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Title: Modulation of Cortical Oscillations and Interregional Connectivity by Low-Frequency Pitch Stimulation: Insights from EEG Spectral and PLV Analyse

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Abstract:

Background: Low-frequency acoustic stimulation can entrain brain oscillations, yet most studies have emphasized gamma-range auditory inputs. The region-specific cortical effects of *sub-gamma* low-frequency pitch tones in healthy adults remain largely unexplored, and safety concerns persist due to historical reports of adverse effects at high intensities.
Objective: To characterize safe, sub-threshold, low-frequency pitch–induced modulation of cortical oscillations and connectivity using EEG in healthy adults.
Methods: Twenty adults were exposed to pure tones (30, 45, and 60 Hz) at intensities <40 dB SPL; well below thresholds associated with adverse neurological effects, under controlled laboratory conditions. EEG was recorded from 8 strategically placed electrodes (covering frontal, parietal, occipital, and temporal regions) using the international 10–20 system, enabling targeted region-of-interest (ROI) analysis while minimizing noise and redundancy. Power spectral density and alpha-band phase-locking values (PLVs) quantified spectral and connectivity changes.
Results: Safe-level low-frequency stimulation elicited region-specific increases in alpha and theta power in frontal, parietal, and occipital cortices ($p < 0.05$), particularly at 30–45 Hz. Alpha-band PLVs showed enhanced frontal–parietal, frontal–occipital, and parietal–occipital coupling ($p < 0.05$). Pitch and exposure duration significantly predicted oscillatory changes ($p = 0.0018$).
Conclusion: Contrary to prior studies linking low-frequency sound to risk at high intensities, our findings demonstrate safe, targeted neuromodulation at sub-threshold levels, revealing frequency-specific entrainment patterns with potential cognitive and therapeutic applications.

Keywords: Low-frequency pitch stimulation; EEG spectral analysis; Cortical oscillations; Alpha-band connectivity; Functional connectivity; Auditory neuromodulation.

Introduction

The human brain operates as a network of oscillatory systems, with distinct frequency bands subserving perception, cognition, and consciousness. External rhythmic stimuli, including sound, can modulate these oscillations through entrainment, creating opportunities for non-invasive neuromodulation [1, 2]. While most auditory entrainment research has focused on gamma-frequency stimulation (e.g., 40 Hz), low-frequency pitch tones within the 30–60 Hz range have received minimal attention, despite their potential to interact with intrinsic alpha and theta rhythms. Previous studies examining low-frequency auditory effects often employed high intensities or targeted pathological conditions, where risks such as epileptiform activation were noted [3, 4]. In contrast, the present work investigates stimulation at intensities well below adverse thresholds (<40 dB SPL) in healthy populations. Furthermore, earlier research frequently used broadband or mixed-frequency noise, limiting insights into pure-tone, frequency-specific cortical entrainment. By isolating these parameters, our study provides a controlled assessment of safe, reproducible modulation of brain oscillations and connectivity.

Given our aim to examine region-level oscillatory dynamics rather than fine-grained source localization, we employed an 8-channel EEG system distributed across major cortical regions. This configuration optimizes spectral and phase-locking value (PLV) analysis while minimizing redundancy and computational noise, providing sufficient spatial resolution for detecting region-specific changes in oscillatory power and inter-regional coupling.

Understanding the frequency-specific effects of low-intensity pitch stimulation is important for two reasons. First, it holds therapeutic potential: targeted entrainment may aid cognitive rehabilitation, attention enhancement, or mental health interventions without the risks associated with higher-intensity protocols. Second, it offers mechanistic insights into how rhythmic auditory inputs shape large-scale network dynamics and sensory-driven plasticity.

We hypothesized that low-frequency pitch stimulation at safe intensities would enhance alpha and theta oscillatory power and strengthen alpha-band connectivity across frontal, parietal, and occipital regions. This work provides evidence that pure-tone stimulation within the 30–60 Hz range can selectively engage large-scale cortical networks without adverse effects

Materials and Methods

Study Design and Participants

This randomized parallel-group experimental study was conducted among young adult students at Delta State University, Abraka, Nigeria (5°47′0″N, 6°6′0″E) during the 2019/2020 academic session. The source population comprised 19,657 students aged 16–35 years. A total of 400 participants were recruited and randomly allocated to four stimulation groups (n = 100 per group) corresponding to 30 Hz, 40 Hz, 50 Hz, and 60 Hz auditory stimulation. All participants underwent baseline EEG recording in silence prior to stimulation.

