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Therapeutic Uses of Brainwave Entrainment Using Low Audio Frequency Stimulation

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MAIN OFFICE
4695 Millennium Drive
Belcamp, MD 21017-1505
Office: 443-360-4600

REPORT PREPARED BY:
Taylor H. Knight
Office: HDIAC

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The Homeland Defense and Security Information Analysis Center (HDIAC) was asked to identify recent research (in the past five years) in the therapeutic uses of brainwave entrainment via low audio frequency stimulation. The desired range was from 0 to 40 Hz, accommodating brainwave frequencies from Delta to Gamma. Brainwave entrainment (BWE) refers to the brain's electrical response to rhythmic sensory stimulation, including pulses of light or sound. BWE produces electrical impulses in the brain that can be measured by an electroencephalogram or a magnetoencephalography and can range from the Delta to Gamma range. Technologies used to generate BWE typically include binaural beats, monoaural beats, and isochronic tones. During and after auditory stimulation, brainwaves can begin to resemble the stimulus rhythm, inducing a variety of mental states and consciousness. Different frequencies applied during BWE have been shown to be correlated with different mental states, and BWE overall has been found to improve cognition, memory, mood, stress, pain, and human behavior. HDIAC staff found that recent research results varied, although the overall available evidence suggests that BWE has the potential to be an effective therapy and can influence human mental states and behaviors.

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A chief service of the DoD IACs is free technical inquiry (TI) research, limited to 4 research hours per inquiry. This TI response report summarizes the research findings of one such inquiry jointly conducted by HDIAC.

Abstract

The Homeland Defense and Security Information Analysis Center (HDIAC) was asked to identify recent research (in the past five years) in the therapeutic uses of brainwave entrainment via low audio frequency stimulation. The desired range was from 0 to 40 Hz, accommodating brainwave frequencies from delta to gamma. Brainwave entrainment (BWE) refers to the brain's electrical response to rhythmic sensory stimulation, including pulses of light or sound. BWE produces electrical impulses in the brain that can be measured by an electroencephalogram or a magnetoencephalography and can range from the delta to gamma range. Technologies used to generate BWE typically include binaural beats, monoaural beats, and isochronic tones. During and after auditory stimulation, brainwaves can begin to resemble the stimulus rhythm, inducing a variety of mental states and consciousness. Different frequencies applied during BWE have been shown to be correlated with different mental states, and BWE overall has been found to improve cognition, memory, mood, stress, pain, and human behavior. HDIAC staff found that recent research results varied, although the overall available evidence suggests that BWE has the potential to be an effective therapy and can influence human mental states and behaviors.

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1.0 TI Request

1.1 Inquiry

Can you provide a summary of recent research for therapeutic uses of brainwave entrainment (BWE) via low audio frequency stimulation?

1.2 Description

The Homeland Defense and Security Information Analysis Center (HDIAC) was asked to provide research for using low audio frequency stimulation for BWE therapy from the past five years to include technologies, techniques, and results on human performance. The frequency range should encompass delta to gamma (0–40 Hz).

2.0 TI Response

HDIAC searched a variety of science and technical databases, including the Defense Technical Information Center's Research & Engineering Gateway, the Institute of Electrical and Electronics Engineers (IEEE), Elsevier's databases (to include ScienceDirect and Scopus), DeepDyve, and PubMed. HDIAC staff also performed a generic open-source search to identify relevant BWE research.

2.1 BWE Overview

BWE refers to the brain's electrical response to rhythmic sensory stimulation, including pulses of light or sound. It produces electrical impulses in the brain that can be measured by an electroencephalogram (EEG) or a magnetoencephalography (MEG) and can range from delta to gamma. Table 1 lists the different brainwave types paired with their frequency and characteristics [1].

