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Characterizing alpha-band electroencephalography activity from cognitive listening test in undergraduate students

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ABSTRACT

This study examined alpha-band electroencephalography (EEG) activity during a cognitive listening test in undergraduate students aged 19 – 22 years. EEG signals were recorded using an EMOTIV EPOC+ device during resting-state conditions and a listening-based cognitive test involving synonyms, antonyms, word analogies, premise-based reasoning, and narrative-audio comprehension tasks. Alpha-band power spectral density (PSD) was estimated using Welch's periodogram method to describe the magnitude and scalp distribution of alpha-band activity in seven undergraduate students (aged 19 – 22 years) during resting state and cognitive task condition. The resting-state results showed consistently higher alpha PSD during eyes-closed than eyes-open conditions, both before and after the cognitive listening test. During task performance, scalp topographies showed substantial inter-individual variation in the magnitude and spatial distribution of alpha band PSD. This descriptive pattern cannot be attributed to specific cognitive processes or strategies because behavioral measures and inferential statistics were not available. The findings indicate that Welch based PSD analysis can be used to describe EEG activity during listening tasks, larger samples, behavioral measures, artifact correction, and statistical comparisons are required before any EEG markers of listening performance can be proposed.

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1. INTRODUCTION

Listening-based cognitive assessments are increasingly important for evaluating auditory comprehension, attention, memory, and rapid response generation. Unlike conventional written examinations, listening tasks demand the integration of perceptual and cognitive processes, thus providing a more comprehensive measure of mental functioning. In academic and professional settings, such as language proficiency tests and interview-based evaluations, the ability to process spoken information effectively is essential for producing accurate and appropriate responses.

Cognitive ability plays a central role in listening comprehension, as it involves the processing of auditory stimuli and the transformation of such information into meaningful understanding. Bloom's

Taxonomy identifies the cognitive domain as the foundational domain of learning, consisting of six hierarchical levels: knowledge, comprehension, application, analysis, synthesis, and evaluation [1]. These levels represent progressively more complex mental operations that are activated during learning and assessment processes. In listening-based tasks, these operations work together as individuals interpret information, connect it to prior knowledge, and generate responses. The neural basis of listening has received increasing attention in recent years. Electroencephalography (EEG) studies have shown that language comprehension and listening effort are associated with dynamic changes in brain activity, particularly within the theta and alpha bands. EEG offers a non-invasive and relatively inexpensive screening tool for cognitive assessment [2]. Previous study found that EEG responses during language comprehension reflect interactive processing between perceptual input and sentential expectations [3], and also reported that adverse listening conditions produce measurable EEG spectral changes, indicating that listening effort places significant demands on cognitive resources [4]. These findings show that EEG can capture activity associated with listening and language processing.

Prior research has shown that brain wave characteristics vary with age and cognitive state, and specific frequency bands such as delta, theta, alpha, beta, and gamma are associated with distinct neural activities [5]. Frontal asymmetry among the activity in the left and right hemispheres, peak frequency in resting-state EEG, and response time in sensory ERP were found to correlate with MMSE scores [6]. EEG studies investigating cognitive decline highlight the role of theta power as a possible indicator for early detection of cognitive decline [7,8]. For example, it was found that frontal theta activity differed substantially in cognitively impaired subjects performing cognitive tasks, compared to healthy seniors. A lack of increased theta activity was shown to serve as a predictor of cognitive decline progression [9]. When performing tasks involving working memory, frontal theta activity increases with the expected increase of the cognitive load levels [10]. Working memory manipulation is one of the ways to modify cognitive load, as explained by the cognitive load theory (CLT). Since working memory capacity is limited, performing a higher difficult task results in simultaneous processing of information elements, which leads to higher cognitive load [11]. Studies using EEG repeatedly show frontal theta increase with higher cognitive load and task difficulty [12]. Studies examining resting-state EEG found that Alpha-to-Theta ratio decreased as the MMSE scores decreased [13]. A recent study stated that novel diagnostic classification based on EEG signals could be even more useful than frontal theta for differentiating between clinical stages [14].

