The Effect of Brainwave Entrainment on Cognitive Performance: An Experimental Study

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This study investigates the impact of brainwave entrainment (BWE) on cognitive performance, measured through tasks assessing alternative uses (AUT) and continuous performance (CPT). Belief in the effectiveness of BWE technology was also examined for its potential correlation with performance improvements. Results from non-parametric the Wilcoxon Signed Ranks Test and Spearman's rho correlation, suggested no significant changes in AUT and CPT performance post-BWE, nor a significant correlation between belief levels and performance changes, although small improvements were found across several metrics.

Keywords: Brainwave Entrainment, Cognitive Enhancement, Alternative Uses Task (AUT), Continuous Performance Task (CPT), Belief and Technology Effectiveness, Pre-post Intervention Study, Binaural Beats, Cognitive Performance Measures

Introduction

Results from studies exploring brainwave entrainment (BWE) have since long sparked interest among researchers in the phenomenon and potential use cases for improved physiological and mental health, as well as enhancement of cognitive function. This study aims to explore the effects of BWE on cognitive tasks, including alternative uses tasks (AUT) and continuous performance tasks (CPT), together with a between-groups analysis to explore the level of significance that brain wave-type/frequency band used has on any potential changes in cognitive performance. The study also aims to investigate presence of placebo effect in any performance changes, by correlational analysis of participants self-reported belief in BWE and similar technology and their potential to affect cognitive functioning, and any changes in the performance metrics pre/post-BEW intervention.

Brainwave entrainment (BWE) is a method that uses auditory or visual stimuli to induce changes in brainwave patterns, and represents a frontier in cognitive enhancement research. This technique presupposes that inducing specific brainwave states can improve cognitive functions, such as attention, memory, and creativity. The theory behind this is the discovery of specific states of the brain, where the collective activity generates a frequency signal in different frequency bands depending on activity, such as the wave bands correlated with the various stages of sleep (alpha, theta and delta, and beta during REM) (Patel et al, 2024). These frequencies are produced by the neurons and can be measured by for example EEG in the cortex, hippocampus and cerebellum (animal studies) according to Basar et al (1996). Various BWE methods utilize visual and/or auditory stimulation in forms of pulsing stimuli, in a certain frequency band, as a way to couple the brains wave frequency to that of the stimuli, and thus inducing a cognitive effect correlating to the frequency band used in the stimulus, such as Kim et al (2014) showing some enhancement of attention and focus after alpha-band stimulation.

The present study aims to explore the efficacy of BWE in enhancing cognitive performance, focusing on two primary tasks: the Alternative Uses Task (AUT) for measuring creative thinking and the Continuous Performance Task (CPT) for assessing attention and ability to maintain focus. Additionally, this study investigates the influence of participants' belief in BWE technology on their performance, addressing a gap in the existing literature regarding the placebo effect in cognitive enhancement technologies. Furthermore, another knowledge gap was attempted to be filled, by investigating the significance of specific stimuli frequency bands/programs selected on performance, or whether performance changes can be seen regardless of program or frequency band of stimuli.

Background

Brainwave entrainment involves synchronizing one's brainwave frequencies with the rhythm of external stimuli, typically through audio beats or light pulses. The premise is grounded in the brain's natural tendency to align its electrical patterns to external frequencies, a phenomenon known as the Frequency Following Response (FFR) – which is auditory-evoked potentials (AEP), that follows periodic characteristics of a sound (Lopez-Caballero et al, 2020), Research in this area has shown that by targeting specific brainwave states associated with different cognitive functions, BWE can facilitate improvements in those areas. For instance, theta waves (4-7 Hz) are often linked to creativity (Stevens and Zabelina, 2019), while beta waves (13-30 Hz) are associated with alertness and concentration (Hendrayana et al, 2020).

A review study by Henao et al (2020) claims that “neural entrainment to auditory stimulation may constitute a unique gateway to modulate human brain functions.”, citing several studies that point to enhanced cognitive functions, such as learning and memory, as well as promising results from animal studies regarding cognitive enhancement in Alzheimer's disease, for example Laccarino et al, (2016). Lee et al (2018) and Martorell et al (2019). Another study named, Ngo et al (2013), with claims that simple acoustic stimuli being able to enhance slow-wave brain activity, with benefits of promoting deeper sleep and memory consolidation.

