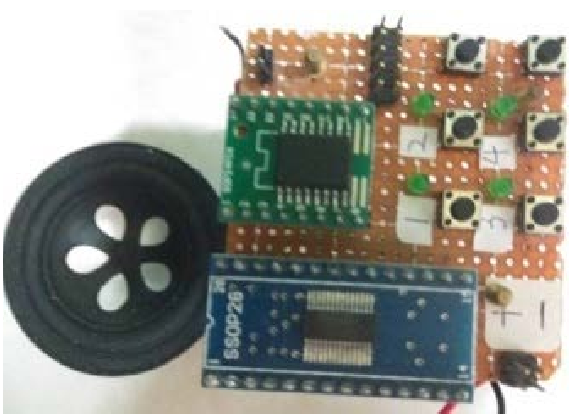
device, as shown in Fig. 7. Although the sound frequency performance of general equipment can be measured in an anechoic room to some degree of accuracy, the measurement of low-volume ultralow-frequency sound in this frequency band lies outside the measurement range of anechoic chambers in Taiwan.

However, a high-sensitivity accelerometer is suitable for measuring low-amplitude signals, and accelerometers designed to measure low-frequency vibrations can be used to measure the low-frequency vibration spectrum as accurately as possible. Because the target sound wave is emitted by the speaker, the speaker vibration spectrum can be measured to provide a vibration test. The acquired monaural beat audio signals for low α, θ and δ are shown in Fig. 8(a), (b), and (c), respectively.

The experimental results showed that the proposed approach can effectively produce monaural beats at an

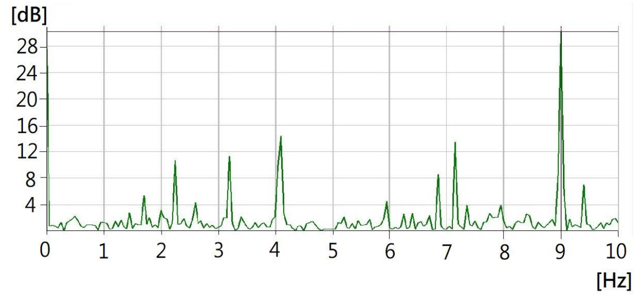
(a)

(b)

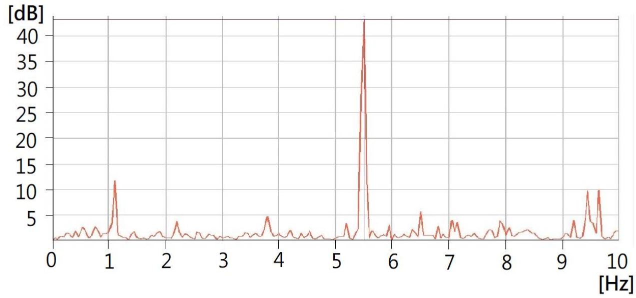


(c)

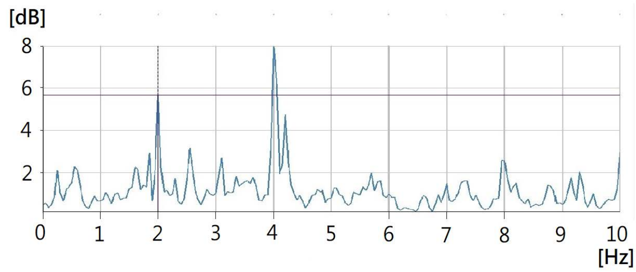
FIGURE 7. **Vibration signal testing devices: (a) Brüel & Kjær 3050-A-060 PULSE signal analyzer, (b) Brüel & Kjær Accelerometer model 4507-002, and (c) playback device.**



(a)



(b)



(c)

FIGURE 8. **Vibration signal test results with the (a) low α (9 Hz), (b) θ (5.5 Hz), and (c) δ (2 Hz) signals.**

ultralow frequency. According to B&K Taiwan, actual vibration values below 3 Hz should be higher than the measured data because of characteristic limitations of the accelerometer itself.

B. RELAXATION TEST RESULTS

The relaxation test is carried out according to the procedure planned in Part III, Item IV, System Utility Test.

1) SUBJECTS

To evaluate the degree of relaxation for subjects without ontological or neurological disease, 20 subjects (12 males and 8 females) were asked to participate in this experiment. The age of the actual participants was between 20 and 24, and the average age was 21.95±0.83. In addition, the subjects did not have sleep and physical and mental disorders and were in normal condition on the day before the experiment, without eating and drinking food containing caffeine. Each subject was tested four times, for a total of 80 times, and the same subject completed only one test a day. This experiment was reviewed and approved by the Human Research Ethics Committee (HREC) of National Cheng Kung University, Tainan, Taiwan.

2) DEGREE OF RELAXATION RESULTS AND ANALYSIS

In this study, the relaxation scale results were examined using overall means and sigma distribution ANOVA F test and paired t test methods to compare the differences in relaxation values among the three groups of monaural stimulation and the control group (marked as "None") that did not use any monaural beat.