Alpha-band activity is widely associated with attentional regulation and the inhibition of task irrelevant information [15-17]. Alpha power also varies with attentional demands during cognitive tasks [18], and alpha oscillations in left perisylvian cortices have been linked to semantic processing [19]. These findings make the alpha-band a suitable starting point for describing neural activity during listening tasks that combine semantic retrieval, attention, and response selection. However, most EEG studies on cognitive load and cognitive decline have focused on theta activity or clinical populations. To our knowledge, little is known about how alpha-band power spectral density (PSD) and its scalp distribution vary across different listening task categories within one assessment framework in healthy young adults, particularly using low-cost wearable EEG.

To address this gap, the present study investigates alpha-band EEG activity in undergraduate students performing five categories of cognitive listening tasks: synonym recognition, antonym recognition, word analogy, premise-based reasoning, and narrative-audio comprehension. Alpha-band PSD is estimated using Welch's periodogram method from EEG recordings obtained during pre-task and post-task resting conditions and selected intervals corresponding to the five task categories. Scalp topographies are used to describe the spatial distribution of alpha-band activity and its variability across individual participants. The novelty of this study lies in the combined exploratory characterization of alpha-band PSD and individual scalp-topography patterns across these five listening-task categories within the same assessment framework, rather than in the development of a new signal-processing method. This exploratory study aimed to: (1) describe alpha-band PSD during eyes-open and eyes-closed resting conditions before and after the cognitive listening test; and (2) characterize inter-individual variation in the scalp distribution of alpha-band PSD across the five cognitive listening tasks. Given the small sample size and descriptive design, the findings are intended to provide preliminary evidence for subsequent studies incorporating larger samples, behavioral performance measures, artifact-correction procedures, and inferential statistical analyses.

2. RESEARCH METHODS

2.1. Participants

A total of 11 participants were initially recruited for this study aged 19 – 22 years. However, after selection based on inclusion criteria, only 7 participants (63.6%) met the requirements and were included in the data analysis. Four participants were excluded due to poor EEG data quality resulting from intermittent electrode signal loss and excessive movement artifacts during recording. All participants were in good general health, had no history of neurological or psychiatric disorders, and were not taking any medication that could affect brain activity. In addition, the participants had normal or corrected to normal vision and normal hearing and were able to follow the experimental instructions properly. Participants were required to be well rested, to avoid consuming caffeine, to have breakfast, to arrive at the laboratory without rush, and to have clean, healthy hair and scalp condition. All participants voluntarily agreed to take part in the study and provided informed consent before the EEG recording session began.

2.2. Task and Stimuli

The cognitive listening test consisted of 40 multiple-choice questions presented in Indonesian. The test included five task categories: 10 synonym questions, 10 antonym questions, 10 word-analogy questions, 5 premise-based reasoning questions, and 5 narrative-audio comprehension questions. All participants completed the same questions in the same fixed order: synonym, antonym, word analogy, premise-based reasoning, and narrative-audio comprehension. The auditory stimuli were recorded before the experiment and presented to participants through headphones. The answer choices were displayed on a computer monitor and were also read aloud while the auditory stimulus was presented. Thus, participants received the response alternatives through both visual and auditory modalities. Participants selected their answers using the response interface provided on the monitor.

The items were adapted from components of the Indonesian Academic Potential Test. The present study did not include an independent pilot test or formal psychometric validation to quantify item difficulty. Therefore, the task categories were analyzed according to their intended cognitive demands rather than empirically validated difficulty levels. Synonym and antonym items were designed to assess lexical-semantic retrieval; word-analogy items required relational semantic reasoning; premise-based items involved logical reasoning; and narrative-audio items required listening comprehension and retention of spoken information.

2.3. Experimental Protocol

The experimental session lasted approximately 17 minutes and consisted of three conditions. In the first condition, participants rested in a relaxed seated position. Baseline EEG was recorded for 30 seconds with eyes-closed, followed by 30 seconds with eyes-open. The eyes-closed recording was conducted first to obtain a baseline condition with minimal visual input.

In the second condition, participants completed the cognitive listening test. The auditory questions were presented through headphones, while the answer options were displayed on a computer monitor. EEG data for the stimulus-task condition were segmented into five one-minute intervals: minutes 2 – 3, 5 – 6, 8 – 9, 11 – 12, and 14 – 15. These intervals represented the five cognitive-task stages: synonym, antonym, word analogy, premise, and narrative-audio comprehension, respectively. The intervals between recording segments were not included in the primary analysis to minimize the influence of transitions between task stages and possible non-task-related artifacts.

