

Article

Sensory Modality Shapes Early Non-Phase-Locked Alpha Activity Independently of Frequency Definition

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Abstract

Alpha-band activity has been widely associated with sensory and cognitive processing, yet the functional role of non-phase-locked alpha modulation during early sensory stages remains incompletely understood. In particular, it is unclear whether such activity reflects modality-specific neural mechanisms and to what extent its characterization depends on the frequency range used for its estimation. The present study investigated phase-locked and non-phase-locked alpha activity during visual and auditory oddball tasks, focusing on their temporal dynamics and topographical organization. In addition, we examined whether the observed effects depend on the definition of the alpha band by comparing a conventional frequency range (8–13 Hz), subdivided bands (8–10.5 Hz and 10.5–13 Hz), and individualized frequency ranges based on the individual alpha frequency (IAF). Results revealed clear modality-dependent differences, with shorter latencies for auditory responses and a dissociation between anterior and posterior regions, with auditory activity predominating in central areas and visual activity in parieto-occipital regions. Non-phase-locked alpha activity showed a spatial distribution similar to phase-locked activity but with opposite polarity. Importantly, these patterns were consistent across all frequency definitions, indicating that early alpha modulation is primarily determined by sensory modality and cortical organization, rather than frequency definition.

Keywords: alpha oscillations; non-phase-locked activity; sensory modality; EEG; neural noise



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1. Introduction

The analysis of brain oscillatory activity has become a central approach for understanding the neural mechanisms underlying information processing. In particular, spectral analysis of electroencephalographic (EEG) signals provides a powerful framework for characterizing the temporal and functional organization of neural activity across different cognitive domains [1,2]. By decomposing the EEG signal into its frequency components, spectral methods allow researchers to investigate how oscillatory dynamics relate to perception, attention, and memory processes.

Among the different frequency bands, alpha activity (typically defined within the 8–13 Hz range) has long been recognized as a dominant feature of human brain dynamics. Early studies characterized alpha oscillations as a hallmark of relaxed wakefulness, particularly over posterior regions, leading to the classical interpretation of alpha as an

index of cortical idling [3]. However, subsequent work challenged this view, demonstrating that alpha activity is systematically modulated during task engagement and is closely linked to cognitive performance [4,5]. In particular, alpha oscillations have been shown to play an active role in cognitive functions such as attention and working memory, with their amplitude and spatial distribution reflecting the allocation of processing resources and the prioritization of relevant information [6,7]. These findings support the notion that alpha activity constitutes a dynamic mechanism involved in the temporal coordination and functional organization of neural processing, rather than a passive marker of cortical inactivity.

Several methodological approaches have been developed to analyze the spectral properties of EEG signals, including alpha-band modulations. Classical techniques such as the Fast Fourier Transform (FFT) and power spectral density (PSD) estimation provide a global characterization of frequency content over time, but lack temporal resolution [8]. To overcome this limitation, time–frequency approaches have been introduced, including wavelet transforms, event-related desynchronization/synchronization (ERD/ERS), and Hilbert-based methods, which allow the study of dynamic changes in oscillatory activity with high temporal precision [4,9,10].

Among these approaches, Temporal Spectral Evolution (TSE) represents a particularly useful method for analyzing oscillatory dynamics. TSE involves band-pass filtering of the signal, rectification, and subsequent averaging, providing a direct measure of amplitude modulation over time [11]. Similar approaches focusing on the temporal evolution of oscillatory amplitude have been widely used in MEG and EEG studies to characterize the dynamics of neural rhythms [12]. Compared to other techniques such as ERD/ERS, which rely on power estimation (i.e., squaring the signal) [4], TSE involves fewer mathematical transformations of the data, preserving the original signal characteristics to a greater extent. This makes TSE especially suitable for studying subtle modulations in oscillatory activity.

Importantly, TSE also allows the separation of phase-locked and non-phase-locked components of the EEG signal. By subtracting the phase-locked (evoked) response from the total activity, it is possible to isolate non-phase-locked (induced) oscillatory modulations that are not strictly time-locked to stimulus onset. This distinction is critical for isolating neural processes that are not captured by traditional evoked responses [13,14]. Building on this framework, work from our laboratory has demonstrated that non-phase-locked alpha activity can reveal task-related dynamics that are not observable in conventional evoked analyses [15,16].

More specifically, recent findings suggest that decreases in non-phase-locked alpha activity may reflect a reduction in background neural noise, facilitating sensory processing by enhancing the signal-to-noise ratio in relevant cortical areas. This interpretation has been supported by studies showing that early alpha desynchronization is associated with enhanced perceptual processing, particularly in the visual modality [15].

The present study extends this line of research by investigating whether this potential noise-reduction mechanism is also present in the auditory modality, and whether it is localized in cortical regions associated with modality-specific sensory processing. Although previous studies have reported alpha-band modulations, including non-phase-locked activity, in auditory tasks [17,18], the functional role of early non-phase-locked alpha dynamics and their direct comparison across sensory modalities remain largely unexplored. Specifically, we examine both phase-locked and non-phase-locked alpha activity during visual and auditory oddball tasks, focusing on their temporal dynamics and topographical organization.

In addition, the present study includes a complementary analysis addressing the potential impact of frequency definition on the observed effects. Although alpha activity is commonly defined within the 8–13 Hz range, alternative approaches have been proposed,

including the use of subdivided frequency bands or individualized frequency ranges based on the individual alpha frequency (IAF) [19,20]. In particular, several studies have distinguished between lower and upper alpha subbands, associating them with different functional roles in cognitive processing [21,22]. In this context, the present work systematically compares results obtained using a conventional alpha band (8–13 Hz), subdivided bands (8–10.5 Hz and 10.5–13 Hz), and IAF-based definitions, in order to assess the extent to which the characterization of alpha modulation depends on the selected frequency interval.

Based on the framework outlined above, the present study was designed to test the following hypotheses. First, we expected modality-dependent differences in alpha activity, with distinct temporal and topographical patterns for visual and auditory processing. Second, we hypothesized that phase-locked and non-phase-locked alpha activity would show systematic differences in their temporal dynamics and polarity, while maintaining a shared spatial organization. Third, we predicted that non-phase-locked alpha modulation would reflect early sensory processing mechanisms, potentially associated with a reduction in background neural noise in modality-specific cortical regions. Fourth, we examined whether the characterization of these effects depends on the definition of the alpha band, testing the hypothesis that temporal and spatial patterns of alpha modulation would remain largely stable across conventional (8–13 Hz), subdivided, and IAF-based frequency ranges. Finally, to further validate the independence of non-phase-locked activity, we analyzed the phase distributions of both phase-locked and non-phase-locked alpha activity across participants, with the aim of determining whether the latter could be explained by residual contributions from evoked responses.

2. Materials and Methods

2.1. Ethical Statement

All participants provided written informed consent prior to their inclusion in the study. The experimental procedures were conducted in accordance with the principles outlined in the Declaration of Helsinki. The study protocol was reviewed and approved by the Ethics Committee of the University of Seville (project code: PSI2010-16825).

2.2. Participants

A total of 29 adults were recruited from university students and staff. All participants reported no history of neurological disorders or current use of psychoactive medication. Two participants were excluded from further analyses due to the presence of non-removable artifacts affecting at least one electrode within the regions of interest (see Section 2.5 for details). The final sample consisted of 27 adults (10 males, 17 females), aged between 18 and 47 years (mean = 24.2 ± 6.27). All but two participants were right-handed. Participants completed two cognitive tasks, consisting of auditory and visual oddball paradigms, with task order counterbalanced across participants. No channel interpolation procedures were applied, in order to avoid potential alterations of the data that could impact subsequent topographical analyses. Regarding age distribution, 12 participants were between 18 and 22 years old, whereas the remaining 15 participants were between 23 and 47 years old. The individualized alpha frequency approach was implemented to minimize the impact of interindividual variability in alpha-band characteristics across this age range.

2.3. Cognitive Task

The experimental design included two oddball tasks, one visual and one auditory, both requiring the detection of infrequent target stimuli embedded within a sequence of frequent standard stimuli. In both tasks, target stimuli were presented with a probability of 25%, whereas standard stimuli accounted for the remaining 75%. Participants were

instructed to respond to target stimuli by pressing a mouse button with their right index finger while ignoring standard stimuli.