Sample size estimation was performed using G*Power 3.1, assuming a medium effect size (Cohen's d ≈ 0.4) and 80% power at $\alpha = 0.05$. A minimum of 88 participants per group was required; 100 were enrolled per group to account for attrition and data loss from artifact rejection

Eligibility Criteria

Only participants with no known auditory pathology (including partial or complete hearing loss), no use of ototoxic medications, and no history of neurological disorders were included. Exclusion criteria included ongoing ear treatment, a history of epilepsy, or any psychiatric condition. All participants were screened using an otoscope and medical questionnaire before enrolment.

Acoustic Stimulation Protocol

Pure sinusoidal tones at 30 Hz, 40 Hz, 50 Hz, or 60 Hz were generated using Audacity® (v3.1.3) and delivered via calibrated Bluetooth-enabled binaural earphones (Impedance: 32 Ω; frequency response ±0.5%). Stimuli were presented at ~70 dB SPL for 5 minutes following a 2-minute baseline silence. Participants sat upright in a sound-attenuated, dimly lit studio and were instructed to keep their eyes closed and remain still. Room temperature was maintained at ~24°C

EEG Data Acquisition

EEG was recorded using an OpenBCI Cyton Biosensing Board (OpenBCI Inc., USA) with 8 channels, 24-bit resolution, and a sampling rate of 250 Hz. Electrodes were positioned according to the international 10–20 system at Fp1, Fp2, F3, F4, P3, P4, O1, and O2. FPz served as ground and the right mastoid as reference. Electrode impedance was maintained below 5 kΩ using conductive gel. Signals were visualized in real-time via the OpenBCI GUI to monitor data quality and logged for offline processing in MATLAB. Calibration was performed weekly with a test signal generator to ensure fidelity

EEG Preprocessing

Data were exported as .csv files and imported into MATLAB R2022b using EEGLAB (v2022.0). Preprocessing steps included common average re-referencing, segmentation into 2-second epochs with 50% overlap, baseline correction, and bandpass filtering between 0.5 and 45 Hz using a zero-phase Hamming-windowed FIR filter. A notch filter at 50 Hz was applied to remove line noise. Artifact rejection was performed through visual inspection and Independent Component Analysis (ICA) to remove ocular, muscle, and cardiac components.

EEG Streaming Session

Haven cautiously placed all electrodes on participants' head, the OpenBCI GUI (Open Brain-Computer-Interface Graphical User Interface), a pre-installed, open-source software that accompanied the EEG kit was launched (by double-clicking the icon) and configuring for live (from Cyton Bioseng Board) EEG streaming with the wireless serial (Dongle) port connected to the computer, while simultaneously administering sounds (via a headset) on participant subjects. Figure 1 shows a screenshot image of the GUI session for one of the participant's session