In the third condition, participants rested after completing the cognitive listening test. Post-task resting EEG was recorded for 30 seconds with eyes-closed and then for 30 seconds with eyes-open, using the same procedure as the pre-task baseline condition.

2.4. Experimental Device

EEG signals were recorded using a 14-channel EMOTIV EPOC+ wireless EEG headset (EMOTIV Inc., San Francisco, CA, USA). Recording electrodes were positioned at AF3, F7, F3, FC5, T7, P7, O1, O2, P8, T8, FC6, F4, F8, and AF4 according to the international 10 – 20 system. The device used a reference montage with CMS and DRL reference sensors positioned at P3 and P4, respectively. EEG data were recorded at 128 Hz, exported in EDF format, and converted to EEGLAB SET

format for preprocessing and spectral analysis. All 14 channels were included in the initial recording and scalptopography analysis.

2.5. Signal Acquisition

All channels were used during the recording process, and the recorded data was obtained in (.edf) format, which was subsequently converted to (.set) format using EEGLab software for data segmentation, resulting in shorter-duration data to eliminate noise caused by mental state transitions to exclude transition periods between mental states, or vice versa.

2.5.1. Centering and Filtering

Each EEG channel was mean-centered to remove the DC offset. A band-pass filter (8-13 Hz) was applied to attenuate slow drifts and high-frequency noise. No systematic artifact detection, rejection, or correction procedures, such as amplitude thresholding or independent component analysis (ICA), were performed. Therefore, residual ocular, muscle, and movement artifacts may have contributed to the estimated power spectral density (PSD), particularly at frontal electrodes (AF3 and AF4). Frequency bands were defined as delta (0.5 – 4 Hz), theta (4 – 8 Hz), alpha (8 – 13 Hz), beta (13 – 30 Hz), and gamma (30 – 50 Hz) [15]. The analysis focuses exclusively on the alpha band.

2.5.2. Periodogram Welch Method

The third stage employed Welch's periodogram method for PSD computation. Welch's method divides the time signal into successive blocks, forms the periodogram for each block, and averages them to obtain a smoothed power spectral density estimate. In this study, the Welch periodogram was calculated using a Hamming window, which provides optimal frequency resolution for EEG signal analysis with minimized spectral leakage. The Hamming window coefficients are generated using the Equation (1):

$$w(n) = 0.54 - 0.46\cos\left(\frac{2\pi n}{M-1}\right), 0 \le n \le M-1 \quad (1)$$

where M is the window length. The window length (128), overlap percentage 50%, and number of FFT points (128) were determined according to the implemented MATLAB analysis procedure. The PSD calculation yields the distribution of power across frequency bands, enabling the quantification of brain activity changes enabling quantification of spectral power within each frequency band. The Hamming window is particularly advantageous for EEG spectral analysis as it reduces spectral leakage and minimizes discontinuities at the edges of signal frames, thus improving the accuracy of spectral analysis [20].

Alpha-band PSD was calculated as the mean PSD within the 8 – 13 Hz frequency range. The alpha-band PSD values were calculated for each EEG channel and subsequently averaged across the 14 channels for the overall comparison. Alpha peak frequency was defined as the frequency corresponding to the maximum PSD within the 8 – 13 Hz range. Scalp topographies were generated by spatial interpolation of the 14-channel PSD values using the EEGLAB topoplot function. Because the EPOC+ montage does not include electrodes at all central and midline parietal locations, the corresponding spatial patterns are interpolated estimates and should therefore be interpreted cautiously.

3. RESULTS

3.1. Alpha PSD Characterization During Resting State Condition (Eyes-Open and Eyes-Closed)

Alpha-band PSD was higher during eyes-closed than eyes-open in all seven participants, both before and after the listening test as Figure 1 and Table 1, consistent with the well-known eyes-closed alpha enhancement [21,22]. Alpha frequency also shifted slightly between pre- and post-task without a consistent direction across participants in Figure 1.

3.2. Alpha PSD During the Cognitive Listening Test

A common color scale was used across participants, allowing the relative magnitudes of PSD values to be compared between maps. The scalp topographies showed substantial inter-individual var-

iation in the magnitude and spatial distribution of alpha-band PSD across the five task segments. Some participants showed relatively widespread high-power regions, whereas others showed more localized or diffuse patterns. These are visual descriptions of the maps; they do not establish statistically reliable differences between participants, electrodes, regions, or task categories.