The visual task followed a standard visual oddball paradigm. Target stimuli consisted of a rectangle displaying a red-and-white checkerboard pattern, whereas standard stimuli were matched in size and structure but presented a black-and-white checkerboard pattern. Stimuli were presented centrally on the screen, and a fixation point was continuously displayed during interstimulus intervals to minimize eye movements. The viewing distance was set at 70 cm, resulting in stimulus dimensions of $7.98^\circ \times 9.42^\circ$ of visual angle (horizontal $\times$ vertical). Each visual stimulus was presented for 500 ms, followed by an interstimulus interval of 1000 ms. A total of 400 trials were presented in a pseudorandom order, distributed across two experimental blocks.

The auditory task followed a standard auditory oddball paradigm. Stimuli consisted of pure tones, with standard tones presented at 400 Hz and target tones at 1000 Hz. No additional differences in stimulus characteristics were introduced. Tones were delivered binaurally through headphones at an intensity of approximately 70 dB SPL. Each auditory stimulus had a total duration of 70 ms, including 10 ms rise and 10 ms fall times. The interstimulus interval was set at 750 ms. A total of 400 trials were presented in pseudorandom order across two blocks. As in the visual task, a fixation point was continuously displayed on the screen throughout the auditory condition to reduce eye movements.

Behavioral measures, including reaction times and accuracy rates for target stimuli, as well as overall accuracy considering correct withholding of responses to standard stimuli, were computed at the end of the experiment.

2.4. EEG Recording

The electroencephalogram (EEG) was recorded from 58 Ag/AgCl scalp electrodes positioned according to the extended international 10–10 system (see Figure 1 for the detailed electrode layout) [23]. Signals were amplified using BrainAmp amplifiers and continuously recorded with BrainVision Recorder software (version 1.05; Brain Products GmbH, Gilching, Germany). During acquisition, all channels were referenced to linked earlobes and subsequently re-referenced offline to the common average.

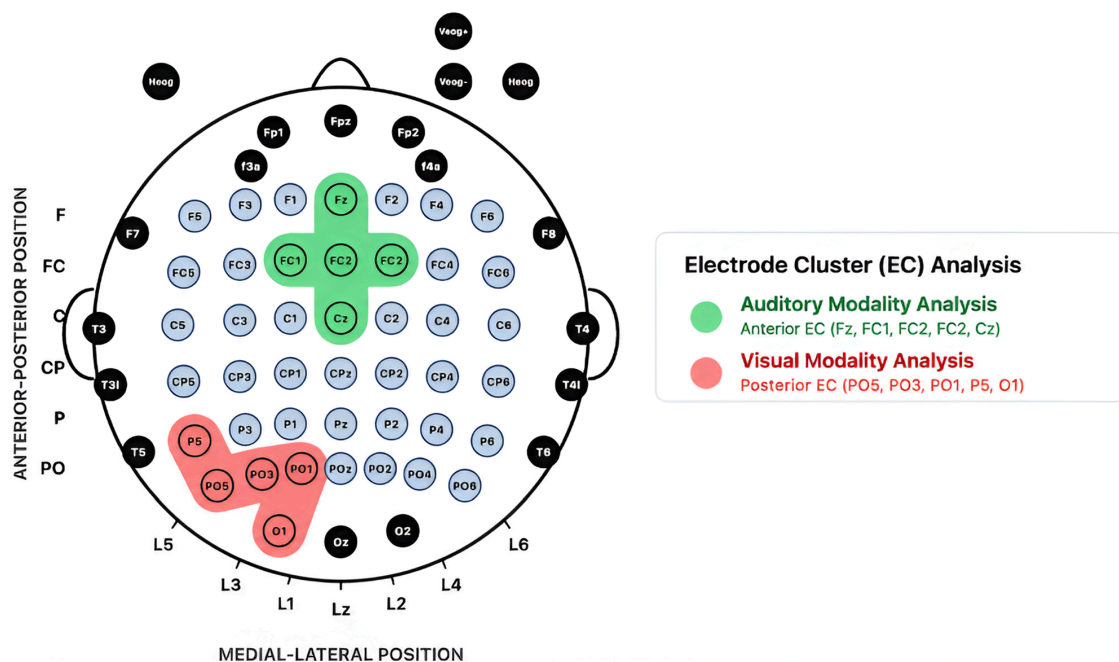


Figure 1. Layout of the 58 scalp electrodes used for EEG recording. Topographical correlation analyses were performed on the 6×7 electrode matrix highlighted in blue. Two electrode clusters

(EC) were defined for latency and amplitude analyses. The anterior EC (Fz, FC1, FCz, FC2, Cz) was selected because it encompassed the scalp region showing the maximum auditory alpha modulation in the grand-average maps. The posterior EC (PO5, PO3, PO1, P5, O1) included the scalp region exhibiting the maximum visual alpha modulation. Abbreviations: F (frontal), FC (frontocentral), C (central), CP (centroparietal), P (parietal), PO (parieto-occipital), L (lateral), z (midline).

Vertical and horizontal electrooculographic activity (VEOG and HEOG) was monitored using bipolar recordings. VEOG was obtained from electrodes placed above and below the left eye, while HEOG was recorded from electrodes positioned at the outer canthi of both eyes. Data were sampled at 500 Hz with an online band-pass filter of 0.01–100 Hz. Electrode impedances were maintained below 5 k Ω throughout the recording session. All recordings were conducted in an electrically shielded and sound-attenuated room.

2.5. EEG Preprocessing

EEG preprocessing and signal analysis were conducted using BrainVision Analyzer (version 2.2; Brain Products GmbH, Gilching, Germany). The following preprocessing steps were applied prior to the calculation of phase-locked and non-phase-locked activity. First, ocular artifacts due to eye blinks were corrected using the regression-based procedure proposed by Gratton et al. [24], which estimates and removes blink-related activity from EEG channels using the EOG recordings while preserving non-ocular neural activity. Continuous EEG data were then segmented into epochs ranging from –200 to 1000 ms relative to target stimulus onset (0 ms). Baseline correction was applied using the pre-stimulus interval (–200 to 0 ms). Trials containing horizontal eye movements were rejected if the HEOG signal exceeded ± 75 μ V. In addition, electrode Pz was monitored to detect non-ocular artifacts occurring in scalp regions close to the alpha modulations under study. Trials exceeding ± 75 μ V at Pz were also rejected. No independent component analysis (ICA) procedures were applied.

At this stage, two complementary processing pipelines were implemented to extract phase-locked and non-phase-locked alpha activity from the EEG signal (Figure 2). To obtain phase-locked alpha activity, the signal was first averaged across trials, and the resulting waveform was subsequently band-pass filtered between 8 and 13 Hz using a Butterworth filter with a roll-off of 48 dB/octave. The filter was applied in a forward–backward manner: the waveform was filtered first in the original temporal direction and then again in the reverse direction. This procedure cancels the frequency-dependent phase shift introduced during each individual pass, yielding an overall zero-phase response and therefore preventing phase distortion or temporal displacement of the alpha-band waveform [10]. The resulting signal was subsequently rectified following the procedure described in previous studies [15].

For the estimation of non-phase-locked alpha activity, a temporal spectral evolution (TSE) approach was applied [12]. This involved band-pass filtering (8–13 Hz) of single-trial EEG epochs, followed by rectification and averaging across trials for the target condition. To isolate non-phase-locked activity, the phase-locked component was subtracted from the TSE, yielding the induced (non-phase) response [15].

These analyses were initially conducted using a conventional fixed alpha band (8–13 Hz). In order to further characterize the spectral organization of alpha activity, additional analyses were performed by subdividing the alpha range into lower (8–10.5 Hz) and upper (10.5–13 Hz) bands. Finally, an individualized approach was implemented by defining subject-specific alpha bands based on the individual alpha frequency (IAF), allowing comparison between fixed and individualized frequency definitions [25]. The IAF was estimated for each participant from resting-state EEG recorded under eyes-closed conditions. Power spectral density (PSD) was computed using a Fast Fourier Transform

(FFT) with a Hanning window applied to artifact-free segments. The spectral estimate was obtained from electrode PO5, where alpha activity showed the highest prominence. The IAF was defined as the peak alpha frequency (PAF), corresponding to the frequency showing maximum power within the 8–13 Hz range. Based on this value, individualized alpha bands were defined for each participant by selecting frequency ranges spanning from PAF -2 Hz to PAF $+2$ Hz.

