Beyond the Source of Distraction: Shared Neural Signatures of Internal and External Distraction in Drivers

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Abstract: Driver distraction remains a critical threat to road safety, encompassing both external stimuli and internal mind-wandering. This study investigated neurophysiological correlates of distraction during simulated driving using electroencephalography (EEG). EEG signals were recorded from 21 participants while they performed a continuous driving task, with instructions to detect and respond to police cars that appeared by pressing a button. Three types of audio distractions were presented: internal-focus (prompting self-referential thoughts), non-task-relevant (irrelevant background sounds), and task-relevant (driving-related but secondary information) stimuli.
Reaction times (RTs) to police car detections were used to classify attentional states on a trial-by-trial basis: the 25th percentile (fastest RTs) defined the 'Attentive' state, while trials exceeding the 75th percentile (slowest RTs) defined the 'Distracted' state. Power spectral density (PSD) was analyzed in theta (4-8 Hz) and alpha (8-12 Hz) bands across three regions of interest: temporal, frontocentral, and parieto-occipital.
Paired t-tests with false discovery rate (FDR) correction revealed that the Distracted state exhibited significantly lower theta power in all three regions, alongside higher alpha power compared to the Attentive state. Complementary single-trial repeated-measures correlations (rmcorr) corroborated these findings, demonstrating linear associations between delayed RTs and increased alpha power coupled with decreased theta power across all regions ($p < 0.001$), with the strongest correlations observed in the temporal region.
These results highlight distinct oscillatory signatures of distraction - reduced theta (linked to diminished cognitive engagement) and elevated alpha (indicative of reduced cortical activation) - offering potential biomarkers for real-time monitoring of driver inattention.

1. Introduction

Driver distraction is a major threat to road safety and may arise from both external stimuli and internal mind-wandering (Lee et al., 2008; Forster & Lavie, 2014). In driving, both forms of distraction compete with task-relevant processing and can delay responses to critical events (Taatgen et al., 2021; Voinea et al., 2025). Previous research has shown that mind-wandering is associated with attentional decoupling and measurable changes in neural oscillations, suggesting that EEG may provide a continuous index of moment-to-moment attentional state (Baird et al., 2014; Smallwood & Schooler, 2015).

In this study, we investigated whether alpha- and theta-band EEG activity can differentiate attentive and distracted states during simulated driving. We further examined whether these neural measures vary systematically with trial-by-trial reaction time. A key contribution of this work is showing that distraction across the studied conditions is associated with a common oscillatory pattern characterized by increased alpha and reduced theta activity.

2. Method

EEG data were obtained from the BCIT Mind Wandering dataset (Touryan et al., 2022). After excluding two participants due to excessive artifacts, the final sample comprised 19 participants with normal or corrected-to-normal vision and no reported neurological or psychiatric disorders. Participants performed a continuous simulated driving task in which they maintained lane position and speed while detecting police cars and responding via button press. During driving, they were exposed to three 30-minute auditory conditions: task-relevant, non-task-relevant, and internal-focus audio.

Behavioral performance was assessed using reaction time (RT) and response accuracy to police-car targets. A repeated-measures ANOVA showed no significant differences across auditory conditions for either RT or accuracy. Therefore, trials from all conditions were pooled for EEG analysis.

To maximize contrast between attentional states, trials were classified using RT quartiles: the fastest 25% were labeled Attentive, and the slowest 25% were labeled Distracted. For each target, a 5-second post-stimulus EEG segment was extracted, divided into 1-second epochs, cleaned using an automated artifact rejection pipeline derived from the proprietary signal-processing framework of the InnoBrain Human Cognitive Monitoring Platform (Osia et al., 2025), and averaged to compute PSD. Analyses focused on theta (4–8 Hz) and alpha (8–12 Hz) activity across three regions of interest: frontocentral, temporal, and parieto-occipital. Mean PSD values were compared between attentive and distracted states using paired t-tests with FDR correction. In addition, repeated-measures correlation was used to test trial-by-trial associations between RT and band power within individuals.

