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Effect of binaural beat brainwave entrainment on brainwave ratios in students with learning difficulties

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ABSTRACT

This study examined the impact of binaural beat brainwave entrainment (BB BWE) on cognitive function and learning performance (LP) in children aged 8-13 with learning difficulties. A group of 52 participants was divided into a test group (TG) receiving BB BWE for four weeks and a control group (CG) without intervention. Results showed significant improvements in the TG, with LP increasing by up to 78% by week 4 according to cognitive assessment methods. EEG data corroborated these findings, showing a 74% improvement in TG students' performance. Favorable changes in Electroencephalography (EEG) ratios were observed, including decreased theta/beta and theta/alpha ratios and an increased alpha/beta ratio. Topographical EEG maps revealed more balanced brain activity patterns post-BWE. The CG showed no significant changes. Notably, performance in the TG declined after discontinuing BWE, suggesting the need for ongoing intervention to maintain benefits. These findings indicate that BB BWE could be an effective non-invasive method for enhancing cognitive function and learning capacity in individuals with learning difficulties. However, further research is needed to establish long-term effects and optimal application protocols.

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1. INTRODUCTION

Digital media, particularly social media, has become an integral part of modern society, with devices like laptops, smartphones, and tablets serving as primary sources of potential addiction. WHO research shows that digital distractions hinder children from completing essential tasks [1]. Focus on learning difficulties (LD) in children is crucial because it impacts core skills like reading, writing, and problem-solving, which can affect their confidence and academic progress, so early intervention can significantly improve their social, emotional, and cognitive development [2]–[5]. Current methods like behavioral interventions, special education, cognitive training, and pharmacological treatments for LD are costly, require specialized resources, and frequently address only symptoms, with some treatments having side effects that may impact overall health [6], [7]. Binaural beat (BB) brainwave entrainment (BWE) is a non-invasive, promising technique to enhance concentration, relaxation, and cognitive performance; it helps synchronize brainwave frequencies (delta, theta, alpha, beta, and gamma) with desired cognitive states, as seen in Figure 1. BB's are generated when two slightly different frequencies are played separately into each ear, creating the illusion of a third tone [8], [9]. In this study, a 20

Hz perceived binaural beat in the beta range is generated by presenting a 300 Hz tone to one ear and a 320 Hz tone to the other as shown in Figure 2.

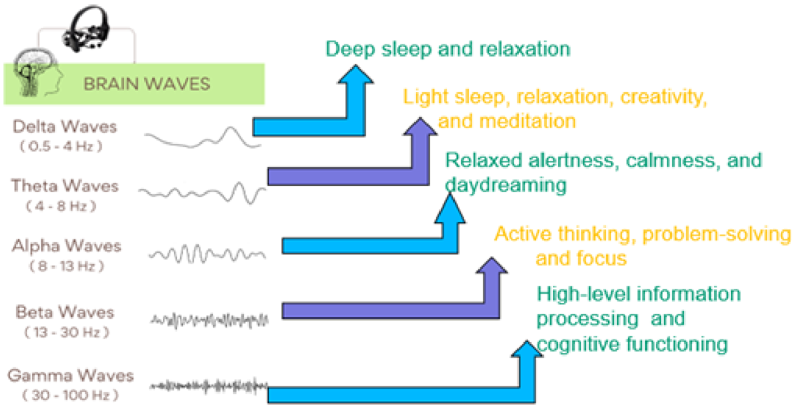


Figure 1. BWE frequencies and associated cognitive functions

Figure 2. BB entrainment entering the brain with 20 Hz frequency

Brainwave ratios are relationships between specific brainwave frequencies, which show imbalances or areas of activity that may relate to certain mental health conditions, cognitive functions, or responses to interventions like BWE. In this study, delta and gamma frequencies are excluded. Theta/beta ratio (TBR), theta/alpha ratio (TAR), and alpha/beta ratio (ABR) are particularly considered as they are significant for research objectives. Lower TBR is generally associated with better cognitive performance, including improved attention and working memory [10]. The TAR offers insights into attention, memory formation, and information processing, with a balanced ratio linked to optimal cognitive states for learning [11]. The ABR indicates a state of relaxed focus when balanced, conducive to learning and cognitive performance [12]. Elevated or lowered ratios can signify various cognitive challenges. These ratios typically change with age, reflecting the maturation of cognitive systems.