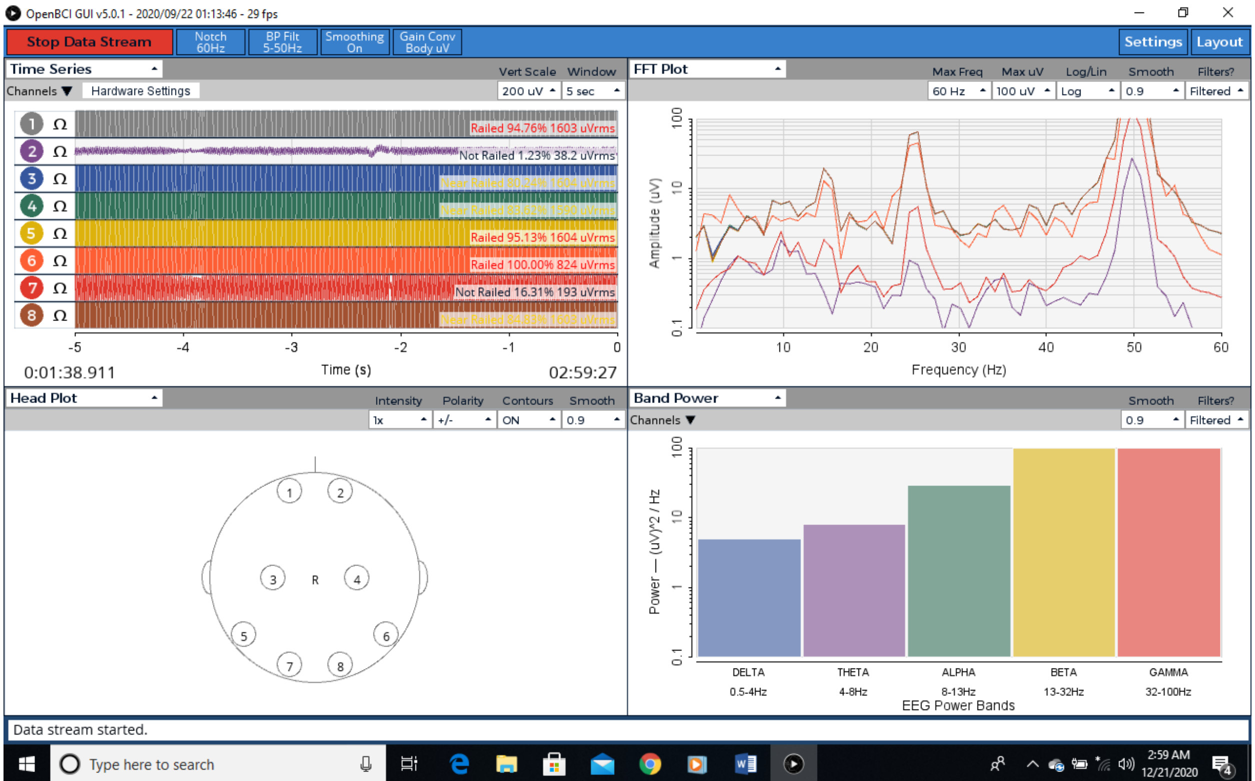

Figure 1: Screenshot image of the Open BCI GUI session for one of the participants. EEG signals were visualized in real-time using the OpenBCI GUI and logged for subsequent export as .csv files for offline processing in MATLAB

Note: This entire procedures were recorded for all of the sampled subjects and subsequently accessed within the notepad file (figure 2), before exporting as `.csv` for METLAB analysis.

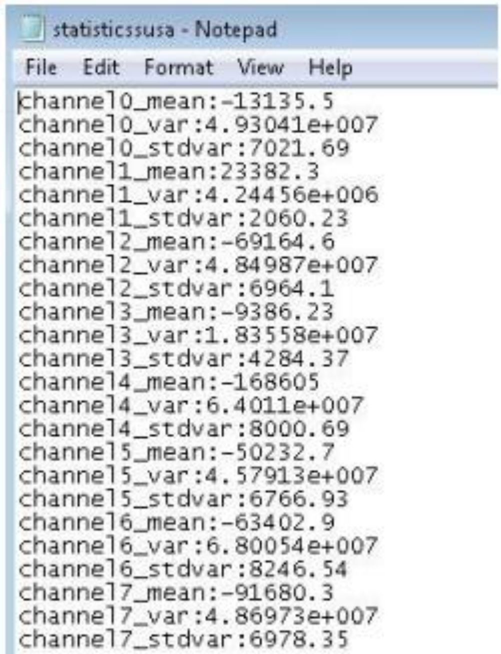
statisticssusa - Notepad
File Edit Format View Help
channel0_mean:-13135.5
channel0_var:4.93041e+007
channel0_stdvar:7021.69
channel1_mean:23382.3
channel1_var:4.24456e+006
channel1_stdvar:2060.23
channel2_mean:-69164.6
channel2_var:4.84987e+007
channel2_stdvar:6964.1
channel3_mean:-9386.23
channel3_var:1.83558e+007
channel3_stdvar:4284.37
channel4_mean:-168605
channel4_var:6.4011e+007
channel4_stdvar:8000.69
channel5_mean:-50232.7
channel5_var:4.57913e+007
channel5_stdvar:6766.93
channel6_mean:-63402.9
channel6_var:6.80054e+007
channel6_stdvar:8246.54
channel7_mean:-91680.3
channel7_var:4.86973e+007
channel7_stdvar:6978.35