Many studies has focused specifically on the 40 Hz audiovisual frequency spectra, after discoveries of this frequency range surrounding 40 Hz being linked to many physiological and cognitive functions, increasing interest of stimulations in this range as a non-invasive clinical rehabilitation method for brain dysfunctions such as cognitive/language/motor functions, and mood and sleep dysfunctions, according to Chen et al (2022). The authors states however that the underlying mechanisms behind these positive effects and gamma-band (30-100 Hz) oscillation-stimulation is not well known, but promising results have shown increased synaptic plasticity as well as modification to the connection between brain networks from gamma-band stimulation.

The ideas behind modulating oscillation-rhythms via external stimuli, in order to affect cognitive performance dates back to the 1930s (Adrian and Matthews, 1934), and has been explored throughout the modern history, together with questions regarding stimulation of the 40 Hz gamma-frequency band and potential health gains from that, through studies by Basar et al (ca 30 studies between 1972 and 1996 on the topic of induced gamma-band responses), as well as functional correlates between vibrations in memory structures and memory-binding in Stryker (1989). Evidence that gamma-band responses in the brain can be elicited in the brain with audio/visual stimulation has been presented by Basar et al (1987) and Pantev and Elbert (1994), showing the potentiality of inducing brain states using external stimuli. It has further been shown in insect nervous systems, indicating it is not correlated with higher cognitive capabilities (Kirschfeld, 1992), leading to assumptions that found effects not being able to be willful in nature, but rather subconscious/automatic. Other studies point to evidence of gamma wave stimulation (amplitude varied), affects level of attentiveness in a test subject (Bouyer et al, 1987), indicating that induced brain states actually are able to affect cognitive function.

Research Question and Hypothesis

This study is guided by three primary research questions:

1. Does BWE alter cognitive performance on AUT and CPT tasks?
2. Does the type of brainwave stimulated (correct vs. incorrect for the given task) affect AUT performance?
3. Is there a correlation between belief in BWE and similar technology and performance change? (thus indicating presence of potential placebo effect)

Based on the literature review and theoretical background, this study hypothesize that:

Participants will show improved performance on both AUT and/or CPT tasks following BWE sessions. Participants receiving brainwave stimulation congruent with the cognitive task (e.g., Theta-Alpha stimulation for AUT) are also hypothesized to perform better than those receiving incongruent stimulation (Beta-Gamma). The study has no reason to expect present placebo effect.

Method

Participants

The study was based on data from 10 participants in total. They were recruited in academic and social circuits using personal invitation. The participants' ages ranged from 24 to 48, with an average age of 33,2 years. 3 of the participants identified as "male", 7 as "female", and none as "other". There were no specific selection criteria. Participants were asked for known/historic epileptic issues, however no participants were excluded.

Materials

In this study 2 separate cognitive tasks were performed by the participants, pre-intervention and then repeated post-intervention. The tasks were AUT (Alternative Uses Task) and CPT (Continuous Performance Task). In addition, participants were asked for their belief in the efficacy of BWE and similar technology, for cognitive enhancement.

The BWE-device used was the PROTEUS Light Sound Stimulation System, from The MindPlace Company Inc. It consists of eye frames containing eight bicolor LED's (red/green), headphones and a storage device containing 49 pre-programmed sessions. The sessions are grouped into eight categories (Peak performance, Tranquility, Learning, Well-being, Visualization, Energy, Deep rest, Pyrotechnics), each with a number or session programs. The categories and programs differ in frequency bands used, as well as session segment structure. The programs used in the study was:

"Creativity Enhancement" - Ranges from Theta (4-8 Hz) to Alpha (8-12 Hz) frequencies, and proposed to enhance creative thinking, relaxation and light meditation.

"Power Regenerator" - Ranges from Beta (13-30 Hz) to Gamma (>30 Hz) frequencies, claimed to enhance alertness and concentration (but not creativity).