Electroencephalography (EEG) differs from other methods of recording brain activity by its non-invasiveness, portability, and affordability, which makes it especially useful for study. Unlike functional magnetic resonance imaging (fMRI), magnetoencephalography (MEG), positron emission tomography (PET), and near-infrared spectroscopy (NIRS), which, although highly detailed, is expensive, less accessible, and requires participants to remain still in a large machine, electrocorticography (ECoG) is invasive and thus mainly limited to surgical contexts [13]–[15]. EEG enables more realistic movement and may be used in a variety of settings. For research focusing on instantaneous cerebral responses, EEG also provides higher temporal resolution, collecting brainwave variations in real time [14]. Several studies have indicated that alpha frequencies (10–12 Hz) have been shown to promote relaxation and a calm, focused state [16]. Additionally, other BWE techniques like isochronic tones and visual entrainment may provide stronger effects. Also, monaural beats offer an alternative, but they often require specialized equipment and can't easily be used at home, while studying, traveling, or in other everyday situations, which can cause user discomfort [17], [18].

BB BWE demonstrates potential for cognitive enhancement and relaxation; however, there are notable research gaps that need to be addressed. The exact mechanisms through which BB affects brain function are still unclear, and more studies are needed to explore its long-term safety, particularly for children and young adults. Individual responses to BB vary, suggesting a need for personalized approaches. Additionally, research on the optimal frequencies, session durations, and real-world applications is limited by the lack of organized and accessible secondary datasets, further hindering progress in this field.

This study employs a pre-and post-test experimental design to explore how BBs at 20 Hz affect brainwave ratios and enhance concentration, mental alertness, learning, and creativity in children. A syllabus-based study assessment tool is designed to check weekly improvements. Behavioral changes were recorded during the study duration. Post-analysis performances also check for 4 weeks to observe the long-term effects of the entrainment.

2. MATERIALS AND METHODS

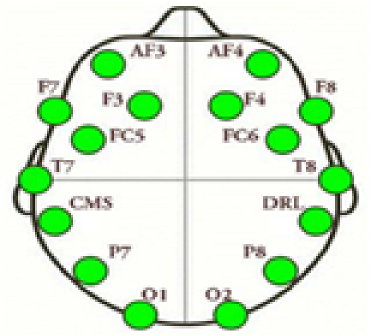
The study involved identifying participants, obtaining consent, and having them complete questionnaires. EEG signals were collected, cleaned, and analyzed. Selected participants abstained from medications for one month before the study. Both pre- and post-intervention data were compared using statistical analysis to assess changes in brainwave ratios. A friendly environment was maintained to ensure participant comfort. This section includes information about participants, devices used, data acquisition and analysis, experimentation procedures, and cognitive state assessments. D Y Patil International University, Pune ethically approved the study. Participants and their parents provided written consent, and the withdrawal option was available, though no withdrawals occurred.

2.1. Participants

The study sample included N=52 students (40 boys and 12 girls) aged 8 to 13 years, selected from renowned schools in Pune, India. Participants were chosen based on teachers' reports and parents' interests. Medical and family histories were recorded, and those with medication, hearing problems, or disorders other than ADHD were excluded. Participants were divided into two groups: the test group (TG) (N=30, including 8 with ADHD) received BWE, while the control group (CG) (N=22) did not.

2.2. Devices

For brainwave recordings, the EMOTIV EPOC X wireless 14-channel EEG headset with EmotivPRO software for real-time brainwave monitoring is used. Saline-based electrodes offered improved signal quality and comfort for young participants. The headset features 8 frontal sensors (AF3, AF4, F3, F4, F6, F7, FC5, FC6), 2 occipital (01, 02), 2 parietal (P7, P8), and 2 temporal (T7, T8) sensors [19]. Figure 3 shows an EEG acquisition setup; Figure 3(a) shows the channel placement, and Figure 3(b) illustrates the headset was mounted on the participant's head during EEG data recording.