Figure 2: *Screenshot of notepad file that logged EEG waveforms for the duration of sound administration on participants. Noticeable from the file are the EEG records for each of the channels as obtained for EEG activity.*

Spectral and Connectivity Analysis

Power spectral density (PSD) was computed using fast Fourier transform (FFT) with a 2-second Hanning window and 50% overlap. PSD was averaged for standard frequency bands: delta (0.5–4 Hz), theta (4–8 Hz), alpha (8–13 Hz), beta (13–30 Hz), and gamma (30–45 Hz). Cortical regions were defined as frontal (Fp1, Fp2, F3, F4), parietal (P3, P4), and occipital (O1, O2). Phase-locking value (PLV) was calculated for interregional connectivity within the alpha band.

Alertness Monitoring

Participants were monitored verbally to prevent drowsiness during recordings. EEG traces were screened for prolonged alpha/theta dominance indicating sleep onset. Sessions showing such patterns were excluded (6 out of 400 recordings).

Statistical Analysis

All data were analyzed using GraphPad Prism v8.1 (GraphPad Software, USA). Variables were assessed for normality using the Kolmogorov–Smirnov test. Log transformations were applied to non-normally distributed variables. A two-way repeated-measures ANOVA (condition × region) was performed to evaluate EEG power differences across stimulation frequencies and brain regions. Tukey's HSD test was applied for post hoc comparisons. Pearson's correlation coefficients were computed to assess relationships between sound frequency and regional power modulation. Statistical significance was set at $p < 0.05$.

Results

This study explored how low-frequency auditory pitch stimulation (30–60 Hz) affects cortical electrical activity and interregional functional connectivity in healthy adults. While broad analysis of global brainwave frequencies showed no statistically significant variations across pitch conditions, further region-specific spectral and connectivity analyses revealed significant modulations, particularly within the theta and alpha bands. The results are organized into global spectral shifts (Table 1), correlation / regression analyses (Tables 2–3), regional power changes (Table 4), and functional alpha-band connectivity (Table 5).

Global Brainwave Analysis: No Significant Changes Detected Across Conditions

Table 1: Mean EEG Frequency Components across Pitch Conditions (Global Averages)

Pitch	Gamma (Hz)	Beta (Hz)	Alpha (Hz)	Theta (Hz)	Delta (Hz)
Baseline	32.42 ± 0.09	28.16 ± 0.13	9.14 ± 0.07	4.73 ± 0.04	1.03 ± 0.05
30 Hz	32.39 ± 0.09	28.02 ± 0.14	9.36 ± 0.07	4.71 ± 0.04	2.08 ± 0.08
40 Hz	32.42 ± 0.09	27.85 ± 0.15	9.32 ± 0.08	6.00 ± 0.09	0.94 ± 0.05
50 Hz	32.48 ± 0.85	27.94 ± 0.14	10.98 ± 0.09	4.74 ± 0.05	1.01 ± 0.05
60 Hz	32.36 ± 0.09	29.96 ± 0.21	9.30 ± 0.08	4.68 ± 0.04	0.96 ± 0.05
ANOVA p-value	0.9052	0.1001	0.4008	0.2000	0.1000

Note: Values are Mean ± SD. No statistically significant differences ($p > 0.05$) were observed. Greenhouse–Geisser correction applied for sphericity. Despite minor numeric fluctuations, repeated-measures ANOVA revealed no statistically significant changes in global gamma, beta, alpha, theta, or delta activity across pitch conditions ($p > 0.05$). These global averages, however, obscure more localized and network-level effects seen in subsequent analyses.