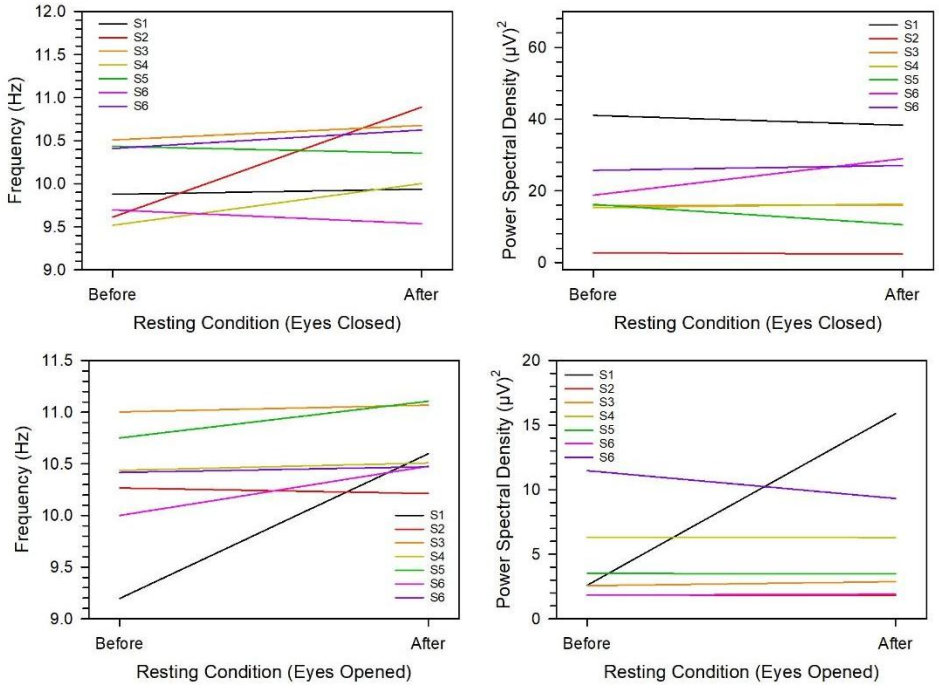


Figure 1. Alpha-band frequency and PSD during resting-state conditions before and after the cognitive listening test: eyes-closed and eyes-open.

Table 1. Alpha-band PSD during resting-state conditions before and after the cognitive listening test: eyes-closed and eyes-open.

Participant	EC pre	EC post	EO pre	EO post
S1	41.06	38.30	2.60	15.89
S2	2.71	2.38	1.84	1.80
S3	15.93	16.04	2.56	2.87
S4	15.29	16.33	6.31	6.29
S5	16.21	10.57	3.51	3.49
S6	18.80	28.99	1.83	1.91
S7	25.72	27.07	11.47	9.32

During synonym recognition (minutes 2 – 3), the maps showed relatively prominent alpha activity in some participants and more heterogeneous distributions in others (see Figure 2). Synonym recognition was intended to involve access to lexical-semantic representations and selection of a response. However, the topographies do not directly measure these processes, and the observed patterns cannot confirm that participants used particular cognitive strategies.

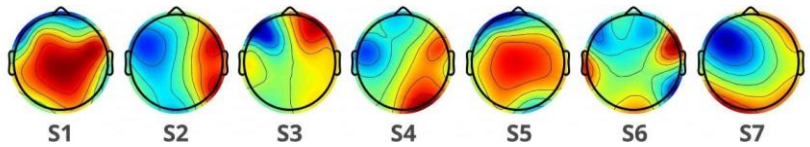


Figure 2. Alpha-band PSD scalp topographies of seven participants during the synonym listening task (minutes 2 – 3).

During antonym recognition (minutes 5 – 6), participants also showed heterogeneous alpha-band distributions, including localized and more widespread patterns (see Figure 3). Antonym items potentially require retrieval of opposing semantic relationships and selection among alternatives. The maps alone cannot determine whether differences reflect semantic processing, attention, response selection, individual baseline differences, or residual artifacts.