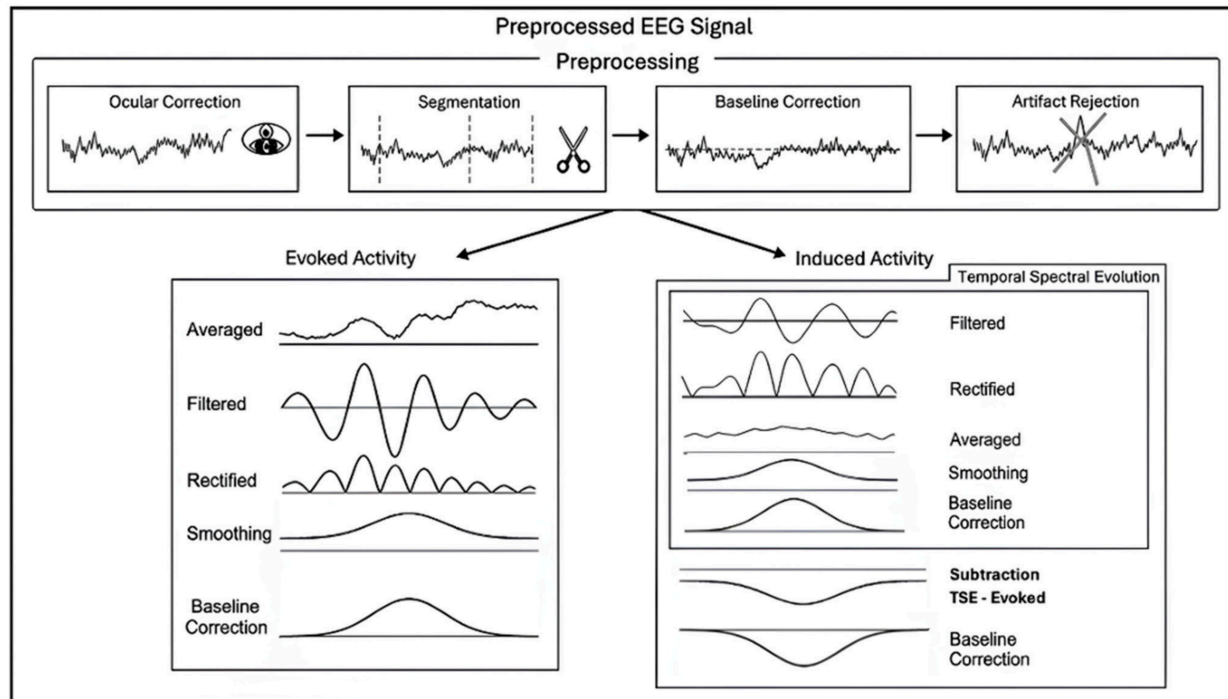


Figure 2. EEG processing pipeline for phase-locked and non-phase-locked activity. From preprocessed EEG data, the diagram outlines the workflow used to obtain both components: phase-locked (evoked) activity is derived in the left branch, while non-phase-locked (induced) activity is estimated in the right branch using TSE. The final step represents the subtraction of phase-locked activity from the total signal to isolate the non-phase-locked component.

Latency values of phase-locked and non-phase-locked alpha activity were calculated for each participant at the electrode showing the maximum amplitude in the grand average, separately for each modality (visual: PO5; auditory: FCz). Latency estimation was performed within a broad temporal window spanning 80–140 ms for both sensory modalities. Within this interval, phase-locked alpha activity was defined as the maximum positive deflection (peak), whereas non-phase-locked alpha activity was defined as the maximum negative deflection (“valley”). To improve peak detection and reduce the influence of high-frequency fluctuations, a low-pass filter (5 Hz, 48 dB/octave) was applied prior to latency estimation, in line with previous studies [15].

The low-pass filtering procedure was implemented using a zero-phase Butterworth filter applied in a forward–backward manner as described above [10]. By filtering the signal in both temporal directions, the phase shift introduced during the forward pass is canceled during the backward pass, thereby avoiding both phase distortion and temporal displacement of waveform components. The same filtering procedure was applied identically across all experimental conditions and therefore cannot account for the observed differences between sensory modalities or activity types. Previous work from our laboratory has shown that this smoothing procedure improves peak detection reliability without introducing measurable latency shifts [15].

Based on the latency results, amplitude analyses were conducted using two narrower time windows (80–110 ms and 110–140 ms) to better capture differences in the temporal dynamics between modalities. Specifically, the earlier window was expected to be more sensitive to auditory effects, whereas the later window was designed to capture visual-related activity. These windows were defined after inspection of the grand-average waveforms. Their selection was motivated by the distinct temporal profiles observed for auditory and visual alpha modulation, with auditory activity showing a more rapid evolution and visual activity displaying a more sustained response. Consequently, these analyses should be considered data-driven and primarily descriptive.

Electrode clusters were empirically defined from grand-average scalp distributions. For each modality, the electrode with maximum modulation was identified and combined with neighboring electrodes to improve robustness and reduce the influence of local noise (see Figure 1). These electrode clusters should not be interpreted as direct estimates of the underlying cortical generators but rather as scalp regions where the observed alpha modulation reached its maximum expression.

2.6. Phase Analysis for Evoked and Induced Activity

To assess whether non-phase-locked modulation reflected genuinely induced activity rather than residual contributions from phase-locked responses, a phase analysis was conducted for both components. The phase-locked component was first estimated by averaging across trials and subsequently subtracted from each individual trial to isolate the non-phase-locked signal [13,14]. The resulting single-trial signals were then band-pass filtered within the alpha range (8–13 Hz), and the Hilbert transform was applied to obtain instantaneous phase values.

Phase values for the non-phase-locked activity were extracted within the predefined early time window (80–110 ms), corresponding to the interval in which induced alpha modulation was observed in the grand-average waveforms. For comparison, phase values of the phase-locked activity were obtained from individual averaged waveforms using the same filtering and phase estimation procedure. This analysis allowed us to determine whether non-phase-locked activity exhibited a random phase distribution, as expected for genuinely induced responses, or whether it showed systematic phase alignment suggestive of residual contamination from evoked activity.

All computations were performed using MNE-Python version 1.12.1, an open-source Python package for exploring, visualizing, and analyzing human neurophysiological data, including MEG and EEG recordings.

2.7. Statistical Analysis

Statistical analyses were performed using IBM SPSS Statistics (version 23; IBM Corp., Armonk, NY, USA). All variables were first tested for normality using the Shapiro–Wilk test. Depending on the outcome, either parametric or non-parametric statistical tests were applied. Reaction times were compared between sessions using paired-sample *t*-tests, whereas accuracy differences were assessed using the Wilcoxon test.

For latency analyses within the conventional alpha band (8–13 Hz), a repeated-measures ANOVA was conducted with two within-subject factors: Sensory Modality (visual, auditory) and Activity Type (phase-locked, non-phase-locked). For analyses involving subdivided alpha bands (8–10.5 Hz and 10.5–13 Hz) or individualized alpha bands based on the IAF (lower vs. upper alpha), an additional within-subject factor, Band, was included, resulting in a three-factor ANOVA design.

Amplitude analyses were conducted using a different factorial structure, including three within-subject factors: Window (80–110 ms and 110–140 ms), Electrode Cluster

(anterior, posterior), and Sensory Modality (visual, auditory). Phase-locked and non-phase-locked activities were analyzed separately using independent repeated-measures ANOVAs. In all ANOVAs, post hoc comparisons were conducted using Bonferroni correction to control for multiple comparisons.