"Concentration" – Operates in Beta (13-30 Hz) frequencies, and proposed to enhance active/analytic thought and focused attention.

To test to what degree choice of brain wave-type/program has on performance, the participants were divided into two equal groups, so that every other participant got correct BWE-program for the AUT/creativity task (the “Creativity Enhancement” program, operating in Theta to Alpha frequencies), and the other half got incorrect BWE-program, namely the “Power Regenerator” program which operates between the Beta and Gamma bands.

The device uses a combination of light pulses in frequency ranges as per above, coupled with synced auditory binaural beats. The binaural beats element uses 2 slightly off-phase frequencies, presented to each ear, which is perceived as a third auditory frequency (which is synced to the light system). Each program starts by fading in audio and visuals, leading to a range of varying intensity and frequency changes, specific to each program, and ends by fading out both audio and visuals.

PsychoPy (2023.2.3) was used for the experiment design and procedure. A welcome screen was presented at session start, followed by text boxes where the participant entered gender and age. After this a series of information screens was presented, describing each part of the experiment clearly. The AUT task consisted of an item or object presented on a timed screen of 150 seconds duration, with a text-input box for the participant to enter alternative uses for the presented item. ´This was followed by another item lasting for another 150 seconds. The participant was instructed to being creative and enter alternative uses in free form, separating words in any way, in English or Swedish. Next a CPT-instruction screen were shown, followed by a 20 second demo, and the actual CPT task. The CPT was constructed using a presented number, randomized between 1-100 using Python-script, wrapped by a loop with 240 repetitions. Each number was presented with 0,7 second duration, followed by 0,3 seconds mask of no number, bringing the total task time to four minutes. Participants were instructed to press space on the keyboard as fast as possible, every time a “4” was present in the presented number (for example 4, 34, 47). The keyboard presses was counted using Python-script, and saved together with the rest of the data in a CSV-file. It also collected number of Misses (a 4 was presented, but no space-press), and False Alarms (space-press with no 4 presented), as well as reaction time measured from number presentation to keyboard press. After the CPT, a survey was conducted with the question “To what extent to you agree with the following statement: ‘I believe that peoples cognitive performance and/or brain states can be enhanced/altered by binaural beats, light-stimulation, and other similar techniques.’”, asking the participants to select a value between 0-10 on a marked scale, where 10 indicated agree fully. This lead to a thank you-screen, and the end of the experiment.

Microsoft Excel was used for data cleaning and collecting, and later imported into PsychoPy. Beyond this, a regular keyboard and mouse was used with a laptop computer.

Procedure

As participants sat down and got comfortable, participant id (sequential starting from 1) and session number (1 for pre-intervention, or 2 for post-intervention) was entered into PsychoPy by the researcher. The participant began by entering gender and age on the screen. After this a series of introductory texts was presented on screen, welcoming the participants to the study, and explaining in successively greater detail what was to be expected during the sessions. The participants was told to take their time and to ask questions as they arose, as well as themselves press right arrow on the keyboard to advance from screen to screen in the study in their own time. After a more detailed AUT-instruction was presented, the participant got to perform a short demo-run consisting of a presented item, and 20 seconds to write alternative uses. This was followed by the actual AUT task, which consisted of 2 separate sections containing one item, each lasting for 2,5 minutes, with a screen in between requiring the participant to press right arrow to proceed to the next item. After this, an instruction screen for the CPT task was presented, followed by a 20 second demo of flashing numbers. This was followed by the actual CPT task, lasting for four minutes, ending with a screen congratulating them for completing the first session.

Following the first, pre-intervention session, participants were asked to equip the BWE gear (glasses and headphones) and sit or lie comfortably. The structure of this second study session was; BWE segment 1 followed by AUT post-segment, then BWE segment 2 followed by CPT post-segment. The first BWE segment consisted of a 20-minute program, “Creativity Enhancement” for group 1, or “Power Regenerator” for group 2. The following AUT task was identical, except there was no demo given pre actual run. Immediately after the AUT, the second BWE segment was performed, this time lasting for 15 minutes, using the “Concentration” program for all participants, again followed by a PsychoPy task, the CPT, again four minutes long. This round ended with a question regarding the participants belief in BWE efficacy in cognitive enhancement, selecting with the mouse on a scale from 0 belief to 10. Lastly a thank you screen was presented.