(a)

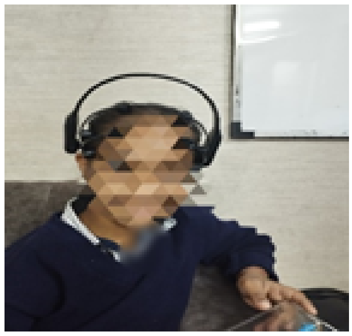

(b)

Figure 3. EEG acquisition setup: (a) channel placement in emotiv EPOC X headset and (b) device on participant's head

The electrode placement, illustrated in Figure 4, followed the 10-20 system, ensuring standardized positioning across studies [20]. High-quality stereo headphones were used to deliver BBs accurately, with over-ear or on-ear models preferred for their sound isolation. Specialized software on tablets and smartphones managed the BB generation, ensuring consistent auditory stimuli throughout the study.

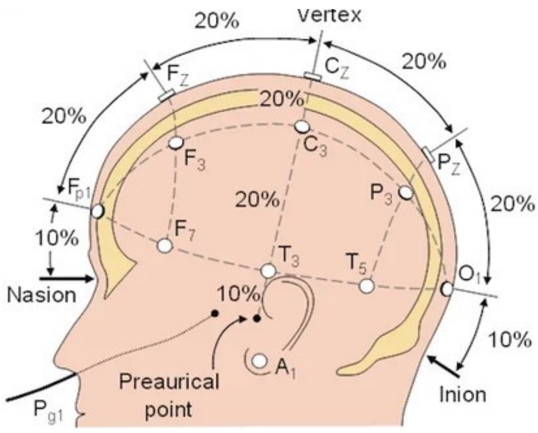


Figure 4. The 10-20 system with front-back (nasion to inion) electrode distances [16]

2.3. Experimentation procedure

Devices were checked for compatibility, and the BB procedure was explained. An initial recording was made before the experiment began. Demo sessions addressed participant queries, and on the first day, participants set up their environment as instructed. Participants listened to a 20 Hz BB stimulus for at least 20 minutes daily, then spent one hour each day memorizing answers to challenging questions. The 30-day (4-week) experiment was conducted both offline at school and online via Zoom and Google Meet for absent students. Progress reports and weekly tests were used to assess performance. A final recording was taken after 4 weeks to compare the results with the initial data. A post-analysis was conducted after the 4-week experiment to evaluate the sustained effects of BB on brainwave activity, cognitive function, and learning performances (LP) with the help of parents and teachers.

2.4. Data acquisition and processing

The EEG signal processing flow is shown in Figure 5. Data were collected in a soundproof room with open-eye EEG recordings for 20 minutes before and after the experiment. Participants were advised to minimize head movement, and good sensor contact was maintained to ensure accurate data collection. Raw EEG data were displayed in μV per sample with a resolution of 128 Hz. Artifacts in EEG signals, including those from head movement, muscle contractions, and electrical noise, can obscure true neural activity [21]. Rigorous preprocessing, such as artifact rejection and signal cleaning, was employed to ensure data reliability [22]. This approach enables accurate evaluation of BB effects on cognitive functions, enhancing focus and learning. The results from EEG analysis, including brainwave ratios, power spectral density (PSD), and topological maps, were compared with behavioral findings to gain comprehensive insights. Additionally, a post-experiment analysis was conducted. Data from 52 participants has been organized and is available upon request. To fill up the identified research gaps, this study's methodology is a systematic approach.

EEG data stored in European data format (EDF) were pre-processed using MNE-Python. The process included notch filtering to remove 50 Hz interference, artifact removal with independent component analysis (ICA), and high-pass and low-pass filtering. Band-pass filters isolated theta (4-8 Hz), alpha (8-12 Hz), and beta (12-30 Hz) frequencies, while delta waves were excluded due to their association with deep sleep rather than active cognitive functions [23]. Data were segmented into 2-second epochs with 50% overlap and analyzed using the fast fourier transform (FFT) and Welch's method for power spectral density [24]. Paired t-tests compared pre- and post-BB BWE measurements [25].