To assess the correspondence between topographical maps, Pearson's product-moment correlation coefficients (r) were computed across a 6×7 electrode matrix (see Figure 1). For each comparison, values were extracted at the latency corresponding to the maximum amplitude for each combination of factors (sensory modality, activity type—phase and non-phase—and frequency definition). Following Kileny and Kripal [26], the significance threshold was adjusted by dividing the nominal alpha level ($p = 0.05$) by the total number of comparisons ($n = 60$), yielding a corrected significance level of $p < 0.00083$.

Finally, to assess whether non-phase-locked activity exhibited a preferred phase, Rayleigh's test of circular uniformity was applied separately to the phase values obtained for each of the 27 participants. For each participant, the test evaluated the null hypothesis that phase angles were uniformly distributed over the circular range from 0 to 2π , against the alternative hypothesis that they were concentrated around a preferred direction. In this case, because IBM SPSS Statistics does not provide a native implementation of Rayleigh's test, the analysis was performed using a custom Python script.

Because phase is a circular variable, each observed phase angle was represented as a unit vector pointing in the corresponding direction in the complex plane. If the phases are uniformly distributed, these vectors tend to cancel when averaged, whereas a concentration of phases around a preferred direction produces a mean vector with a nonzero length. Rayleigh's test assesses whether the observed mean vector length is greater than expected under circular uniformity. The test statistic was computed from the mean resultant vector length, $(\bar{R})$, as $(Z = N\bar{R}^2)$, where (N) is the number of phase observations. Because Rayleigh's test was applied separately to each of the 27 participants and to each of the two sensory modalities, a total of 54 tests were performed. The significance threshold was adjusted using the Bonferroni correction by dividing the nominal alpha level ($p = 0.05$) by the total number of tests ($n = 54$), yielding a corrected significance level of ($p < 0.00093$).

3. Results

3.1. Behavioral Data

Reaction times differed between sensory modalities, with faster responses observed in the auditory modality (Visual: 326 ± 25.2 ms; Auditory: 283 ± 45 ms; $t = 4.37$, $p < 0.001$). No significant differences were found in overall accuracy between modalities ($Z = 0.849$, $p = 0.395$), considering both target detections and correct rejections of standard stimuli (Visual: $99.3 \pm 0.63\%$; Auditory: $99.0 \pm 1.13\%$). Similarly, no differences were observed in target detection accuracy ($Z = 0.865$, $p = 0.386$) (Visual: $98.1 \pm 2.25\%$; Auditory: $97.1 \pm 4.44\%$).

3.2. Phase and Non-Phase Alpha Activities

3.2.1. Latency

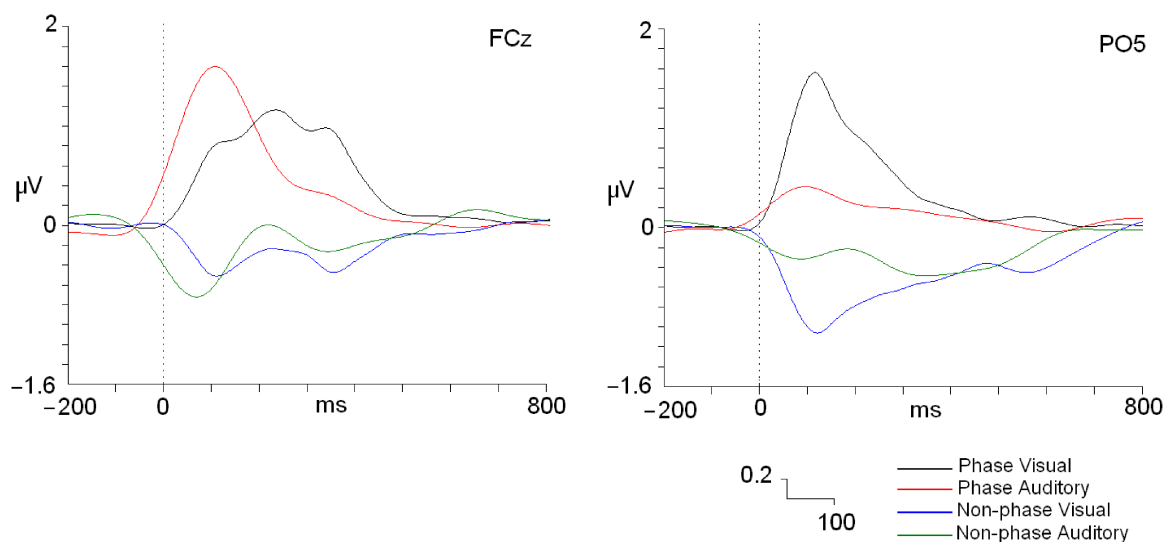
A repeated-measures ANOVA conducted within the conventional alpha band (8–13 Hz) revealed a significant main effect of "Sensory Modality" ($F(1,26) = 16.7$, $p < 0.001$, $\eta^2 = 0.391$), with shorter latencies observed in the auditory condition (93 ms) compared to the visual condition (120 ms) (see Table 1 and Figure 3).

A significant main effect of "Activity Type" was also found ($F(1,26) = 11.3$, $p = 0.002$, $\eta^2 = 0.304$), indicating differences between phase-locked (113 ms) and non-phase-locked (101 ms) alpha activity.

Table 1. Statistical results for the latency of phase-locked and non-phase-locked alpha modulations across the different frequency definitions.

Factors	8–13 Hz Effect	Latency
Sensory Modality	$F(1,26) = 16.71$ $p < 0.001$	V: 121—A: 93
Activity Type	$F(1,26) = 11.35$ $p = 0.002$	P: 113—NP: 101
Interaction SM $\times$ AT	$F(1,26) = 28.50$ $p < 0.001$	ANP: 79 AP: 107 VNP: 123 VP: 118
Factors	8–10.5 Hz/10.5–13 Hz Effect	Latency
Sensory Modality	$F(1,26) = 17.83$ $p < 0.001$	V: 124—A: 95
Activity Type	$F(1,26) = 14.11$ $p < 0.001$	P: 116—NP: 103
Interaction SM $\times$ AT	$F(1,26) = 21.73$ $p < 0.001$	ANP: 79 AP: 111 VNP: 127 VP: 122
Factors	IAF (Low/High) Effect	Latency
Sensory Modality	$F(1,26) = 19.75$ $p < 0.001$	V: 123—A: 95
Activity Type	$F(1,26) = 12.49$ $p = 0.001$	P: 115—NP: 103
Interaction SM $\times$ AT	$F(1,26) = 28.51$ $p < 0.001$	ANP: 79 AP: 110 VNP: 127 VP: 120

Abbreviations: Hz: Hertz; SM: Sensory Modality; AT: Activity type. V: Visual; A: Auditory; VP: Visual–Phase; VNP: Visual–Non-Phase; AP: Auditory–Phase; ANP: Auditory–Non-Phase. All values are expressed in milliseconds.

**Figure 3.** Grand-average phase-locked and non-phase-locked traces for both sensory modalities at the PO5 and FCz electrodes in the 8–13 Hz band. The x-axis represents time (ms), and the y-axis represents the amplitude of phase-locked and non-phase-locked activity (μV). The vertical dashed line indicates stimulus onset. Black and red traces correspond to phase-locked activity in the visual and auditory modalities, respectively, whereas blue and green traces represent non-phase-locked activity in the same modalities. Abbreviations: ms (milliseconds), μV (microvolts).

Importantly, a significant interaction between “Sensory Modality” and “Activity Type” was also observed ($F(1,26) = 28.5$, $p < 0.001$, $\eta^2 = 0.523$). This interaction was primarily driven by the shorter latency of non-phase-locked alpha activity in the auditory modality (79 ms) compared to all other conditions (all $p < 0.001$).

When analyses were conducted using subdivided alpha bands (8–10.5 Hz and 10.5–13 Hz) as well as individualized frequency ranges based on the IAF method, latency results closely mirrored those obtained for the conventional 8–13 Hz band (see Figures 4 and 5). In particular, the main effect of Sensory Modality was consistently observed across all frequency definitions, with shorter latencies in the auditory condition compared to the visual condition. Significant effects of Activity Type and the Sensory Modality $\times$ Activity Type interaction were also found. As in the 8–13 Hz analysis, this interaction was primarily driven by the shorter latency of non-phase-locked alpha activity in the auditory modality. Mean values and detailed statistical results are provided in Table 1 for clarity and conciseness.