The ANOVA F test [45] was used to verify whether there was a significant difference in the degree of relaxation among the three monaural beat (α, θ, δ) audio stimulation segments and the control segment without monaural beat waves. Paired t tests were used to verify the effectiveness of relaxation by comparing the degree of relaxation between the beat audio groups and the control group.

The four relaxation segments are regarded as four distinct situations for discussion. In both ANOVA and paired t tests, the degree of relaxation with the α and δ monaural beats was significantly different compared with the control group. However, regardless of whether ANOVA or paired t tests were used, the δ monaural beats seemed to be the most effective in promoting relaxation.

a: RELAXATION RESULTS BASED ON OVERALL MEAN AND SIGMA DISTRIBUTION STATUS

In this test, the mean and sigma values from the low α, θ, δ and "None" conditions were 7.175±1.5973, 6.8125±1.9297, 7.4±1.6351 and 6.5375±1.7714, respectively.

Based on the averages, the degree of relaxation with all types of monaural beats (low α, θ and δ) was higher than that in the control condition; the average with δ was the highest, and the order was δ (7.4) > low α (7.175) > θ (6.8125) > "None" (6.5375). The sigma distribution was low α (1.5973) < δ (1.6351) < "None" (1.7714) < θ (1.9297). The variation in the degree of relaxation in the low α band was the smallest, followed by δ, and that with the θ monaural beat was the most scattered, which exceeded that obtained in the control condition.

b: RELAXATION RESULTS BASED ON ANOVA F TEST ANALYSIS

To confirm the influence of low α, θ and δ monaural beat audio stimulation on relaxation, an ANOVA F test was used to assess whether the average effects in each condition were significant. Mauchly's test p value = 0.218 > 0.05 indicated that the spherical assumption in the variance analysis was not violated, as the minimum value of ε was 0.333; the Greenhouse–Geisser test value was 0.947, and the Huynh-Feldt test value was 0.986. Both indicators exceeded the standard of 0.75 and showed that the data did not violate the spherical assumption; therefore, no correction was needed.

The F value of the treatment effect was 5.535, which reached the significance level ($p < 0.05$), and thus the null hypothesis H_0: $\mu_1 = \mu_2 = \mu_3 = \mu_4$ should be rejected; that is, the subjects' degree of relaxation was significantly different across conditions. In addition, pairwise comparisons showed that levels of relaxation with both the δ and α monaural beats were significantly better than those in the control condition, and relaxation with δ was significantly better than that with the θ monaural beat. However, the relaxation values with θ were not significantly different from those in the control condition with this test.

TABLE 4. Paired-sample tests.

Pairs	Sig. (single)
Pair 1 None–low α	0.0065
Pair 2 None–θ	0.1195
Pair 3 None–δ	0.0001

c: RELAXATION RESULTS BASED ON PAIRED T TEST ANALYSIS

To confirm the details, paired-sample t tests were used to compare the degree of relaxation in individual users in the same test across conditions with the α, θ and δ monaural beat audio stimulation and without the monaural beat waves, as shown in Table 4. The following is the analysis of statistical results for participant number 80:

The significance in the difference in the degree of relaxation assumed that the values were greater in the stimulation conditions than in the None condition, so a single-tailed p value was used. The significant results of the paired t tests showed that δ ($p = 0.0001$) was the best, α ($p = 0.0065$) was next, and θ ($p = 0.1195$) was the least significant. The explanations of p values from three segments are as follows:

- The p value from the low α condition was 0.0065 (< 0.01), which meets the strict p <0.01 standard of significance. The null hypothesis should be rejected, which means that when the tester was in a state of excitement, the degree of relaxation during the α monaural beat audio stimulation being used alone to promote relaxation was significantly greater than the degree of relaxation when no monaural beat was used. Low α is the closest to the brainwave frequency band observed during wakefulness [12], [23], [44], and it is also the first phase that people go into from wakefulness into relaxation without entering the sleep stage. Additionally, perhaps because the relaxation period in this experiment was not long (approximately 10∼15 minutes), it might be expected that the relaxation value with α monaural beat audio stimulation would therefore be higher.
- The p value from the comparison with θ was 0.1195 (> 0.05), and the null hypothesis cannot be rejected. Regarding the ambiguity of the overall performance with θ, the inference is that although θ should be a calmer brainwave band than low α, θ is a dormant dream state [12], [23], [44], and normally, people must go through the low α stage first before entering θ. However, θ

brainwaves do not yet represent a deeply relaxed state and are still quite active. Thus, compared to the state of waking excitement, there is neither the ease of low α nor a truly unconscious relaxation period. In this case, it may represent a kind of "deliberate" relaxation. In certain situations, it may not be easy to skip the low α state and directly go into the θ frequency band brainwave state, and therefore, it is presumably possible to cause stress when the θ monaural beat is used alone for only a short period of time.