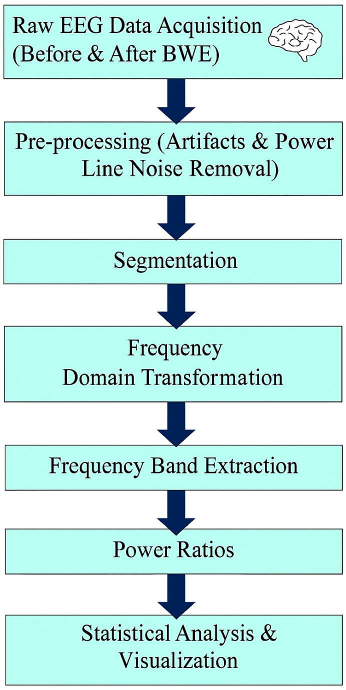


Figure 5. Overall EEG signal processing flow

2.5. Cognitive states assessment

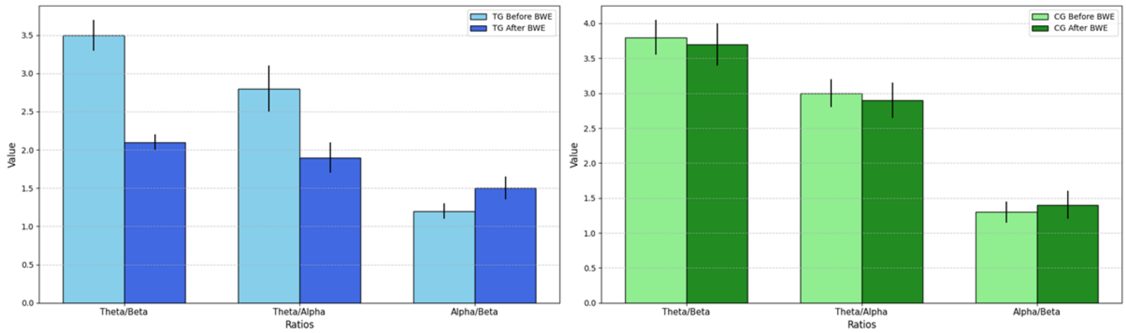
Cognitive states assessment provided additional insights into mental and behavioral skill improvements. A mental states questionnaire was developed to evaluate changes in mental states and emotions before and after the experiment. It covered study-related, academic, family, and personal questions to assess mental health and improvements from BBs. Parents and teachers rated subjects using:

- Frequency scale: ranges from 0 to 10, where 0 represents "Never," 5 signifies "Occasionally," and 10 indicates "Often."
- Performance scale: includes categories such as "Excellent," "Average," and "No Improvement." This multidimensional approach aimed to provide a comprehensive view of mental health and measure the intervention's effectiveness in enhancing cognitive and emotional states.

3. RESULTS AND ANALYSIS

From this experimentation work, it was found that those with LD had higher theta wave activity relative to beta waves, based on initial EEG data. In the TG, 18 participants, and in the CG, 6 participants showed this condition. Figure 6 illustrates the analysis of EEG ratios before and after BB BWE, revealing significant differences. As shown in Figure 6(a), substantial improvements were observed in TG: the TBR decreased from 3.5 to 2.1, the TAR decreased from 2.8 to 1.9, and the ABR increased from 1.2 to 1.5, all with p-values less than 0.05, indicating statistical significance. In contrast, the CG did not exhibit significant changes, with TBR decreasing slightly from 3.8 to 3.7, TAR from 3.0 to 2.9, and ABR increasing from 1.3 to 1.4, all with p-values greater than 0.05 as illustrated in Figure 6(b). Table 1 summarizes these findings, showing mean values and standard deviations of EEG ratios before and after BWE, alongside the p-values indicating statistical significance. The significant improvements in the TG, with p-values below 0.05, confirm the effectiveness of BB BWE in enhancing cognitive functions, while the stable ratios in the CG reinforce the intervention's impact.

Figure 7 presents EEG topological maps showing changes in brain activity for two participants from TG after one month of BB BWE. Participant 1 showed a significant shift from pronounced frontal right activity (red/orange) pre-BWE to a more balanced central activity (blue) post-BWE, suggesting improved cognitive processing and attention illustrated in Figure 7(a). Participant 2, who has ADHD, initially exhibited minimal central and left activity (blue). Post-BWE, there was increased frontal and right activity (red), indicating enhanced engagement of executive function areas illustrated in Figure 7(b). These changes, marked by color transitions from extremes (red and blue) to balanced distributions, suggest positive cognitive processing improvements tailored to individual learning challenges.