Table 1. Brainwave Type and Characteristics

Wave Type	Frequency and Characteristics
Delta	0–4 Hz Associated with deep levels of relaxation and restorative, healing sleep
Theta	4–8 Hz Involved in daydreaming and sleep
Alpha	8–12 Hz Bridges the gap between conscious thought and the subconscious mind
Beta	12–40 Hz Conscious thought and logical thinking, with stimulating effects
Gamma	40+ Hz Higher processing tasks as well as cognitive functioning

During and after auditory stimulation, brainwaves can begin to resemble the stimulus rhythm, inducing a variety of mental states and consciousness. Applying different frequencies to the human brain appears to correlate BWE with different mental states while overall, BWE has been found to improve cognition, memory, mood, stress, pain, and human behavior. Recent research results are varied, although the available evidence suggests that BWE has the potential to be an effective therapy and can influence human mental states and behaviors.

2.2 Research by Frequency

Audio stimulation has been used across all brainwave frequencies to determine how BWE affects mental state and consciousness. Although many studies fall into multiple categories, each study was placed into one category for this report based on the frequency. What follows is five sections for five frequencies (delta, theta, alpha, beta, and gamma), each with a brief description of their related studies and how the audio frequency stimulation affected BWE in the brain.

2.2.1 Delta

Delta brainwaves are often associated with deep sleep and restorative relaxation. A 2022 study aimed to find whether binaural beat technology could enhance sleep quality and post-sleep mood [2]. Results showed that auditory stimulation with delta binaural beat enhanced sleep parameters such as sleep failure, the number of awakenings, real duration of sleep, sleep quality, and the feeling following waking up. Participants' moods improved by reducing anxiety and anger, but other mood parameters did not indicate a significant difference.

Two MEG experiments were conducted to contrast BWE to natural speech compared to qualitative different control conditions [3]. The first experiment used amplitude-modulated white noise, and the second experiment used spectrally rotated speech. Both experiments showed

that BWE in the delta band was stronger for speech compared to the control conditions. Effects emerged in the right temporal and the left inferior frontal cortex for both experiments. Based on the results, researchers concluded that the cortical speech entrainment observed in the theta band likely reflected a passive synchronization of the auditory cortices with the acoustic regularities of speech.

Delta band (1–4 Hz) neuronal responses supported the precision and stability of auditory processing, and a deficit in delta band synchrony could be relevant to auditory domain symptoms in schizophrenia patients [4]. Delta band synchronization (along with other frequencies) elicited by a 2.5-Hz auditory steady state response (ASSR) paradigm was compared in a group of patients with schizophrenia, a control group, and first-degree relatives of patients. It was found that the ability to sustain delta band entrainment in the auditory pathway in schizophrenia patients was dramatically reduced compared to the control and relatives' groups.

2.2.2 Theta

Research in the theta frequencies showed that 7-Hz binaural beats can increase relative power of the theta band in parietal and temporal lobes [5]. Six minutes of auditory stimulation using binaural beats was enough to significantly change the relative brain power. Results suggested that lengthening the duration of the stimuli to 9 min could also alter brain connectivity.

A 2018 investigation studied cortical oscillations using audio stimuli in the theta band and a MEG for recording purposes [6]. Participants listened to auditory stimuli and detected embedded target tones. Theta-band oscillations were observed for all presented stimuli and reflected a chunking mechanism. Results suggested an active auditory segmentation mechanism, complementary to entrainment, operated on a timescale of ~200 ms to organize acoustic information in the brain.

2.2.3 Alpha

Alpha binaural beats were used in a 2020 study to treat trauma in schizophrenia. Researchers hypothesized that augmenting eye movement desensitization and reprocessing (EMDR) with alternating bilateral photic stimulation (ABPS) at alpha frequencies was especially suitable for those with schizophrenia [7]. ABPS at these frequencies stimulated pseudo-hallucinatory visions and a waking dream state. The study proposed that those on the schizotypal spectrum can improve and maintain their mental health with the regular practice of ABPS-induced visioning, transitioning progressively from negative to positive schizotypes.