Importantly, no significant effects were found for the factor Band, indicating that latency values for both phase-locked peaks and non-phase-locked minima did not differ between lower and upper alpha sub-bands, nor between IAF-derived frequency ranges.

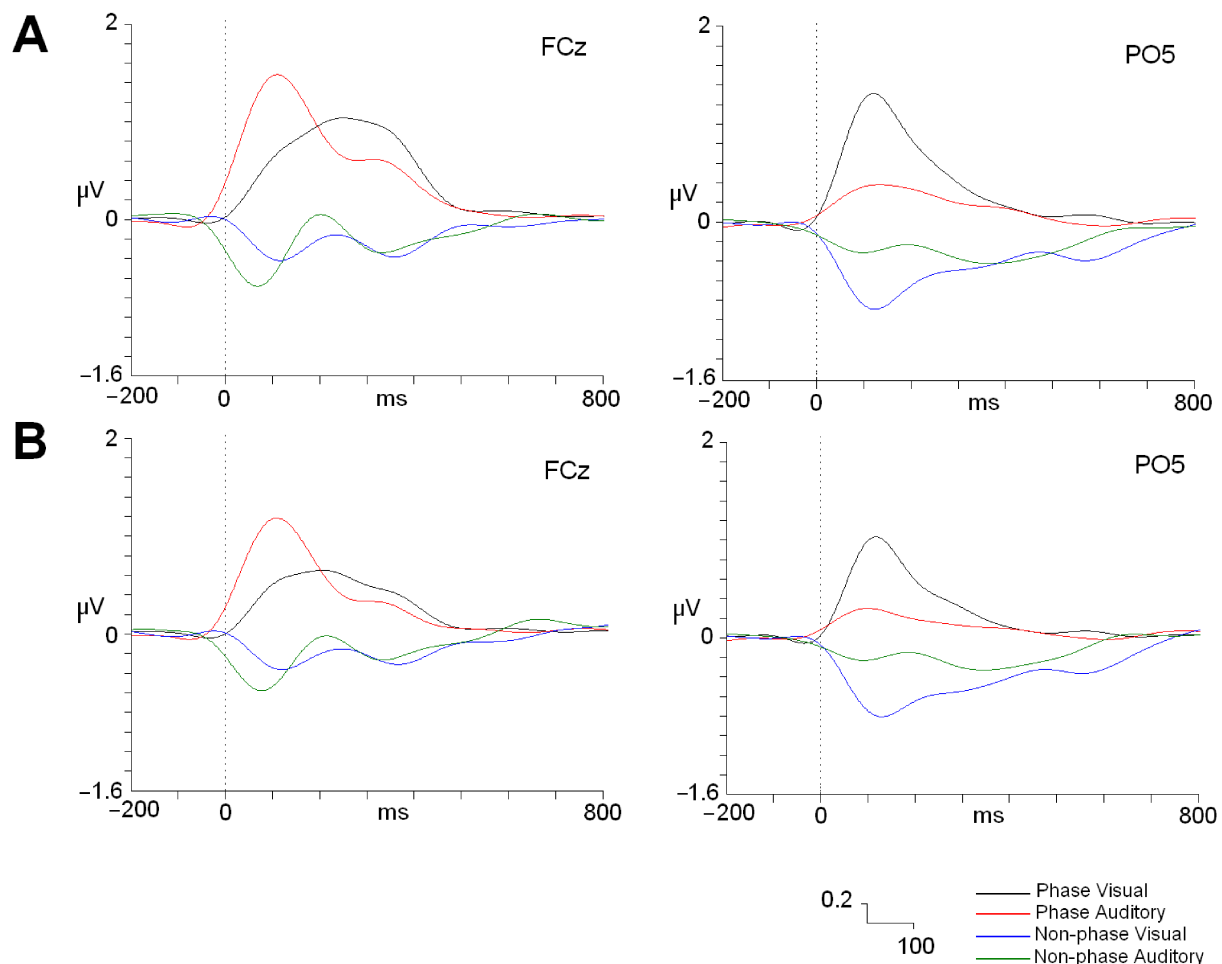


Figure 4. Grand-average phase-locked and non-phase-locked traces for both sensory modalities at the PO5 and FCz electrodes in the 8–10.5 Hz and 10.5–13 Hz bands. (A) Waveforms in the 8–10.5 Hz. (B) Waveforms in the 10.5–13 Hz. The x-axis represents time (ms), and the y-axis represents the amplitude of phase-locked and non-phase-locked activity (μV). The vertical dashed line indicates stimulus onset. Black and red traces correspond to phase-locked activity in the visual and auditory modalities, respectively, whereas blue and green traces represent non-phase-locked activity in the same modalities. Abbreviations: ms (milliseconds), μV (microvolts).

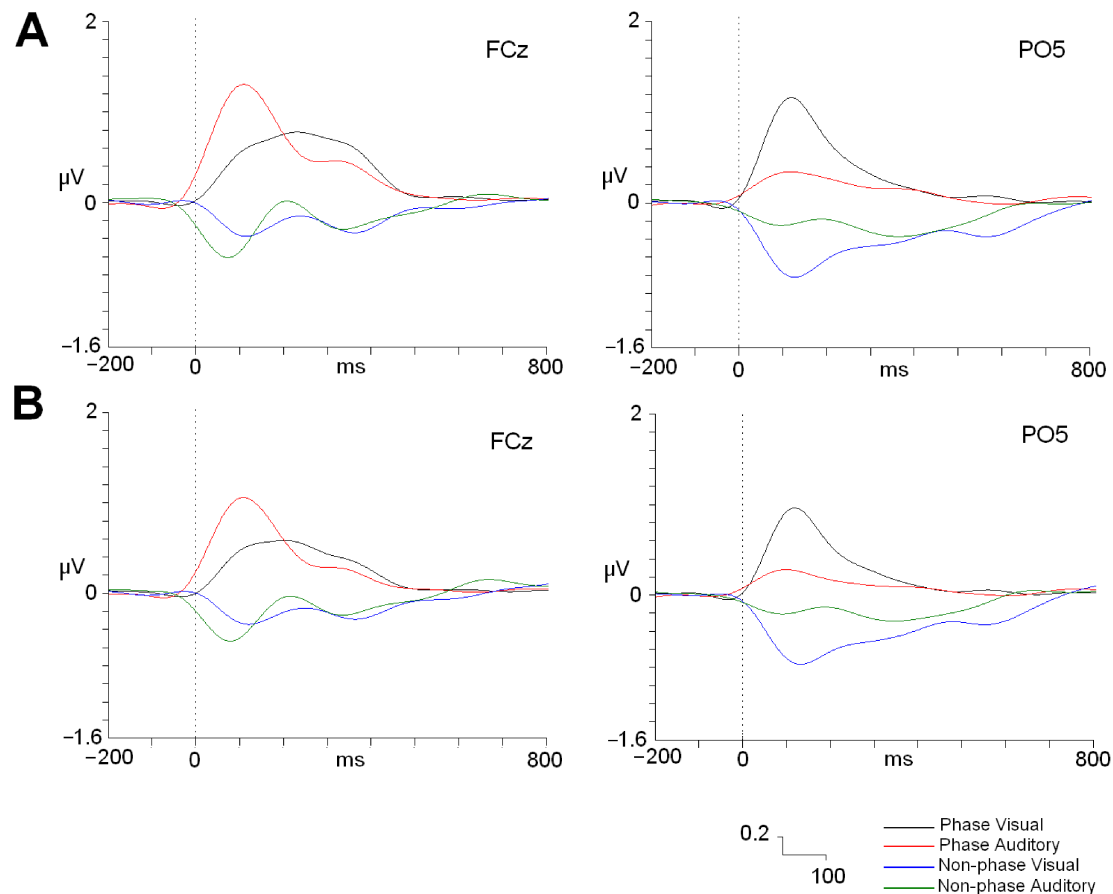


Figure 5. Grand-average phase-locked and non-phase-locked traces for both sensory modalities at the PO5 and FCz electrodes in the lower and upper IAF ranges. (A) Waveforms in the Low IAF. (B) Waveforms in the High IAF. The x-axis represents time (ms), and the y-axis represents the amplitude of phase-locked and non-phase-locked activity (μV). The vertical dashed line indicates stimulus onset. Black and red traces correspond to phase-locked activity in the visual and auditory modalities, respectively, whereas blue and green traces represent non-phase-locked activity in the same modalities. Abbreviations: ms (milliseconds), μV (microvolts).