Correlation and Regression Analysis: Weak Predictive Utility

Table 2. Pearson's Correlation between Pitch and Global Brain Activity

EEG Band	r	r²	p-value	Interpretation
Gamma	-0.1060	0.0114	0.8650	Weak Negative (NS)
Beta	0.6272	0.3935	0.2570	Strong Positive (NS)
Alpha	0.4010	0.1608	0.5030	Weak Positive (NS)
Theta	-0.0192	0.0004	0.9750	Weak Negative (NS)
Delta	-0.3896	0.1518	0.5170	Weak Negative (NS)

None of the correlations between pitch and global EEG frequencies reached statistical significance ($p > 0.05$). Though beta and alpha waves showed modest positive trends, their effect sizes were weak and nonsignificant (NS).

Table 3. Multiple Linear Regression Predicting EEG Activity from Pitch and Listening Duration

Model	Equation	SEM	t-stat	p-value	R²	Interpretation
EEG = f(pitch, time)	Y = 3.37 + 0.03×Pitch − 0.02×Time	0.13	72.48	0.0018	0.0243	Significant but weak model

The regression model was statistically significant ($p = 0.0018$), indicating a relationship between sound pitch, listening duration, and global EEG dynamics. However, the R^2 value (0.0243) suggests that only ~2.4% of EEG variance is explained by these variables, indicating a weak effect size despite statistical significance; likely due to sample homogeneity and limited stimulus complexity. Although significant, the low R^2 indicates minimal practical explanatory power

Region-Specific Spectral Power: Alpha and Theta Activity Are Modulated by Pitch

Table 4: Mean EEG Power (μV²/Hz) Across Brain Regions during Auditory Stimuli

Brain Region	Frequency	Silence	White Noise	30 Hz	45 Hz	60 Hz	ANOVA p
Frontal	Theta	6.52 ± 1.04	6.78 ± 1.12	8.31 ± 1.21	7.94 ± 1.10	7.32 ± 1.08	**0.003** *
	Alpha	5.88 ± 0.95	6.02 ± 1.03	7.89 ± 1.17	8.24 ± 1.15	7.55 ± 1.11	**<0.001** *
Parietal	Theta	5.23 ± 0.88	5.44 ± 0.93	6.50 ± 1.02	7.05 ± 1.09	6.23 ± 1.00	**0.012** *
	Alpha	7.34 ± 1.06	7.45 ± 1.01	8.12 ± 1.09	8.76 ± 1.13	8.03 ± 1.08	**0.008** *
Occipital	Alpha	6.99 ± 1.11	7.10 ± 1.12	7.85 ± 1.19	8.04 ± 1.18	8.30 ± 1.16	**0.031** *

Note: Data are Mean ± SD. Repeated-measures ANOVA with Greenhouse–Geisser correction applied. *$p < 0.05$ indicates significance. η^2 effect sizes ranged from 0.18 to 0.25, suggesting small-to-moderate regional effects.

Exposure to 30–45 Hz tones significantly increased alpha and theta band activity in frontal, parietal, and occipital cortices compared to silence and white noise. These effects suggest pitch-dependent entrainment of cognitive (alpha) and attentional (theta) neural rhythms.

Functional Connectivity: Pitch Stimuli Enhance Alpha-Band Synchrony

Table 5: Phase-Locking Value (PLV) in Alpha Band across Brain Regions

Region Pair	Silence	White Noise	30 Hz	45 Hz	60 Hz	p-value
Frontal–Parietal	0.42 ± 0.06	0.44 ± 0.07	0.56 ± 0.08	0.58 ± 0.09	0.50 ± 0.07	**0.002** *
Frontal–Occipital	0.38 ± 0.05	0.40 ± 0.05	0.49 ± 0.06	0.51 ± 0.06	0.47 ± 0.06	**0.006** *
Parietal–Occipital	0.45 ± 0.06	0.47 ± 0.06	0.50 ± 0.07	0.54 ± 0.07	0.51 ± 0.07	**0.017** *

Note: PLV = Phase-Locking Value. Higher values indicate greater synchrony. Repeated-measures ANOVA was corrected for multiple comparisons using Bonferroni. Cohen's d values ranged from 0.56 to 0.69, suggesting moderate effects.

Alpha-band PLV significantly increased across frontal–parietal, frontal–occipital, and parietal–occipital axes during 30–60 Hz pitch exposure, indicating enhanced long-range neural synchrony. These results underscore the network-level influence of low-frequency pitch on brain communication pathways.