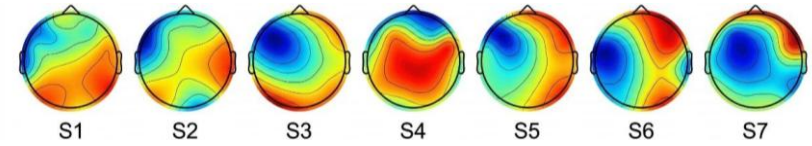


Figure 3. Alpha-band PSD scalp topographies of seven participants during the antonym listening task (minutes 5 – 6).

During word analogy (minutes 8 – 9), the scalp maps varied across participants in both the location and apparent magnitude of alpha-band activity (see Figure 4). Word analogy potentially involves identifying a relationship between word pairs and applying that relationship to a new pair. Although alpha activity has been discussed in relation to attentional regulation and semantic processing [21,22], the current descriptive maps do not establish a specific mechanism or indicate that the task produced a distinct cognitive-load response.

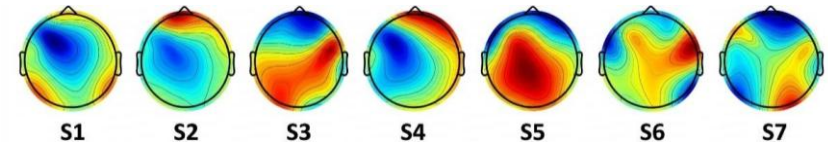


Figure 4. Alpha-band PSD scalp topographies of seven participants during the word-analogy listening task (minutes 8 – 9).

During premise-based reasoning (minutes 11 – 12), the maps again showed inter-individual variation (see Figure 5). The task was intended to involve integration of premises and evaluation of logical relationships, but its relative difficulty was not independently assessed. Consequently, the spatial patterns should not be interpreted as evidence of greater or lesser reasoning effort. In particular, alpha activity is not a unique indicator of working-memory demand or task difficulty.

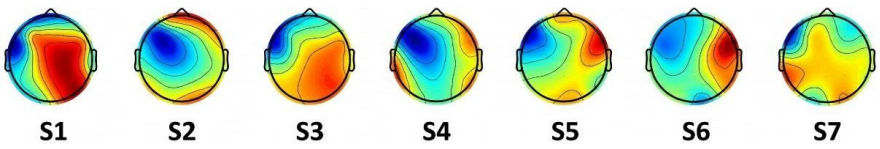


Figure 5. Alpha-band PSD scalp topographies of seven participants during the premise-based listening task (minutes 11 – 12).

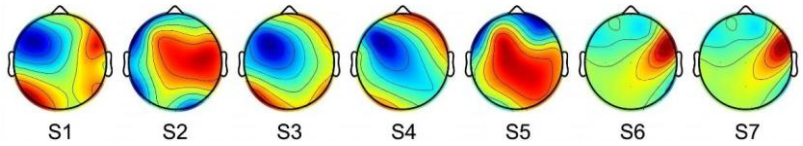


Figure 6. Alpha-band PSD scalp topographies of seven participants during the narrative-audio comprehension task (minutes 14 – 15).

During narrative-audio comprehension (minutes 14 – 15), participants also showed differences in the apparent magnitude and spatial distribution of alpha-band PSD (see Figure 6). This task potentially required sustained attention and retention or integration of spoken information. However, be-

cause answer alternatives were presented both visually and auditorily, the recorded activity may reflect a combination of auditory processing, visual attention, cross-modal integration, response selection, and individual variability. The present data cannot separate these contributions.

4. DISCUSSION

This study characterized alpha-band PSD in seven undergraduate students during resting-state recordings and five listening-task segments. Alpha-band PSD was higher with eyes closed than with eyes open in all seven participants, whereas the scalp distribution of alphaband PSD during the listening tasks showed substantial inter-individual variability.

Alpha-band activity has been associated with attentional regulation, the inhibition of task-irrelevant information, and semantic processing [15-17]. Alpha power has also been reported to vary with attentional demands during cognitive tasks [18]. In the present study, the observed interindividual differences in alpha-band PSD may reflect variability in neural activity during the listening tasks. However, these differences cannot be attributed to specific attentional or semantic processes because behavioral performance, baseline-normalized measures, and inferential statistical comparisons across task categories were not available. Furthermore, no statistically significant differences in absolute alpha-band power were identified among the four listening tasks compared in the analysis. Therefore, the observed spectral patterns should be interpreted descriptively rather than as evidence of task-specific cognitive-load effects.