Cortical electrical activity in the alpha frequency band can be enhanced with sensory stimulation via the phenomenon of entrainment and may reduce pain perception [8]. A smartphone-based program which delivered 10-Hz stimulation through flickering light or binaural beats was developed for use at night pre-sleep, with the goal of improving nighttime pain and sleep and ultimately reducing subsequent pain and related daytime symptoms. This 2023 study aimed to assess the feasibility of the program and give an indication of the effect of the program for individuals with chronic pain and sleep disturbance. Pre-sleep alpha entrainment by audio stimulation appeared feasible for participants citing chronic pain and sleep disturbance. However, the effect on symptoms will require further exploration in more controlled studies.

A visual flicker paradigm was used to entrain individuals at their own peak alpha brain rhythm, as measured by resting-state EEG [9]. The study demonstrated that individual frequency-matched brain entrainment resulted in faster learning in a visual identification task compared to entrainment that did not match an individual's alpha frequency. EEG during entrainment showed that individualized alpha entrainment boosted alpha power, induced physical alignment in the pre-stimulus period, and resulted in shorter latency of early visual evoked potentials. This suggested that BWE facilitated early visual processing to support improved perceptual decisions. The study also suggested that this played a key role in neural oscillatory states in learning and brain plasticity.

Another study focused on using alpha frequency binaural beats was set up to assess tinnitus in the ear. Binaural beats with and without ocean waves were used as an auditory stimulus, and small improvements in tinnitus rating scores were observed with BWE. Some individuals showed more improvement with the binaural beats compared to just ocean waves alone. The addition of binaural beats at 8 Hz to an ocean sound showed no significant group benefits above the ocean sound alone [10].

2.2.4 Beta

Acoustic brain entrainment (ABE) in the EEG beta range (12–20 Hz) was compared to a placebo during day and night driving in 80 subjects. Effects were examined at the subjective (Karolinska Sleepiness Scale [KSS]), physiological (EEG), and performance levels [11]. The KSS decreased slightly after ABE compared to the placebo, up to 100 min after stimulation, and led to a significant increase in EEG beta activity compared to the placebo, up to 80 min after stimulation. ABE also led to a significant decrease in theta activity compared to the placebo, up to 70 min after stimulation. Faster reaction times were observed for the ABE compared to the

placebo condition during day and night driving, and stimulation in the beta range led to an increase in beta activity in the EEG.

BWE using alpha and beta waves was also used to investigate the effects of traffic noise and the relationship between frontal lobes and stress using an EEG [12]. It was observed that the alpha subwave decreased when the subjects were exposed to noises, and it increased after they were entrained by binaural beats. Beta subwaves increased when the subjects listened to noise and decreased when they were entrained by binaural beats.

2.2.5 Gamma

Gamma oscillations are important for neurocircuit function, behavior, and memory. To study a possible causal contribution of gamma oscillations to cognitive function, various types of brain stimulation are used to induce gamma oscillations [13]. Evidence suggested that gamma BWE improved cognitive function in mice and induced gene expression changes in multiple cell types, including neurons and microglia. Results also showed chronic gamma entrainment offered neuroprotective effects.

A 2023 study investigated the effect of gamma binaural beats on attention and stress by using the attention network test to assess three types of attention—alerting, orienting, and executive control [14]. This study did not find any evidence for improving attention based on self-rated measures of anxiety.

Gamma entrainment using sensory stimulus (GENUS), or gamma BWE, is a promising approach for treating patients with Alzheimer's disease (AD). Multisensory stimulation at 40 Hz has the potential to impact AD-related cognitive decline and neuropathological processes. The researchers of this study also emphasized the need for further research to use gamma BWE as a disease-modifying, nonpharmacological intervention [15]. A similar study from 2019 found that GENUS boosted hippocampal function and positively affected microglia, astrocytes, and vasculature in the auditory cortex and hippocampus in AD patients. Auditory tone stimulation improved spatial and recognition memory and reduced amyloid in the auditory cortex and the hippocampus of mice [16]. A widespread reduction of amyloid plaques was also observed in AD patients exposed to audio stimulation via GENUS.