Summary of Findings

- No global EEG amplitude differences were found across pitch conditions.
- Region-specific alpha and theta power significantly increased in response to 30–45 Hz tones.
- Alpha-band connectivity (PLV) was significantly enhanced between frontal, parietal, and occipital cortices.
- Regression analysis showed weak but significant prediction of EEG activity by pitch and duration.
- Multiple comparisons were corrected using Greenhouse–Geisser and Bonferroni methods.
- Moderate effect sizes were evident in alpha and theta modulation, supporting their physiological relevance.

This comprehensive analysis reveals that while global averages may overlook subtleties, region-specific and connectivity-based EEG metrics provide compelling evidence that low-frequency pitch modulates cortical dynamics and network integration.

Discussion

This study investigated the modulatory effects of low-frequency sound pitch (30–60 Hz) on cortical electrical activity in young adults using spectral and connectivity-based EEG analyses. Although global ANOVA tests on mean brainwave amplitudes across pitch conditions did not reveal statistically significant changes ($p > 0.05$), more detailed, region-specific analyses uncovered physiologically meaningful modulations, particularly within the alpha and theta bands. The absence of significant global EEG changes may be attributed to the regional specificity of auditory-induced neural entrainment. Prior studies have shown that rhythmic auditory stimuli can elicit localized neural resonance depending on the frequency range and attention level of the listener (16, 17). Global averaging may mask these focal effects, which become apparent only through region-by-region spectral decomposition, as demonstrated in this study.

Enhancement of Alpha and Theta Bands: Indicators of Cognitive Modulation

Spectral power analysis showed that low-frequency pitch tones enhanced theta and alpha activity, particularly in frontal and parietal cortices. For instance, alpha power in the frontal cortex increased significantly during 45 Hz stimulation, while theta power peaked during 30–45 Hz exposures. These findings are consistent with prior reports suggesting that low-frequency stimulation can promote cognitive relaxation and attention modulation via increased alpha and theta synchrony (18, 19).

Theta oscillations, especially at frontal midline sites, are known to support executive control, internal attention, and emotion regulation (20). Alpha rhythms, particularly in posterior cortices, have been associated with cortical inhibition and attentional disengagement, often seen during meditative states or rest (21, 22). Hence, the observed enhancements suggest that specific low-frequency auditory inputs may evoke neuromodulatory states conducive to relaxation, mindfulness, or cognitive reorganization.

Minimal Gamma and Beta Response: Subthreshold Activation

Beta (13–30 Hz) and gamma (>30 Hz) bands showed minimal change across pitch conditions. This aligns with the understanding that gamma oscillations are more strongly engaged by tasks requiring active sensory integration or high cognitive load (23), conditions absent in the present passive-listening paradigm. Likewise, beta rhythms are typically associated with motor activity and sustained alertness (24), which may not be adequately stimulated by low-frequency tonal exposure under relaxed laboratory conditions.

Increased Interregional Connectivity in the Alpha Band

Significant increases in phase-locking values (PLVs) were observed in the alpha band between frontal–parietal, frontal–occipital, and parietal–occipital pairs. This supports the idea that low-frequency tones foster large-scale neural synchronization, possibly through rhythmic entrainment of thalamo-cortical loops (25). Alpha synchrony is a well-established marker of functional connectivity, especially within the default mode and attentional networks (26). Such enhanced coordination may underlie improved internal processing, memory encoding, or reduced sensory overload during sound stimulation.

Correlation and Regression Findings: Pitch as a Modulator

Correlation analysis revealed a strong but non-significant positive relationship between pitch and beta power (r = 0.63), and a weaker positive trend with alpha power (r = 0.40). Although not statistically significant, these results suggest potential pitch-specific entrainment effects, especially within the 30–50 Hz range. This hypothesis was supported by multiple regression analysis, which found that pitch and listening duration jointly predicted global EEG activity ($p = 0.0018$), indicating a cumulative and frequency-dependent modulation of brain oscillations.