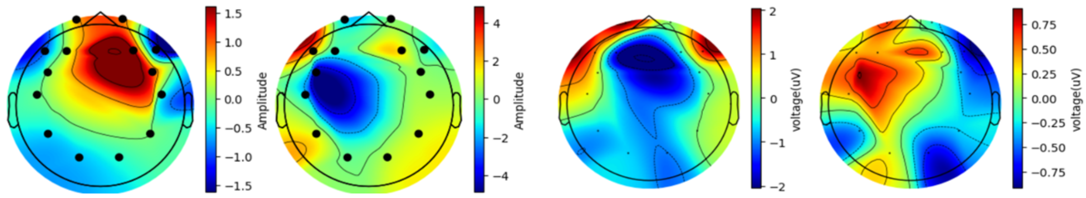


(a) (b)

Figure 6. Brainwave rations before and after the completion of week 4: (a) TG and (b) CG

Table 1. EEG ratios before and after experimentation

Group	Ratio	Before BWE (Mean ± SD)	After BWE (Mean ± SD)	p-value
	TBR	3.5 ± 0.2	2.1 ± 0.1	<0.05
TG	TAR	2.8 ± 0.3	1.9 ± 0.2	<0.05
	ABR	1.2 ± 0.1	1.5 ± 0.15	<0.05
	TBR	3.8 ± 0.25	3.7 ± 0.3	>0.05
CG	TAR	3.0 ± 0.2	2.9 ± 0.25	>0.05
	ABR	1.3 ± 0.15	1.4 ± 0.2	>0.05



(a) (b)

Figure 7. Topographical maps for TG participants before and after BB BWE: (a) participant 1 (learning issues) and (b) participant 2 (learning issues + ADHD)

Figure 8 shows the power spectral density (PSD) graph pre- and post-BB BWE with 30 TG participants. Before BWE (solid black line), peaks in theta, alpha, and beta bands indicated cognitive inefficiency, moderate relaxation, and focus. After BWE (dashed dark red line), theta power decreased, alpha power slightly increased, and beta power significantly rose, reflecting improved cognitive efficiency, relaxation, focus, and alertness. These changes, aligned with a 74% improvement in LP, underscore the effectiveness of BB BWE in enhancing cognitive functions and learning.

Prior to the experimentation, participants showed a pattern of memorizing 2-3 long answers within an hour but forgetting them within 2-3 days, requiring re-memorization. This forgetfulness cycle, reported by both parents and teachers, worsened if repetition didn't occur within a week. The study targeted problematic subjects to assess LP, aiming to determine BWE's effectiveness in improving retention and academic performance. This focused approach allowed for a targeted assessment of BWE's potential benefits for students with LD. Table 2 presents the weekly performance test results of the TG and CG over seven weeks, focusing on the number of question-answers memorized (QA) in one hour and the percentage improvement in LP. The TG showed significant LP increases, peaking at 78% by week 4 but declined to 40% by week 7 after discontinuing BWE. The CG, which did not undergo BWE, had modest and fluctuating improvements, peaking at 22% in week 2 and stabilizing at 16% by week 7. After one month, the TG regressed to problematic conditions, except for six participants who continued BWE and retained good LP. The CG showed no long-term benefits, highlighting the impact of BWE on LP.