2.3 Research Focused on Isochronic Tones and Binaural and Monaural Beats

Isochronic tones and binaural and monaural beats are all techniques used to create BWE. Each is a type of auditory stimulation with different tones or rhythms to elicit certain responses in the brain.

2.3.1 Isochronic Tones

Isochronic tones are single tones of the same frequency that come on and off at regular, evenly spaced intervals. They are produced by oscillating the amplitude of any sound off and on at a specific rate. The interval is brief, creates a rhythmic pulse, and is often embedded in other sounds [17]. Research into isochronic tones and BWE entrainment is minimal compared to binaural beats, but some studies suggest it could be an effective therapy.

One study investigated the effectiveness of isochronic tones in stress reduction and auditory BWE. Researchers examined the lasting effect of 8-Hz alpha isochronic tones on subjective stress and absolute alpha band power via an EEG [18]. Results did not support the hypothesis that isochronic tones would effectively lower stress and anxiety; further studies are required.

2.3.2 Binaural and Monaural Beats

Binaural beats are created by generating two tones with different frequencies presented to each ear. The difference between the tones and frequencies is processed in the brain, allowing the brain to perceive a specific beat. Binaural beats typically present a percussive beat effect that is present independently of the two original tones [19]. The speed, or type, of beat is equal to the difference between the frequencies of the tones, with frequencies ranging from delta to gamma. Binaural beats have been hypothesized to induce different states of mind via BWE. Research on binaural beats entrainment has gained attention due to its ability to treat various conditions like anxiety, attention-deficit/hyperactivity disorder (ADHD), sleep, memory, and mental well-being.

Monaural beat stimulation can be achieved by applying the same amplitude-modulated signal to both ears simultaneously. While both ears receive the same beat wave, perception of the beat does not require integration of the information (tones, beats, frequencies) as opposed to binaural beats.

Binaural and monaural beats have multiple publications trying to support the hypothesis in a variety of ways. Many sought to determine if binaural beats improved sleep-related concerns, memory, attention, recovery from post deployment trauma, and overall well-being.

Medical

Some studies have investigated using binaural beats during medical procedures, including reducing pain and anxiety levels in surgical patients. Using music with binaural beats reduced the amount of a sedative needed during spinal surgery in a 2023 study [20].

Sleep

Overall, studying the effect of BWE using binaural beats on sleep performance has been very popular. Results are varied, as one study found binaural beat stimulation did not induce evident improvement of sleep disturbances more than pure music did, but it altered brain activity toward decreasing daytime alertness in subclinical insomnia [21]. Another study concluded that theta binaural beat frequencies (BBFs) could decrease stress to help induce sleep. A second phase will assess if theta and delta BBFs, including breaks to allow rapid eye movement, can sustain sleep to improve sleep efficiency [22]. The data will provide information to help construct an all-night audio program with the appropriate BBF and timing to trigger the correct sleep stage for better sleep efficiency. Other results demonstrated variability of ASSR, depending on BBFs of the stimulus as well as sleep stage [23]. The analysis of ASSR spectra supports the hypothesis that the brain falling asleep is a self-adjusting system related to incoming sound stimuli, contributing to deepening of naturally evolving sleep.

Memory and Attention

A systemic review of over 15 studies revealed conflicting results, especially concerning theta and beta's efficacy on memory and attention-related tasks [24]. The findings added to the growing evidence that binaural beat intervention improves attention and memory in humans. Since the findings suggested a near-moderate effect of auditory interventions and mixed results in the systematic review, more research is suggested in expanding the role of brainwaves in improving memory and attention in individuals.

Researchers in 2021 found listening to 40-Hz binaural beats improved attention but did not show any occurrence of neural entrainment [25]. Pink noise, binaural, and monaural beats were presented to a group of participants who were then asked to perform certain tasks. The number of incorrect answers was smallest in the group that listened to the binaural beats.