3.2.2. Amplitude

For phase-locked alpha amplitude in the 8–13 Hz band, the ANOVA did not reveal a significant three-way interaction between Window, Electrode Cluster, and Sensory Modality ($F(1,26) = 0.452$, $p = 0.506$). However, post hoc analyses indicated that some comparisons showed statistically significant differences (see Table 2). Specifically, higher amplitude values were observed for the auditory modality in the anterior electrode cluster in both time windows (80–110 ms and 110–140 ms). In contrast, within the posterior electrode cluster, the visual modality showed significantly higher amplitudes than the auditory modality across both windows (all $p < 0.001$).

A similar pattern was observed for non-phase-locked alpha activity, with one notable exception. No significant differences between auditory and visual modalities were found in the anterior electrode cluster during the second time window (110–140 ms), whereas all other effects replicated those observed for phase-locked activity. A detailed description of all observed effects is provided in Table 2.

Importantly, this pattern of results was consistently reproduced across all additional analyses, including subdivided alpha bands (8–10.5 Hz and 10.5–13 Hz) and IAF-based frequency ranges, for both phase-locked and non-phase-locked activity (see Table 2).

Table 2. Statistical results for the amplitude of phase-locked and non-phase-locked alpha modulations across the different frequency definitions.

Type of Activity		8–13 Hz		
Phase-locked	Window 1	Anterior EC	V: 0.68—A: 1.41	$p < 0.001$
		Posterior EC	V: 1.22—A: 0.40	$p < 0.001$
	Window 2	Anterior EC	V: 0.78—A: 1.40	$p < 0.001$
		Posterior EC	V: 1.29—A: 0.40	$p < 0.001$
Non Phase-locked	Window 1	Anterior EC	V: −0.45—A: −0.64	$p < 0.001$
		Posterior EC	V: −0.85—A: −0.29	$p < 0.001$
	Window 2	Anterior EC	V: −0.48—A: −0.49	n.s.
		Posterior EC	V: −0.94—A: −0.27	$p < 0.001$
8–10.5 Hz				
Phase-locked	Window 1	Anterior EC	V: 0.55—A: 1.31	$p < 0.001$
		Posterior EC	V: 1.04—A: 0.37	$p < 0.001$
	Window 2	Anterior EC	V: 0.67—A: 1.31	$p < 0.001$
		Posterior EC	V: 1.10—A: 0.41	$p < 0.001$
Non Phase-locked	Window 1	Anterior EC	V: −0.37—A: −0.59	$p < 0.001$
		Posterior EC	V: −0.70—A: −0.27	$p < 0.001$
	Window 2	Anterior EC	V: −0.39—A: −0.40	n.s.
		Posterior EC	V: −0.76—A: −0.25	$p < 0.001$
10.5–13 Hz				
Phase-locked	Window 1	Anterior EC	V: 0.46—A: 1.04	$p < 0.001$
		Posterior EC	V: 0.84—A: 0.29	$p < 0.001$
	Window 2	Anterior EC	V: 0.55—A: 1.04	$p < 0.001$
		Posterior EC	V: 0.89—A: 0.29	$p < 0.001$
Non Phase-locked	Window 1	Anterior EC	V: −0.32—A: −0.52	$p < 0.001$
		Posterior EC	V: −0.64—A: −0.22	$p < 0.001$
	Window 2	Anterior EC	V: −0.36—A: −0.40	n.s.
		Posterior EC	V: −0.73—A: −0.20	$p < 0.001$
IAF Low				
Phase-locked	Window 1	Anterior EC	V: 0.48—A: 1.14	$p < 0.001$
		Posterior EC	V: 0.92—A: 0.33	$p < 0.001$
	Window 2	Anterior EC	V: 0.58—A: 1.15	$p < 0.001$
		Posterior EC	V: 0.97—A: 0.35	$p < 0.001$
Non Phase-locked	Window 1	Anterior EC	V: −0.33—A: −0.54	$p < 0.001$
		Posterior EC	V: −0.66—A: −0.23	$p < 0.001$
	Window 2	Anterior EC	V: −0.36—A: −0.40	n.s.
		Posterior EC	V: −0.73—A: −0.22	$p < 0.001$
IAF High				
Phase-locked	Window 1	Anterior EC	V: 0.43—A: 0.93	$p < 0.001$
		Posterior EC	V: 0.79—A: 0.27	$p < 0.001$
	Window 2	Anterior EC	V: 0.51—A: 0.93	$p < 0.001$
		Posterior EC	V: 0.85—A: 0.27	$p < 0.001$
Non Phase-locked	Window 1	Anterior EC	V: −0.30—A: −0.48	$p < 0.001$
		Posterior EC	V: −0.61—A: −0.20	$p < 0.001$
	Window 2	Anterior EC	V: −0.34—A: −0.38	n.s.
		Posterior EC	V: −0.69—A: −0.18	$p < 0.001$

All values are expressed in microvolts. Window 1: 80–110 ms. Window 2: 110–140 ms. Abbreviations: Hz: Hertz; ms: milliseconds; n.s.: non-significant ($p \geq 0.05$). Anterior electrode cluster (EC): Fz, FC1, FCz, FC2, Cz; Posterior electrode cluster (EC): PO5, PO3, PO1, P5, O1.

3.2.3. Topographical Correlations

Correlation analyses were conducted to assess the consistency of topographical patterns across sensory modalities, activity types, and frequency definitions.

- **Sensory Modality:** Correlations between topographical maps for visual and auditory modalities confirmed the differences observed in the amplitude analyses. Both phase-locked and non-phase-locked activity showed distinct spatial distributions across modalities. Specifically, correlation values obtained using the 8–13 Hz band were -0.701 and -0.763 for phase-locked and non-phase-locked activity, respectively, indicating opposite or markedly different spatial configurations. Comparable results were observed across all other frequency intervals (see Table 3).

Table 3. Correlations between voltage maps across sensory modalities and activity types under the different frequency definitions.

SENSORY MODALITY	8–13 Hz	8–10.5 Hz	10.5–13 Hz	IAF Low	IAF High
VP—AP	-0.701	-0.696	-0.714	-0.715	-0.711
VNP—ANP	-0.763	-0.787	-0.805	-0.796	-0.799
TYPE OF ACTIVITY	8–13 Hz	8–10.5 Hz	10.5–13 Hz	IAF Low	IAF High
VP—VNP	-0.981	-0.975	-0.980	-0.978	-0.991
AP—ANP	-0.943	-0.957	-0.961	-0.958	-0.962

Abbreviations: Hz: Hertz; VP: Visual–Phase; VNP: Visual–Non-Phase; AP: Auditory–Phase; ANP: Auditory–Non-Phase. All comparisons were significant below the corrected p -value ($p = 0.00083$).

- **Activity Type:** When comparing phase-locked and non-phase-locked activity within each modality, correlation analyses revealed a striking pattern. In the 8–13 Hz band, correlations between both activity types reached -0.981 for the visual modality and -0.943 for the auditory modality. These values indicate that the spatial distributions of phase-locked and non-phase-locked activity were nearly identical in their topography but opposite in sign, with positive amplitudes characterizing phase-locked responses and negative amplitudes characterizing non-phase-locked activity. Similar results were obtained across all other frequency intervals (see Table 3).
- **Frequency Intervals:** Correlations between topographical maps obtained from different frequency definitions (fixed band, subdivided bands, and IAF-based ranges) were consistently high for each activity type and sensory modality. In all cases, correlation values exceeded 0.980 and, in some instances, reached 1.000, indicating virtually identical spatial distributions across frequency intervals (see Figure 6). Detailed correlation values for all comparisons are provided in Table 4.

Table 4. Correlations between voltage maps for the different combinations of sensory modality and activity type between the standard frequency band (8–13 Hz) and the remaining frequency definitions.