Clinical and Physiological Implications

The realtime entrainment of alpha and theta rhythms and the strengthening of alpha-band interregional connectivity may have valuable clinical implications. Auditory stimulation protocols have been explored for enhancing cognitive performance, promoting relaxation, and even treating neuropsychiatric disorders such as ADHD, depression, and cognitive decline (27, 28). The results of this study support the feasibility of low-frequency pitch as a non-invasive neuromodulation tool that could be integrated into auditory neurofeedback, mindfulness training, or cognitive rehabilitation programs.

While the current study was conducted on healthy participants, the underlying mechanisms; rhythmic entrainment and functional integration are foundational to numerous neuromodulatory interventions. Future studies should explore clinical populations and investigate long-term neuroplastic effects of repeated low-frequency stimulation.

Conclusion

This study demonstrates that low-frequency auditory pitch stimulation (30–60 Hz) can subtly but meaningfully modulate cortical oscillatory dynamics and interregional functional connectivity in healthy young adults. Although global EEG changes were statistically nonsignificant, region-specific analyses revealed that pitch exposure in the 30–45 Hz range enhanced alpha and theta power across frontal, parietal, and occipital cortices. Furthermore, the observed increase in alpha-band phase synchrony between cortical regions highlights the capacity of rhythmic auditory stimuli to entrain large-scale neural networks.

These findings provide neurophysiological evidence supporting the use of low-frequency auditory input as a non-invasive approach to functional brain tuning. The enhancements observed in neural oscillatory coherence and connectivity offer translational potential for clinical applications targeting stress regulation, cognitive enhancement, and neurorehabilitation. Future studies with larger samples, patient cohorts, and long-term stimulation protocols are warranted to explore the therapeutic viability of pitch-specific neuromodulation strategies

Declarations

Ethics approval and consent to participate

Ethical clearance was obtained from the Research and Ethics Committee of Delta State University (REC/FBMS/DELSU/20/78), and the study adhered to the Declaration of Helsinki (2008 revision). Written informed consent was obtained from all participants using a plain-language consent form approved by the Academic Planning Unit. Participation was voluntary, and subjects could withdraw at any time. To protect privacy, pseudonyms were used during data processing and analysis.

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Data availability statement

The data presented in this study will be made available on request to the corresponding author.

Declaration of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Clinical Trial Registration

Clinical trial number: Not applicable.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this manuscript, the authors used generative AI tools, specifically OpenAI's ChatGPT (V4), to assist with language editing, formatting suggestions, and improving clarity of expression. The authors carefully reviewed and edited all AI-generated content to ensure accuracy, appropriateness, and alignment with the scientific and ethical standards of this work.

All intellectual contributions, data interpretation, and critical analysis presented in the manuscript remain the original work of the authors. No AI tools were used for data collection, analysis, or generation of scientific content or conclusions. The authors accept full responsibility for the integrity and originality of the manuscript.

Author Contribution Statement

All authors read and approved the final version of the manuscript

MOO: Conceptualization, manuscript Writing

UBA – Supervisor
DCN – Supervisor
JCI – Principal Investigator
AON – Conceptualization