Data Analysis

Variables

Participant ID, Gender (Male, Female, Other), Age, Group (1/2), Belief (0-10), AUT Score pre & post, CPT Actual, CPT Hits pre & post, CPT Hit Percent pre & post, CPT Misses pre & post, CPT False Alarms pre & post, CPT RT pre & post, AUT Diff, CPT Hit Percent Diff, CPT RT Diff.

AUT Score - refers to the average number of generated alternative uses for item 1 and 2, for pre and post conditions. CPT Actual – the number of times a “4” was presented during a session. CPT Hits – the number of times the participant correctly pressed space when a “4” was presented. CPT Hit Percent – the ratio of Hits to Actual. CPT Misses –

number of times a “4” was presented, but the participant failed to press space. CPT False Alarms – Number of times the participant pressed space with no “4” presented. CPT RT – average reaction time of space-presses (total summed reaction time of all space presses, divided by (Hits + False Alarms)). AUT Diff/CPT Hit Percent Diff/CPT RT Diff – The difference in performance from the pre- to the post-condition.

Tests

Shapiro-Wilk tests for normality were performed on relevant variables. The tests of normality as per below, showed in some cases that parametric tests were justifiable, due to normality assumption not ruled out. A comparison between results on CPT RT, using parametric (paired samples t-test) and non-parametric (Wilcoxon signed ranks test) showed similar significance levels ($p = 0,386$ & $p = 0,316$). However, based on the similar results above, the low sample size, and for consistency, the conservative non-parametric tests were decided on across the board.

As for non-parametric testing, the following tests was used:

- Pre/Post comparisons: Wilcoxon Signed Ranks Test was used for related samples (pre/post testing of AUT scores, CPT Hit Percentages, and CPT RT).
- Group comparisons: The Mann-Whitney U test was used for comparison between groups 1 and 2, in AUT scores.
- Correlation analysis: Spearman’s Rho was used to explore correlation between performance change and the Belief variable.

Results

Overview of Statistical Analyses

This study employed a 3-way analysis strategy – a pre/post-intervention comparative analysis (Wilcoxon Signed Ranks Test), a between-groups comparative analysis (Mann-Whitney U test), and a correlational analysis (Spearman's Rho). After normality assumption tests (Shapiro-Wilk Test for Normality), it was decided that non-parametric tests would be used for all analyses (further discussed in the Tests of Normality section below). In the Results section, "Z" refers to the test statistic for Wilcoxon Signed Rank test, indicating the degree of difference between pre and post scores. "U" refers to the Mann-Whitney U test statistic, comparing differences between two independent groups. "rho" refers to the metric in Spearman's Rho correlational test, where positive rho indicates a direct relationship, and negative rho an inverse relationship.

Descriptive Statistics

The study in its first analysis indicated slight changes in cognitive performance pre/post intervention measures across three different metrics: AUT Scores, CPT Hit Percentage, and CPT RT. Sample size (N) for all tests was 10.

AUT Scores

Participants exhibited a slight increase in alternative uses generated, with mean scores in the AUT, rising from 8,6 (SD = 3,627) pre-intervention, and 9,15 (SD = 4,1903) post-intervention. Values ranged between 3,5 – 14,5 pre, and 4,0 – 15 post.

CPT Hit Percent

Changes in CPT performance measured in accuracy (through Hit Percent) showed a slight decrease in accuracy from a pre-intervention mean of 99,22% (SD = 1,27) to 98,91% (SD = 1,56) post. Values ranged between ,970 – 1,0 pre, and ,956 – 1,0 post.

CPT RT

Reaction time improved slightly post intervention, decreased from 457 milliseconds (SD = 45,73) pre, to 450 milliseconds (SD = 31,91). The min/max span was 396 – 533 milliseconds pre, and 399 – 489 milliseconds post.