3. Results

3.1 *Performance evaluation*

The initial behavioral analysis using a repeated-measures ANOVA revealed no significant main effect of auditory condition on overt performance. Specifically, no significant differences were found across the three auditory scenarios for either reaction time, $F(2, 32) = 0.40$, $p = 0.673$, $\eta^2G = 0.011$, or response accuracy, $F(2, 32) = 2.40$, $p = 0.107$, $\eta^2G = 0.015$ (Fig. 1). Pairwise comparisons likewise showed statistically non-significant (ns) differences across conditions, supporting the pooling of trials for subsequent neural analyses. Fig. 1 shows mean reaction time and response accuracy across the three auditory conditions.

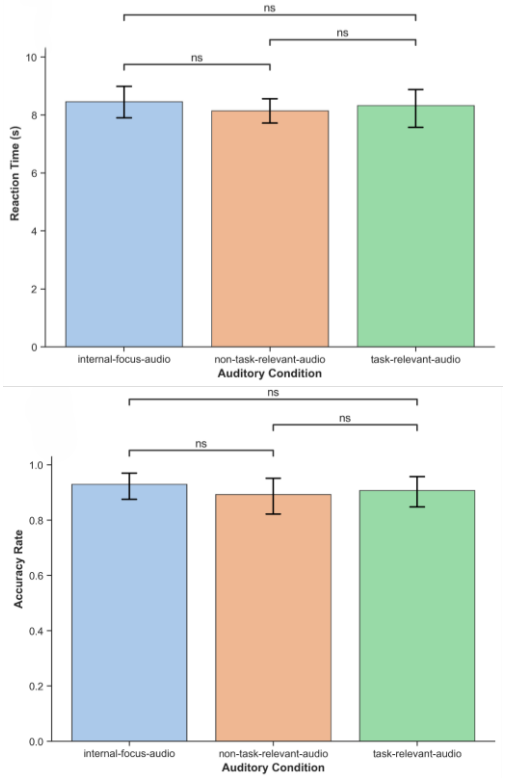


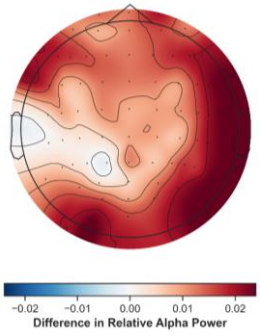
Fig. 1. *Behavioral performance across auditory conditions, (a) Reaction time, (b) Response accuracy.*

3.2 *PSD distribution*

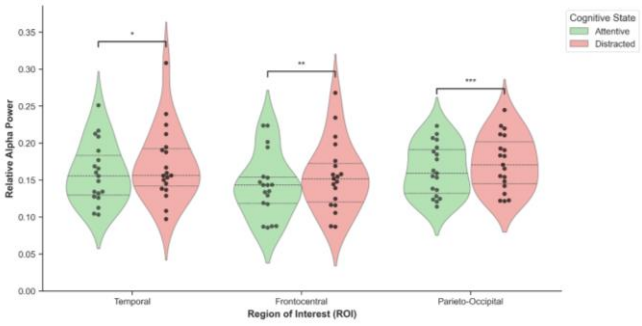
Paired-samples t-tests were conducted to compare relative Alpha and Theta power between the Attentive and Distracted states, with all p-values corrected using the FDR procedure.

Relative Alpha power was significantly higher in the Distracted state across all analyzed regions: parieto-occipital, $t(18) = 4.19$, $p_{fdr} = 0.001$, $d = 0.27$; frontocentral, $t(18) = 3.42$, $p_{fdr} = 0.004$, $d = 0.25$; and temporal, $t(18) = 2.78$, $p_{fdr} = 0.012$, $d = 0.25$ (Fig. 2).

In contrast, relative Theta power was significantly lower in the Distracted state across all regions: temporal, $t(18) = -5.22$, $p_{fdr} < 0.001$, $d = 0.37$; frontocentral, $t(18) = -4.59$, $p_{fdr} < 0.001$, $d = 0.31$; and parieto-occipital, $t(18) = -3.59$, $p_{fdr} = 0.003$, $d = 0.36$ (Fig. 3).