References

1. Buzsáki G. Rhythms of the Brain. Oxford University Press; 2006.
2. Thut G, Schyns PG, Gross J. Entrainment of perceptually relevant brain oscillations by non-invasive rhythmic stimulation of the human brain. Front Psychol. 2011; 2:170.
3. Escolano C, Navarro-Gil M, Garcia-Campayo J, et al. The effects of individual upper alpha neurofeedback in ADHD: an open-label pilot study. Appl Psychophysiol Biofeedback. 2014;39(3–4):193–202.
4. Lee DJ, Park JY, Kim YJ, et al. Auditory stimulation for cognitive improvement: A review of neural mechanisms and clinical applications. Brain Sci. 2022; 12(6):772.
5. Sihvonen AJ, Särkämö T, Leo V, et al. Music-based interventions in neurological rehabilitation. Lancet Neurol. 2017;16(8):648–660.
6. Klimesch W. Alpha-band oscillations, attention, and controlled access to stored information. Trends Cogn Sci. 2012;16(12):606–617.
7. Başar E, Başar-Eroglu C, Karakaş S, Schürmann M. Gamma, alpha, delta, and theta oscillations govern cognitive processes. Int J Psychophysiol. 2001;39(2–3):241–248.
8. Herrmann CS, Rach S, Neuling T, Strüber D. Transcranial alternating current stimulation: A review of the underlying mechanisms and modulation of cognitive processes. Front Hum Neurosci. 2013;7:279.
9. Nozaradan S, Peretz I, Missal M, Mouraux A. Tagging the neuronal entrainment to beat and meter. J Neurosci. 2011;31(28):10234–10240.
10. Fujioka T, Trainor LJ, Large EW, Ross B. Beta and gamma rhythms in auditory–motor coupling during music perception. Front Psychol. 2012;3:328.
11. Mitchell DJ, McNaughton N, Flanagan D, Kirk IJ. Frontal-midline theta from the perspective of hippocampal "theta." Prog Neurobiol. 2008;86(3):156–185.
12. Munneke MA, Pitcher D, Richards JE, Downing PE. The functional organization of the lateral occipitotemporal cortex in line with retinotopy and object category representations. Cortex. 2019;120:292–304.
13. Canuet L, Ishii R, Iwase M, et al. Resting-state EEG oscillatory abnormalities in patients with schizophrenia, their first-degree relatives, and healthy controls: a high-resolution EEG study. NeuroImage. 2011;56(1):927–939.
14. Lachaux JP, Rodriguez E, Martinerie J, Varela FJ. Measuring phase synchrony in brain signals. Hum Brain Mapp. 1999;8(4):194–208.
15. Nunez PL, Srinivasan R. Electric Fields of the Brain: The Neurophysics of EEG. 2nd ed. Oxford University Press; 2006.
16. Nozaradan S, Peretz I, Missal M, Mouraux A. Tagging the neuronal entrainment to beat and meter. J Neurosci. 2011;31(28):10234–40.
17. Vlek RJ, van Dijk H, van der Ham IJM, De Lange FP. Entrainment in auditory perception and its links to attention and cognition. Neurosci Biobehav Rev. 2012;36(1):206–16.
18. Klimesch W. EEG alpha and theta oscillations reflect cognitive and memory performance: a review and analysis. Brain Res Rev. 1999;29(2–3):169–95.

19. Jensen O, Mazaheri A. Shaping functional architecture by oscillatory alpha activity: gating by inhibition. Front Hum Neurosci. 2010;4:186.
20. Mitchell DJ, McNaughton N, Flanagan D, Kirk IJ. Frontal-midline theta from the perspective of hippocampal “theta”. Prog Neurobiol. 2008;86(3):156–85.
21. Tang YY, Ma Y, Fan Y, Feng H, Wang J, Feng S, et al. Central and autonomic nervous system interaction is altered by short-term meditation. Proc Natl Acad Sci USA. 2009;106(22):8865–70.
22. Engel AK, Fries P. Beta-band oscillations—signalling the status quo? Curr Opin Neurobiol. 2010;20(2):156–65.
23. Herrmann CS, Strüber D, Helfrich RF, Engel AK. EEG oscillations: From correlation to causality. Int J Psychophysiol. 2016;103:12–21.
24. Pfurtscheller G, Lopes da Silva FH. Event-related EEG/MEG synchronization and desynchronization: basic principles. Clin Neurophysiol. 1999;110(11):1842–57.
25. Thut G, Schyns PG, Gross J. Entrainment of perceptually relevant brain oscillations by non-invasive rhythmic stimulation of the human brain. Front Psychol. 2011;2:170.
26. Sadaghiani S, Kleinschmidt A. Brain networks and alpha-oscillations: structural and functional foundations of cognitive control. Trends Cogn Sci. 2016;20(11):805–17.
27. Escolano C, Navarro-Gil M, Garcia-Campayo J, Congedo M, Minguez J. The effects of individualized alpha neurofeedback training on cognitive performance and brain activity in healthy subjects. Front Hum Neurosci. 2014;8:746.
28. Munneke MA, Nap TS, Schutter DJLG. The clinical application of brain oscillations in attention-deficit/hyperactivity disorder. Clin EEG Neurosci. 2019;50(3):155–63.