Alpha- and theta-based indices, including alpha-to-theta ratios, have been investigated as potential measures of cognitive workload [23,24]. Future studies could examine these indices alongside absolute band power to investigate whether the five listening-task categories are associated with different patterns of EEG activity. Such analyzes should incorporate independent measures of task performance and cognitive demand to determine whether the observed spectral patterns correspond to differences in cognitive workload. The wide inter-individual range of resting alpha-band PSD observed in this study Table 1 also highlights the importance of evaluating baseline-normalized measures in future research. Normalizing task-related PSD to individual resting-state values may help account for interindividual differences in baseline EEG activity.

The observed inter-individual variation in alpha-band PSD highlights the importance of considering individual variability when interpreting EEG activity during cognitive listening tasks. Although the present findings provide a descriptive characterization of alpha-band activity across listening-task segments, they do not establish alpha PSD as a validated indicator of cognitive performance or task-specific cognitive demand. Further studies involving larger samples, counterbalanced task sequences, behavioral measurements, and statistical comparisons are needed to evaluate the potential implications of alpha-band analysis for cognitive assessment.

4.1. Limitations

This study has several limitations. First, the sample size was small, with only seven participants included in the final analysis, limiting the generalizability of the findings. Second, the analysis was exploratory and descriptive, without inferential statistical comparisons across listening-task categories. Consequently, the observed differences in alpha-band PSD distributions cannot be interpreted as statistically supported task-specific effects. Third, behavioral performance, including response accuracy and reaction time, was not incorporated into the analysis, preventing direct assessment of the relationship between EEG activity and task performance. Fourth, no systematic artifact detection, rejection, or correction procedures were applied. Residual ocular, muscle, and movement artifacts may therefore have affected the estimated PSD, particularly at frontal electrodes. Fifth, the 14-channel EMOTIV EPOC+ montage does not include electrodes at all central and midline parietal locations. consequently, the corresponding scalp topographies rely on spatial interpolation, and regional patterns should be interpreted as approximate rather than direct measurements at those locations. Sixth, the task sequence and the eyes-open/eyes-closed recording order were fixed, preventing the effects of task type from being separated from potential order, habituation, or fatigue effects. Seventh, task difficulty was not independently validated, and the simultaneous visual and auditory presentation of answer options may have influenced EEG activity, including posterior alpha-band activity. Collectively, these limita-

tions preclude definitive conclusions regarding task-specific cognitive effects and prevent the validation of alpha-band PSD as an objective indicator of cognitive workload or performance.

5. CONCLUSION

This study provides an exploratory characterization of alpha-band EEG activity in seven undergraduate students during a cognitive listening test. Alpha-band PSD was higher with eyes closed than with eyes open in all participants, while scalp topographies across the five listening-task segments showed substantial inter-individual variability. These findings demonstrate the descriptive utility of Welch-based PSD analysis for characterizing EEG activity during cognitive listening tasks. However, given the small sample size, the absence of behavioral performance measures and systematic artifact correction, and the lack of inferential statistical comparisons across listening tasks, the observed patterns cannot be interpreted as validated indicators of cognitive listening performance. Future studies involving larger samples, behavioral assessments, systematic artifact handling, and statistical comparisons of absolute and relative PSD across multiple frequency bands are needed to evaluate the reproducibility and potential application of EEG spectral analysis in cognitive listening assessment.

AUTHOR CONTRIBUTIONS

Feby Nur Sakinah: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft. Zulfa Zulfa: Investigation, Data curation, Software, Visualization. Yuanita Puspita Dewi Sudarso: Methodology, Validation, Writing – review & editing. Siti Nurul Khotimah: Supervision, Resources, Validation, Writing – review & editing. All authors read and approved the final manuscript.

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DECLARATION OF AI USE

The authors declare that no AI tools were used in preparing this manuscript.

CONFLICT OF INTEREST

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

All data supporting this study are included in the article. No separate datasets are available.

ETHICAL APPROVAL

Ethical approval was unnecessary, as no humans or animals were involved.

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