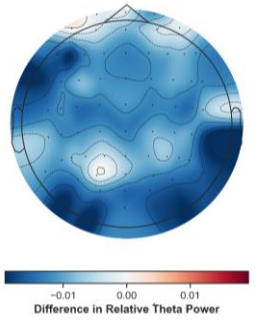


(a)

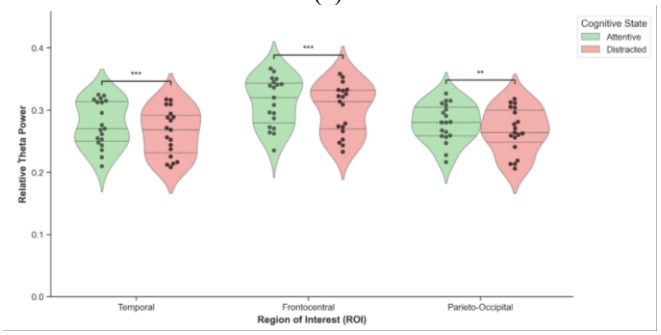


(b)

Fig. 2. *Alpha band (8–12 Hz) oscillatory dynamics differentiating Attentive and Distracted cognitive states.* ***(a)*** *Scalp topography of relative Alpha power (Distracted − Attentive). Red spectrum indicate increased Alpha synchronization during the distracted state,* ***(b)*** *Comparison of relative Alpha power across Temporal, Frontocentral, and Parieto-Occipital regions of interest (ROIs). Internal dashed lines represent the quartiles and median, while black dots represent mean values per participant. Asterisks denote statistical significance following FDR correction (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).*



(a)



(b)

Fig. 3. *Theta band (4–8 Hz) oscillatory dynamics differentiating Attentive and Distracted cognitive states.*

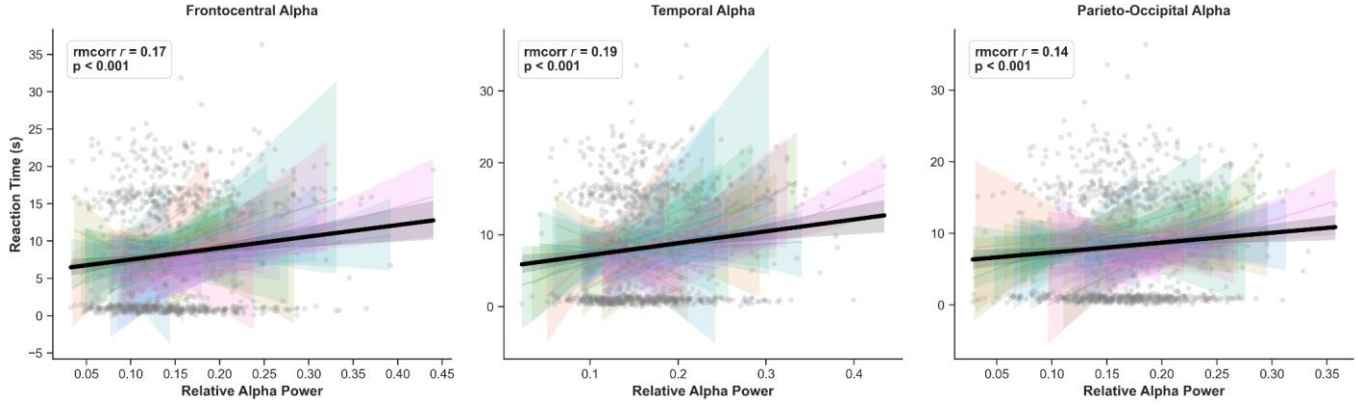
(a) *Scalp topography of relative Theta power (Distracted − Attentive). Blue spectrum indicate a widespread suppression of Theta activity during the distracted state,* ***(b)*** *Comparison of relative Theta power across Temporal, Frontocentral, and Parieto-Occipital ROIs.*
*Asterisks denote statistical significance following FDR correction (** $p < 0.01$, *** $p < 0.001$).*