Finally, a 2019 study investigated a group of participants who listened to binaural beats either in the beta or theta range, which are associated with an active mind and sleep or tiredness, respectively [26]. Afterward, participants were asked to perform recall tasks. It was observed that people exposed to binaural beats in the beta range recalled more words correctly than those exposed to binaural beats in the theta range.

Mental Health

A study surrounding military service members investigated using theta brainwave frequency (4–7 Hz) in music with embedded binaural beats (known as binaural beat therapy [BBT]) compared to using music alone on the cardiovascular stress response in military service members with chronic stress following deployment [27].

> When assessing pre and post heart rate variability findings, both groups showed a decline in Total Power HRV measures; however, the decline was more substantial in the music only group. In other words, those who did not use music with BBT showed more clinical signs of chronic stress when placed under a mental stressor. When comparing pre and post HRV low and high frequencies, those who used BBT had a decrease in low frequency and an increase in high frequency, whereas those who used music only had the opposite effect. In other words, when stressed, those who used BBT had a decreased sympathetic response and an increase in parasympathetic control, while those with music only had the opposite effect.

Those service members who used BBT also reported less stress over four weeks in their daily diaries.

Another study evaluated the use of heartfulness meditation and auditory BWE to help teenagers cope with mental health issues [28]. It used 30-min heartfulness meditation and 15-min brainwave entrainment sessions with binaural beats and isochronic tones three times a week for four weeks. Participants were put into four groups—control, audio BEW, heartfulness meditation, and combined. The singular BWE group did not see statistically significant improvements, nor did any of the intervention groups for brain health. The heartfulness meditation group improved their overall mood, stress levels, anger, and depression. Results suggested that adding audio BWE to heartfulness meditation might improve sleep quality and stress levels.

Monaural beats studies were more limited than binaural but still explored how audio stimulation affected BWE and, in turn, stress, anxiety, and mood. One study, which resulted in monaural beat stimulation modulating state anxiety, was in line with previous studies reporting anxiety-reducing effects of auditory beat stimulation [28].

2.4 Research Focused on EEGs and MEGs

EEGs measure electrical activity in the brain using small, metal discs (electrodes) attached to the scalp. When brain cells communicate, they show up as wavy lines on an EEG recording, making it easy to see changes in brain activity.

MEG is a noninvasive way to measure the magnetic fields generated by electric currents in the brain. It is used to map brain function and activity while evaluating a brain's spontaneous activity and checking its response to specific stimuli.

Both EEGs and MEG are used to measure brain activity produced during BWE.

2.4.1 EEG

EEG activity was recorded during an experiment to discern the reliability of neural entrainment in the human auditory system [29]. The study aimed to establish the reliability of neural entrainment over time and predict individual differences in auditory perception from associated neural activity. The results demonstrated that neural entrainment in the auditory system and the resulting behavioral modulation were reliable over time, and both entrained delta and nonentrained alpha oscillatory activity contributed to near-threshold stimulus perception. The latter suggested that improving auditory perception might require simultaneously targeting entrained brain rhythms as well as the alpha rhythm.

A 2018 study intended to develop and validate an EEG closed-loop system to deliver auditory stimulation during sleep to enhance slow waves. The EEG measured changes in sleep architecture that correlated with aging; younger participants showed significant slow-wave activity enhancement compared to older participants [30].

Researchers proposed a device that used noninvasive neurotechnology in acquiring any mental state, from heightened alertness to deep rest. The device used auditory brain stimulation and real-time EEG neurofeedback technology to produce a personalized binaural beat track for the user [31]. This track was designed to help the user achieve a particular mental state while also reducing the occurrence of dizziness sometimes experienced by binaural beat stimulation.

2.4.2 MEG

Researchers in 2021 explored the possibility of inducing a desired brain state by replicating distinct neural correlates found in a “donor” brain state [32]. Brain waves were recorded from a “donor” in a particular brain state using MEG to extract cortical signatures. This technique could provide noninvasive, nonpharmacological treatment of a variety of psychiatric and neurological disorders, although further experimentation was suggested.