	VP	VNP	AP	ANP
8–10.5 Hz	0.990	0.994	0.998	0.997
10.5–13 Hz	0.996	0.998	1.000	0.996
IAF Low	0.999	1.000	0.999	0.999
IAF High	0.997	0.999	0.999	0.999

Abbreviations: Hz: Hertz; VP: Visual–Phase; VNP: Visual–Non-Phase; AP: Auditory–Phase; ANP: Auditory–Non-Phase. All comparisons were significant below the corrected p -value ($p = 0.00083$).

3.3. Phase Analyses

With regard to the potential contribution of phase-locked to non-phase-locked activity, phase analyses revealed a dispersed distribution of phase values for non-phase-locked

activity, which was not aligned with the phase values observed for phase-locked activity within individual participants. Figures 7 and 8 illustrate the distribution of phase values for phase-locked and non-phase-locked alpha activities across participants for the visual and auditory sensory modalities, respectively.

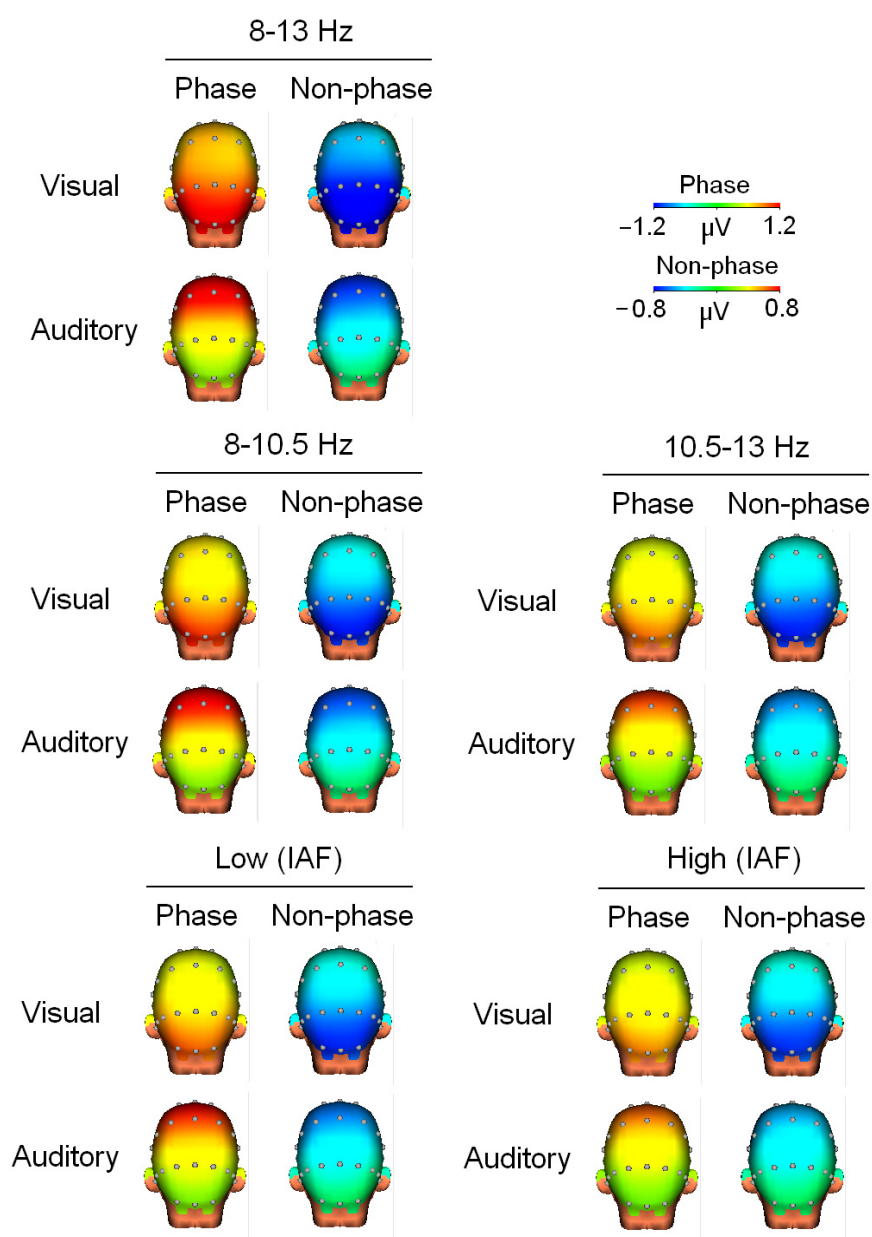


Figure 6. Three-dimensional head maps of phase-locked and non-phase-locked activity for both sensory modalities. The color scale represents voltage values, ranging from -1.2 to 1.2 μV for phase-locked activity and from -0.8 to 0.8 μV for non-phase-locked activity, with values transitioning from dark blue (negative) to dark red (positive). Note that color scales were adjusted independently for phase-locked and non-phase-locked activity. Abbreviations: μV (microvolts).

Rayleigh's test did not reject the null hypothesis of circular uniformity for any participant in either the visual or the auditory task. None of the 54 tests reached statistical significance, as all p -values exceeded both the nominal significance level of 0.05 and the Bonferroni-corrected threshold of 0.00093. Thus, no significant preferred phase was detected in the non-phase-locked activity, and the observed phase distributions were compatible with circular uniformity.



Figure 7. Polar plot of phase values for phase-locked and non-phase-locked alpha activity (8–13 Hz) across the twenty-seven participants in the visual modality. Blue dots indicate phase values for non-phase-locked activity, whereas red crosses represent phase values for phase-locked activity.



Figure 8. Polar plot of phase values for phase-locked and non-phase-locked alpha activity (8–13 Hz) for each of the twenty-seven participants in the auditory modality. Green dots indicate non-phase-locked phase values and red crosses represent phase-locked phase value.

4. Discussion

Behavioral analyses revealed significant differences between sensory modalities, with faster responses observed for auditory compared to visual stimuli. This pattern is consistent with previous studies comparing auditory and visual oddball paradigms, which typically report shorter reaction times for auditory targets due to faster sensory processing and transmission in the auditory system [27–29].

Importantly, no differences were observed in accuracy measures, either for target detection or overall performance. This indicates that the observed reaction time differences cannot be attributed to a speed–accuracy tradeoff, supporting the interpretation that modality-related effects reflect genuine differences in processing speed rather than strategic adjustments in task performance.

A comparable modality effect was also observed at the electrophysiological level, specifically in the latency of alpha-band modulations. The results showed a clear latency advantage for the auditory modality compared to the visual modality. This finding is consistent with previous evidence indicating that auditory evoked responses typically occur earlier than their visual counterparts due to differences in sensory transduction and cortical processing pathways [27,30]. Given that phase-locked alpha activity reflects the alpha-band representation embedded within evoked responses, this earlier latency is in line with the known temporal hierarchy of sensory processing.

Interestingly, this pattern was also replicated in non-phase-locked activity, suggesting that both phase-locked and non-phase-locked alpha modulations may be linked to common underlying processes. However, non-phase-locked activity showed even shorter latencies than phase-locked activity in the present study. This contrasts with previous reports, where no differences or even delayed non-phase-locked responses have been observed [31,32]. One possible explanation for this variability is that non-phase-locked activity may be influenced by trial-to-trial fluctuations in the phase of ongoing EEG activity at stimulus onset. Previous studies have shown that the pre-stimulus phase of alpha oscillations can modulate cortical excitability and influence subsequent sensory processing dynamics, including response timing [33–35]. In this context, variability in the initial phase state across trials could contribute to differences in the temporal profile of alpha desynchronization, potentially affecting the latency of the observed non-phase-locked modulation. Therefore, conclusions regarding latency effects should be interpreted with caution.

With respect to temporal dynamics, non-phase-locked alpha modulation showed an early decrease (80–110 ms) in both sensory modalities. However, in the later time window (110–140 ms), this effect was only maintained in the visual modality. This pattern indicates that non-phase-locked modulation is more transient in the auditory condition, whereas it is more sustained in the visual condition, suggesting modality-dependent differences in the temporal evolution of alpha activity.