3.3 Trial-by-Trial Brain-Behavior Relationship

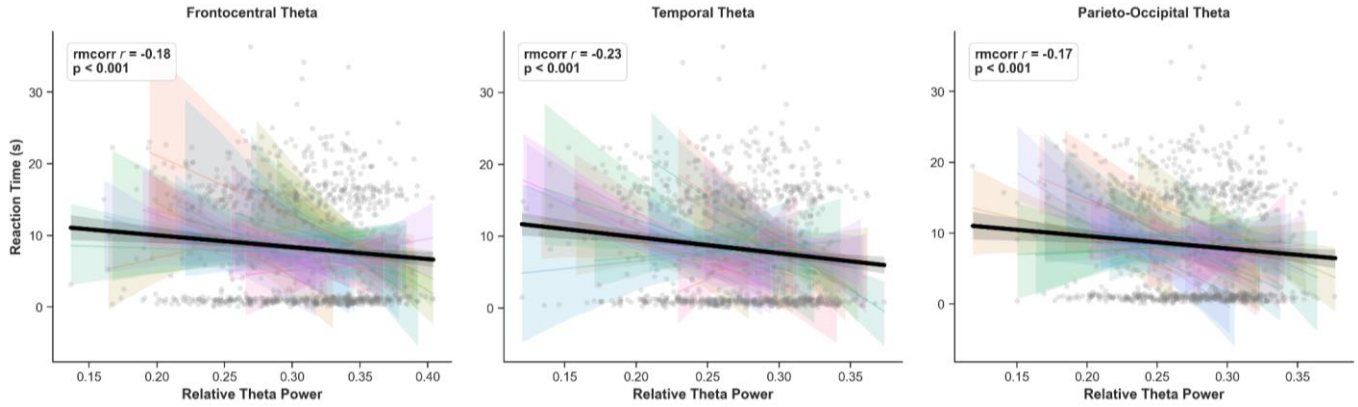
To assess the single-trial association between neural activity and behavioral performance while accounting for intra-individual variance, repeated-measures correlation (rmcorr) was performed between reaction time and relative Alpha and Theta power.

Relative **Alpha** power showed a significant positive correlation with reaction time across all regions, indicating that higher Alpha power was associated with slower responses. The strongest correlation was observed in the Temporal region, $r$rm(933) = 0.188, $p < 0.001$, followed by the Frontocentral, $r$rm(941) = 0.171, $p < 0.001$, and Parieto-Occipital regions, $r$rm(941) = 0.144, $p < 0.001$ (Fig. 4a).

Relative **Theta** power showed a significant negative correlation with reaction time across all regions, indicating that lower Theta power was associated with slower responses. Again, the strongest correlation was found in the Temporal region, $r$rm(933) = -0.232, $p < 0.001$, followed by the Frontocentral, $r$rm(941) = -0.184, $p < 0.001$, and Parieto-Occipital regions, $r$rm(941) = -0.168, $p < 0.001$ (Fig. 4b).



(a)



(b)

Fig. 4. *Trial-by-trial brain-behavior relationships using repeated-measures correlation. Scatter plots depict the single-trial relationship between reaction time (s) and relative power in the* ***(a)*** *alpha frequency bands and,* ***(b)*** *theta frequency bands, across Frontocentral, Temporal, and Parieto-Occipital ROIs.*
Translucent-colored-lines and shaded confidence intervals represent individual participant data fits, while the solid-black-line represents the common within-individual regression slope. The analysis reveals highly significant positive linear associations between reaction time and Alpha power, alongside negative associations with Theta power, across all examined regions.

4. Discussion

These findings are consistent with earlier work linking mind-wandering and distraction to reduced engagement with task-relevant stimuli and altered neural processing (Baird et al., 2014; Smallwood & Schooler, 2015). They also extend prior driving research showing that distraction undermines safe performance and hazard response (Lee et al., 2008; Voinea et al., 2025). The observed increase in alpha and decrease in theta suggest a shift toward reduced cortical engagement and weaker top-down attentional control during distracted driving. Importantly, because behavioral performance did not differ across auditory conditions, the results suggest that distraction across the studied conditions may converge on a common neural pattern, rather than reflecting entirely separate attentional states. This is a key contribution of the study.

5. Conclusion

In conclusion, this research highlights that driver inattention is not merely a transient behavioral lapse but a distinct neurophysiological state characterized by an alpha-theta power shift. These findings have critical implications for the future of human-factors engineering and automotive safety. The identified neural markers provide a highly reliable, unconstrained foundation for the development of passive, real-time Brain-Computer Interfaces (BCIs) and advanced driver-assistance systems (ADAS) capable of continuously monitoring driver cognitive states and mitigating the risks associated with distracted driving.

6. Acknowledgments

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