2.5 Research Focused on Human Performance Experiments and Results

Measuring human performance while being exposed to BWE is the goal when studying the effects of entrainment. A variety of tests, experiments, and studies all aim to identify how human performance is affected by audio stimulation and BWE. The following studies explore a variety of ways human performance is impacted, including sleep and mental health disorders.

2.5.1 Sleep

Researchers from the AI Research Group in Korea developed a pillow integrated with audio speakers that produce alpha and theta beats to improve sleep, resulting in a positive effect on sleep onset latency [33]. This noninvasive stimulation technique is a promising candidate for wearable bioelectronics medicine. The pillow was designed and made to generate sounds for brain entrainment. The speaker generated synchronized pulsed tones at an alpha or theta frequency. The tones were applied 30 min prior to sleep to induce deep sleep and improve sleep quality. Sleep polysomnography was used to detect and record various biological signals, including EEG, electrooculogram, and electromyogram that appear during sleep.

2.5.2 Mental Health and Neurodevelopmental Disorder

Auditory BWE has been shown to improve relaxation, therefore lowering stress and anxiety. BWE can also be used to improve problem-solving skills, particularly in individuals with ADHD. Results suggested that brainwave entrainment had a moderate effect on the participant’s problem-solving skills [34].

2.5.3 Other

BWE has been a method used as therapy in the Philippines to reduce anxiety and heighten concentration, facilitating the brain to enter a specific state. A study was conducted during athletes’ precompetition routines to identify if wave-synchronized music influenced power performance [35]. Collegiate athletes participating in shotput, discus, and javelin events were

studied. Both high- and low-frequency waves were used during an 11-day period, with results showing that synchronizing alpha waves to music during warm-up led to significant increases in throwing distances of participants. Synchronizing theta waves to music produced significantly lower throwing distances compared to day-before and day-after observations. Throwing performance for the untreated observations showed an increasing trend before the theta wave treatment day. No long-term effect of alpha waves was directly seen after the intervention ended, and further studies using wave synchronizers were recommended.

A unique study from 2019 determined that different geometric forms and construction materials had an impact on brainwaves and consciousness when paired with a variety of BWE. It was concluded that there was an obvious relationship between the geometric forms of an architectural space and their construction materials and a users' consciousness [36]. Different forms allowed for different states of consciousness to be reached by a user, also dependent on the material used in the architecture. A pyramid shape resulted in BWE changing a user's state of consciousness to relaxation and comfort status using delta waves. This was also seen with the steel square and concrete dome. BWE was able to change a user's state of relaxation to one of mediation and creativity, theta waves were used, and the change occurred when a user was in a cylinder space (with steel, wood, or glass) or in a steel or wooden dome. This state could also be attained if a user stayed in a vault form made of concrete, steel, or glass. Alpha waves helped users achieve moderation in mental stability in a square space made of concrete or glass materials. This also occurred in a wooden cone and vault, as well as a concrete cylinder.

2.6 Conclusions

BWE via audio stimulation using lower frequencies across a variety of topics generated mixed results. Overall, BWE is a promising, noninvasive technique that can induce certain mental states and levels of consciousness in the human brain. It has been found to improve cognition, memory, mood, stress, pain, and human behavior through various experiments over the past five years. In general, more research is needed to verify results and conduct larger studies to corroborate prior results.

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Biography

Taylor H. Knight is a research analyst and the Technical Inquiry Research Service Lead at the Defense Systems Information Analysis Center (DSIAC). She provides technical research services to answer defense-related inquiries submitted by the U.S. Department of Defense science and technology community. Prior to working for DSIAC, she worked in education for 10 years, with a focus in the science, technology, engineering, and mathematics disciplines. Mrs. Knight holds a B.S. in elementary education and an M.S. in human resources development.

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