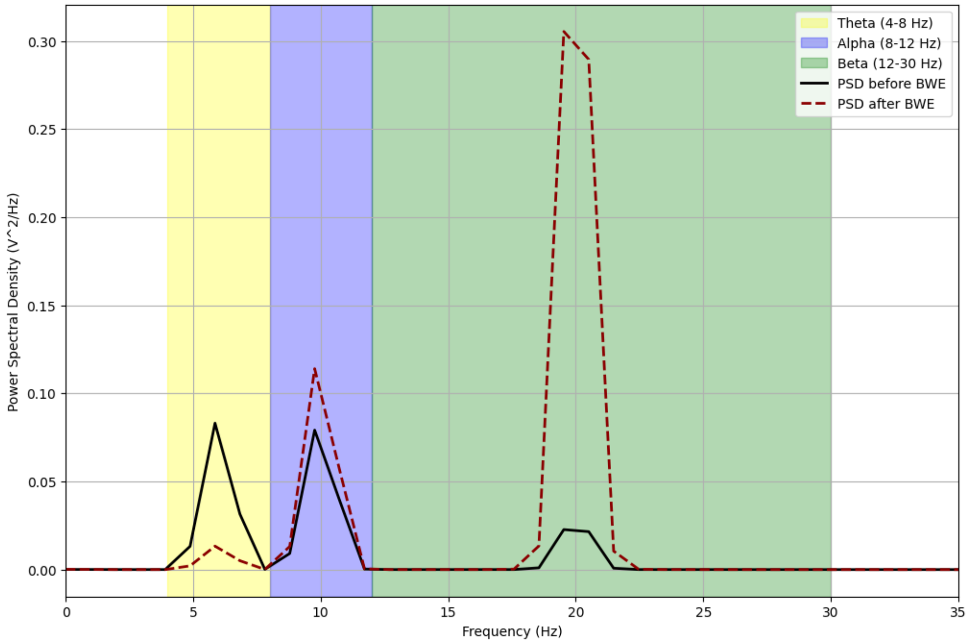


Figure 8. The PSD before and after BB BWE

Table 2. Weekly performance test results and improvement

Session	Week	Average QA (TG)	Average QA (CG)	Improvement (TG)	Improvement (CG)
I	0	QA = 3	QA = 3	–	–
II	1	QA = 4±1	QA = 4±1	20	18
III	2	QA = 5±1	QA = 4±1	30	22
IV	3	QA = 5±2	QA = 4±1	50	15
V	4	QA = 6±1	QA = 4±1	78	21
VI	5	QA = 6±1	QA = 3±1	72	16
VII	7	QA = 4±1	QA = 3±1	40	16

4. DISCUSSION

The study revealed significant cognitive and learning improvements with 20 Hz BB BWE. The TG showed a 78% increase in memorization and LP by week 4 which is remarkable. Moderate improvement in academic performance was noted by teachers. From EEG data analysis reduced TBR and TAR, along with an increased ABR, reflecting enhanced cognitive control and a relaxed yet focused state. The PSD analysis showed a 74% improvement in LP, with increased beta power post-BWE. Topographical maps confirmed more balanced brain activity. We found a good alignment between behavioral analysis and EEG, with an 87.84% correlation. The CG showed only random, minimal changes. According to observations, children with ADHD had less progress than other TG participants, suggesting that longer, more intense sessions are needed to maximize gains. A decline in performance after discontinuing BWE suggests the need for ongoing intervention. The dataset of N=52 participants with LD is organized and available upon request for further research.

5. CONCLUSION AND FUTURE SCOPE

This study provides compelling evidence for the efficacy of BB BWE in improving brainwave ratios, cognitive functions, and LP in individuals with LD. A decline in performance after discontinuing BWE indicates that the benefits may be temporary without continued application. These findings suggest BWE as a promising non-pharmacological intervention for students with learning challenges. This technique is straightforward to use, portable, non-invasive, and reasonably priced. It might greatly benefit a variety of mental health conditions if incorporated into routine.

Future research is needed to achieve the long-term impacts of BB BWE. The use of advanced neuroimaging and machine learning techniques could deepen understanding and optimize strategies. Expanding the database with diverse, larger samples and examining cultural, environmental factors, and academic performance correlations would enhance the robustness and applicability of BWE in educational settings.

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The author(s) declare that no specific funding was received for this research work.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Prabhat Ranjan	✓	✓					✓			✓		✓	✓	
Rajendra More				✓	✓	✓	✓	✓						

C	: **C**onceptualization	I	: **I**nvestigation	Vi	: **Vi**sualization
M	: **M**ethodology	R	: **R**esources	Su	: **Su**pervision
So	: **So**ftware	D	: **D**ata Curation	P	: **P**roject Administration
Va	: **Va**lidation	O	: Writing - **O**riginal Draft	Fu	: **Fu**nding Acquisition
Fo	: **Fo**rmal Analysis	E	: Writing - Review & **E**diting		

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study, and in the case of minors, written consent was obtained from their parents or guardians.

ETHICAL APPROVAL

This study was approved by the Ethical Committee of D Y Patil International University, Akurdi, Pune, India. All procedures performed in the study involving human participants were in accordance with the ethical standards of the institutional research committee.

DATA AVAILABILITY

The data supporting this study's findings are available from the corresponding author (S.K.B.) upon reasonable request. Due to privacy and ethical restrictions, the data are not publicly available.

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