Interestingly, phase-locked alpha activity showed comparable temporal dynamics across sensory modalities, whereas non-phase-locked alpha modulation exhibited clear modality-dependent differences. This dissociation supports the idea that non-phase-locked alpha activity reflects a functionally specific process operating within a restricted stage of information processing. In particular, the transient nature of auditory non-phase-locked modulation is consistent with a temporally precise mechanism, possibly related to the reduction in background neural noise at early stages of sensory processing [15,31].

More broadly, this pattern suggests that non-phase-locked alpha activity may inherit the intrinsic temporal constraints of modality-specific sensory processing streams, reflecting differences in cortical processing speed and integration dynamics across sensory systems [35–37]. Notably, the more sustained modulation observed in the visual modality

suggests that these mechanisms may extend over longer temporal intervals, potentially reflecting prolonged integration demands within visual cortical systems.

Amplitude analyses revealed a clear modality-dependent topographical organization of early alpha activity. Phase-locked auditory responses were predominantly distributed over central regions of the scalp (FCz), whereas visual responses showed a posterior distribution over parieto-occipital areas (PO5). This pattern closely matches the known spatial distribution of auditory and visual evoked potentials, respectively [27,28,30]. Correlation analyses further confirmed that the spatial distributions of alpha activity differed between modalities (values ranging from -0.7 to -0.8).

A similar topographical organization was observed for non-phase-locked activity, with auditory responses concentrated in central regions and visual responses in posterior areas. Considering the early latency of these effects, it is reasonable to interpret non-phase-locked alpha modulation as reflecting processes occurring during the initial stages of sensory processing. Together, these findings suggest that both phase-locked and non-phase-locked alpha activities are strongly dependent on the sensory modality and the cortical networks engaged. This interpretation is consistent with previous views of alpha activity as a regionally specific and functionally heterogeneous phenomenon [36,37], and further supported by evidence showing that alpha oscillations are spatially organized according to task-relevant cortical regions [35] and that modality-specific alpha activity can emerge within auditory cortical networks during selective listening [6,38].

Moreover, the clear topographical relationship between non-phase-locked alpha modulation and phase-locked activity in both sensory modalities, supported by notable anticorrelation values (above -0.9), provides strong evidence for a functional link between these two components. This systematic inverse relationship suggests that regions exhibiting stronger evoked responses are also those showing the greatest reductions in non-phase-locked alpha activity. Such a pattern is consistent with the idea that decreases in alpha amplitude reflect a reduction in background neural noise in task-relevant cortical areas, thereby enhancing the processing of incoming sensory information. In this framework, non-phase-locked alpha suppression would not simply represent a passive by-product of evoked activity, but rather an active mechanism that dynamically facilitates signal processing by optimizing the signal-to-noise ratio within modality-specific networks. The high spatial correspondence between phase-locked and non-phase-locked activity further supports the notion that both processes are tightly coupled and operate within the same cortical regions, reinforcing the interpretation of non-phase-locked alpha modulation as a functionally meaningful component of early sensory processing.

Finally, both latency and amplitude results were highly consistent across all frequency definitions, including the fixed alpha band (8–13 Hz), subdivided bands (8–10.5 Hz and 10.5–13 Hz), and individualized ranges based on the IAF (see high correlation values in Table 4). This convergence indicates that both the temporal and spatial characteristics of the observed alpha modulations are largely independent of the specific frequency definition. Specifically, latency effects remained stable across frequency definitions, supporting the robustness of alpha timing dynamics [19,35], while amplitude and topographical patterns also showed a high degree of consistency, with no meaningful differences emerging from the use of subdivided or individualized bands. Taken together, these findings suggest that, at least in the context of early sensory processing, conventional fixed frequency bands are sufficient to capture the relevant alpha modulations.

In light of this consistency across frequency definitions, the role of individualized approaches such as the IAF warrants further consideration. The IAF approach has been widely proposed as a method to optimize the detection of alpha-related effects by accounting for inter-individual variability in peak frequency [19,20,39]. Indeed, several studies

have reported that IAF-based analyses can improve sensitivity and reveal effects that may be less apparent when using fixed frequency bands [39,40]. However, the present findings indicate that such optimization does not necessarily translate into meaningful differences in the temporal or spatial characteristics of alpha activity. Rather than reflecting distinct functional processes, the use of IAF may primarily enhance detectability under certain conditions without fundamentally altering the underlying neural organization.

In the case of non-phase-locked activity, phase analyses corroborated previous findings from our laboratory [15], indicating that evoked activity does not make a significant contribution to the observed induced modulation in this cognitive task. This pattern was consistently observed in both visual and auditory modalities, where the phase values of non-phase-locked activity were distributed randomly across the full range of possible phase angles relative to the individual average phase value of phase-locked activity. This observation was supported by Rayleigh's tests of circular uniformity, which did not detect a significant preferred phase for any participant in either modality. None of the 54 tests reached statistical significance, as all p -values exceeded the nominal significance level of 0.05 and, consequently, the Bonferroni-corrected threshold of 0.00093. The observed phase distributions were therefore compatible with circular uniformity, supporting the absence of systematic phase locking in the non-phase-locked activity.

Such a distribution supports the interpretation that non-phase-locked modulation reflects genuine induced activity rather than residual contamination from evoked responses. Additionally, the distribution of phase values for phase-locked activity differed between sensory modalities, further suggesting distinct temporal dynamics and differential processing across the auditory and visual neural pathways.

Several methodological considerations should be acknowledged. First, the electrode clusters employed in the present study were defined at the scalp level and therefore should not be interpreted as direct estimates of the underlying neural generators. Future studies combining scalp EEG with source reconstruction techniques may help clarify the cortical origins of the observed alpha modulations. Second, although topographical similarity was assessed using correlation analyses, EEG recordings are characterized by spatial dependencies among neighboring electrodes. Future investigations may benefit from complementing the present approach with cluster-based permutation methods specifically designed to account for spatial autocorrelation.

Third, the analyses focused on early post-stimulus time windows. While this approach was appropriate for examining early sensory processing, it remains unclear whether similar patterns would be observed at later stages of cognitive processing, where different functional dynamics of alpha activity may emerge. This is particularly interesting for the visual sensory modality, which exhibits modulations from 110 ms onward that even extend to anterior scalp regions.

Fourth, the interpretation of non-phase-locked activity should be considered with caution. As discussed, induced activity is sensitive to trial-to-trial variability in ongoing oscillatory phase and may reflect a combination of processes, including desynchronization and fluctuations in baseline neural activity. Although methodological steps were taken to isolate non-phase-locked activity, the precise functional significance of these modulations remains an open question.

Fifth, the present study did not directly manipulate attentional load or task difficulty. Although the observed differences are interpreted primarily in terms of sensory modality, it remains possible that cognitive factors contributed to the reported effects. However, previous evidence from our laboratory showed that increasing cognitive load in a visual go/no-go paradigm significantly affected behavioral performance and P3 activity while leaving both evoked and induced alpha responses unchanged [32]. This suggests that the

alpha measures examined here may be relatively insensitive to cognitive load variations. Future studies specifically designed to manipulate attentional demands across sensory modalities would help further clarify this issue.

Finally, the central scalp distribution observed for auditory alpha activity should not be interpreted as evidence that the underlying generators are located directly beneath FCz. Because scalp potentials reflect the projection of cortical sources through volume conduction, the location of maximum voltage at the scalp surface does not necessarily coincide with the anatomical location of the neural generators. Consequently, the present findings describe modality-dependent differences in scalp distributions rather than direct differences in source localization.

An additional consideration is that, although the present results suggest that frequency definition has a limited impact under the current experimental conditions, the relevance of individualized frequency bands may become more pronounced in tasks involving higher cognitive demands or in populations with greater inter-individual variability.

5. Conclusions

Taken together, the present results indicate that non-phase-locked alpha activity constitutes a rapid and modality-dependent mechanism embedded within early sensory processing, whose temporal dynamics remain stable across frequency definitions. This robustness suggests that alpha-band activity reflects fundamental organizational principles of cortical function rather than methodological constraints, providing a refined framework for understanding the role of oscillatory dynamics in sensory processing.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

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