- The p value from the comparison with δ was 0.0001 (<0.001), which met the most stringent p <0.001 standard of significance and was the most significant of the three bands, and the null hypothesis should be rejected. This indicated that when the tester was in an excited state, the degree of relaxation when the δ monaural beats were used alone to promote relaxation was significantly greater than when they were not used. Overall, the relaxation value after the δ monaural beat segment was the highest of the three stimulation conditions. In terms of brainwave states, δ indicates the high level of relaxation associated with deep sleep and unconscious states [12], [23], [44], and therefore, the high relaxation values with δ stimulation in all aspects were consistent with the expected possible results.

3) QUALITATIVE DIFFERENCES IN THE RELAXATION TEST RESULTS

In the qualitative narrative, one can observe from the text the extent and feelings of the tester's description of different experiences. In the qualitative descriptions, the difference across conditions was clearly described in accordance with the classification characteristics of the brainwave frequency band [12], [23], [44]; the descriptions included (arranged in the order of δ—θ—low α —"none") the following: "Sleep—fall asleep in the back—a little sleep in the back—no feeling"; "It's super comfortable to fall asleep—I don't particularly want to sleep, but the whole body is very relaxed—I don't have a special feeling, I feel sleepy for a while—I don't want to sleep, it feels like being empty"; "The feeling of tranquility—no feeling—nothing special—not very relaxing"; and "Like 3 seconds to sleep—like 5 seconds to sleep—sleep better—slower than relaxation."

The δ resonance wave segment is worth noting. The narration in close to 3/4 of the total entries was in line with the characteristics of the δ brainwave frequency band—deep sleep, dreamless, and deep relaxation—and included the following: "This is the most relaxing and most comfortable"; "I want to sleep"; "I don't think about other things anymore, I'm going to fall asleep"; "The longer the time, the more relaxed you will be"; "At the start is okay, later is easy to sleep"; "Sleep"; "Sleep, it's super comfortable!"; "I want to sleep, I truly fall asleep, the most relaxing. I feel an external force makes me fall asleep"; "Quiet, comfortable"; "Quiet feeling"; "Relaxed"; "How many times I lose consciousness and fall asleep"; "I don't even feel dreaming"; "Can't think about things"; "Very calm"; "Relax till I fall asleep"; "The first half is okay, the second half is very relaxing"; "It's easier to relax"; "I want to sleep quickly"; "I want to sleep more"; "I feel the air is very comfortable"; "It feels heavy"; "Like a deep sleep wave, I feel relaxed and sleepy"; and "Like sleeping in 3 seconds." The above descriptions were in line with the characteristics of the δ band. In addition, some subjects quickly went to sleep in the δ segment and did not know that they were asleep when the experimenter awakened them.

Delta waves should also progress through low α and θ to δ; however, this experiment provided a separate test method for each frequency band. Therefore, in the qualitative description of the experiment, some participants were responding to relaxation that occurred later, which may have affected the self-reported value on the ten-point scale. Therefore, if we adjust the experimental design in the future by following a reasonable relaxation process (low α to θ to δ) and moderately extending the time of the relaxation periods, the expected effect of relaxation with the δ resonance audio stimulation may be more than the feedback received in this experiment.

Compared with δ, approximately 1/3 of the subjects indicated that the θ segment resulted in feeling pressure. It is speculated that this may have been due to skipping the relaxation associated with experiencing α and directly entering the brainwave segment involving a dreaming state, which is not a very natural way to enter this state. In 2017, D'Atri *et al.*'s experiment on θ rhythm and sleep [53] used a 5-Hz θ rhythm to stimulate the frontotemporal region to test its effect on sleep. The conclusion was that the electroencephalography (EEG) chart showed high sleep characteristics, but the sleepiness scale reported by participants included no supporting data. In this experiment, similar results were obtained such that there were relatively subtle differences in the degree of relaxation between the θ wave and other segments. Compared with the numerical analysis data in 4.3.1, the feedback when the θ wave was used alone was more complicated, with both high relaxation values and particularly low records. Perhaps the application of both stimulation and relaxation in the θ band revealed another particularity, and there may be more research and discussion in the future.

VI. CONCLUSION

In this article, a relaxation system based on presenting inaudible monaural beat audio stimulation was developed to help people relax. The audio from the two waveform generators produced the beat wave in the acoustics. The 9-Hz, 5.5-Hz, and 2-Hz ultralow audio stimulations that corresponded with low α, θ and δ brainwave frequencies were successfully emitted by the dual-channel waveform generator with beat wave characteristics. Then, the resonance audio was hidden outside the frequency band that human consciousness can discriminate, thus successfully avoiding interference from unpleasant frequency differences.

Furthermore, testing results for system verification showed that the stimulus signals can be correctly generated and effectively encourage users to relax. Among the separated α, θ and δ monaural beat stimulations, the effects of the δ segment were the most significant regardless of the analysis method.

In addition, the degrees of relaxation in both low α and δ conditions showed significance whether using ANOVA or paired t tests. The application of the monaural beat signal device can effectively promote user emotional relaxation. This is a project worth investigating given today's modern busy society. Because the pressures of work and life after graduation are even greater, it is expected that the comparison of the degree of relaxation using silent brainwave resonance audio stimulation will be more significant for nonstudents.

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