Tests of Normality

AUT Pre/Post showed no significant difference from normality (p = ,760, p = ,115), suggesting that parametric tests could be - but was decided not to be - used. CPT Pre/Post Hit Percentage showed sig departure from normality (p = ,001, p = ,002). CPT Pre/post Average RT did not show signs of departure from normality (p = ,482, p = ,191). The Belief variable did significantly deviate from normality (p = ,025). Furthermore, for AUT Group 1/2, Pre/Post normality could not be ruled out (p = ,194), while for CPT Hit Percentage group 1/2 & for CPT RT group 1/2 normality could be ruled out (p = ,026 & p = ,023).

As discussed above, although several variables showed signs of being normally distributed, which could justify using parametric t-tests, it was decided against in favor of consistency and conservatism.

Pre-Post Intervention Analyses

For AUT Scores, the Wilcoxon test indicated no sig change post-intervention (Z = -,767, p = ,443). A similar lack of significance was found for both CPT Hit Percent (Z = -,135, p = ,893), and CPT RT (Z = -,866, p = ,386).

Between-Groups Comparative Analysis

The results from the Mann-Whitney U test revealed no significance below the ,05 standard (U = 4,500, Z = -1,676, p = ,094).

Correlation with Self-Reported Belief

Spearman's Rho correlation analysis revealed no significant correlation coefficients between self-reported belief and performance changes across AUT Scores, CPT Hit Percent, or CPT RT, suggesting that any observed changes cannot be correlated with participant belief or expectations.

Belief – AUT Diff

A weak positive correlation was observed between Belief and AUT Score change (rho = ,237), although this was not statistically sig (p = ,511).

Belief – CPT Hit Percent Diff

A weak negative correlation detected between Belief and difference in CPT Hit Percent (rho = -,054), with no statistical sig (p = ,882).

Belief – CPT RT Diff

A small positive correlation was revealed between Belief and difference in CPT reaction time (rho = ,158), but similarly at no statistical significance (p = ,662).

Confidence Intervals for Correlations

CI's were calculated to assess precision of the correlations. For Belief - AUT Diff, the interval ranged from -.479 to .763, indicating considerable uncertainty around the correlation estimate. Similarly, the intervals for Belief - Hit Diff (-.673 to .610) and Belief - RT Diff (-.539 to .727) suggested wide ranges of potential true correlation values, and therefore high uncertainty in the findings.

Discussion

The findings suggest that, within this study, BWE did not significantly impact the cognitive performance measures assessed.

Spearman's Rho correlation analysis explored the relationship between participants belief in BEW and similar technologies effectiveness on cognitive performance, and the measured performance changes across AUT Scores, CPT Hit Percent, and CPT RT, revealing no significant correlations. This suggests that any performance changes observed can not be correlated with the participants beliefs or expectations.

The wide intervals observed, such as between Belief and AUT Diff (-,479 to ,763) hints at the uncertainty of the estimated correlations, underscoring the need for further research with larger sample sizes in order to more accurately determine the nature of the relationships.

It is believed, that despite the non-significant results, indications could anyhow propose avenues for future studies in the correlation between belief and performance change, as well as investigate to what degree choice of frequency band matters, including comparative tests between all common wave bands (delta, theta, alpha, beta, gamma), and relevant tasks.

Limitations

The experiment setting varied, for participant convenience, which reduced environmental control. The sample size was also very small with N = 10, which tends to reduce reliability and generalizability significantly. The decision to use non-parametric tests was justified, but lead to potentially lower results. More task-types could have been beneficial, as well as longer task-durations, especially in the CPT task, could have provided insights into focus-maintenance aspects over longer periods. There was also some lack of specific knowledge on the parameters used in the BWE-device and it's programmed sessions.

Conclusions

The results revealed in this study does not support BWE as a method of cognitive enhancement. Effects were found in several tests and comparisons, but the small size of the effects and the levels of significance were insufficient to be able to draw conclusions from. Trials were made using parametric tests for the variables that justified it, to no big difference in p-values. However, since the results in many cases were present and in line with the claims of BWE proponents and practitioners, it suggests that there could be value in further studies, using larger sample sizes and even more robust methods.

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Appendices ***

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