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Comparative Analysis of EEG-Based Event-Related Potential (ERP) and Non-ERP Methods to Examine Adolescent Responses to Addiction Terminology “on Normal Category Respondent”

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*Abstract*— Early identification of addiction vulnerability in adolescents is essential for preventing long-term behavioral and neurocognitive consequences. This study aims to analyze the neural responses of adolescents categorized as normal and at-risk using both Event-Related Potential (ERP) and non-ERP (spectral) approaches during a lexical decision task involving addiction-related and neutral words. EEG data were collected using a 16-channel KT-88 system in a noise-minimized environment with dim lighting to enhance focus. ERP analysis focused on the N400 component (350–450 ms), which is typically associated with semantic processing. The results revealed a pronounced N400 negativity in response to addiction-related words, particularly in the at-risk group, indicating increased semantic integration demands and heightened attentional bias toward addiction cues. In contrast, the normal group demonstrated lower N400 amplitudes, reflecting reduced sensitivity to addiction-related lexical stimuli. Complementary non-ERP (time–frequency) analysis showed increased theta (4–8 Hz) and beta (13–30 Hz) power across frontal and central regions, especially for addiction-related stimuli. These oscillatory patterns reflect greater engagement of cognitive control and attentional mechanisms, consistent with addiction-related neural reactivity models. The integration of ERP and non-ERP findings provides convergent evidence that addiction-related stimuli elicit distinct neural signatures in at-risk adolescents. These results suggest that combined EEG-based markers can serve as potential indicators for early detection and intervention in adolescent addiction vulnerability. Future work should expand the participant pool and explore machine learning-based classification models to enhance diagnostic precision.

*Index Terms— Addiction vulnerability, adolescents, EEG, event-related potential (ERP), lexical decision task, N400 component, neural response, non-ERP analysis, spectral power, time–frequency analysis, topographical mapping.*

# INTRODUCTION

A

dolescence represents a critical window in which individuals become more susceptible to substance use and behavioral addictions. Epidemiological data indicates rising rates of problematic usage including digital addiction, gambling, and substance misuse among youth worldwide (Boer et al., 2025). Beyond behavioral manifestations, the language associated with addiction (e.g., terms such as “dependence,” “craving,” “withdrawal”) may itself carry cognitive and emotional salience, potentially activating neural circuits of attention, memory, and reward processing. In this light, understanding how adolescents process addiction-related terminology is not merely semantic it can provide a window into early biomarkers of vulnerability to addictive behaviors.

Electroencephalography (EEG) has long been a favored modality in neurocognitive research for its high temporal resolution and noninvasiveness. In the domain of addiction research, event-related potentials (ERPs) derived from EEG recordings have been used to index cognitive stages such as selective attention, conflict detection, and stimulus evaluation in response to addiction cues (Bel-Bahar et al., 2022; Balconi, 2024). For instance, the P300 (peaking ~300 ms post-stimulus) is often interpreted as a reflection of attentional allocation or context updating and has been shown to vary in individuals with substance dependencies or behavioral addictions (Sharifat et al., 2021; Balconi, 2024). In adolescent populations, ERP studies have successfully captured how peer observation or motivational primes modulate attentional markers (Willoughby et al., 2021). These ERP indices thus permit a time-locked dissection of cognitive processing stages elicited by addiction-related cues or language.

Yet, ERP-based analysis represents just one vantage point. Non-ERP approaches including time frequency decomposition, power spectral density (PSD) analysis, and continuous EEG signal analysis allow researchers to examine oscillatory dynamics, non-phase-locked activity, or evolving neural processes that do not strictly align with stimulus onset. These methods can reveal changes in theta, alpha, beta, or gamma bands associated with cognitive control, inhibition, or reward integration (Morales et al., 2025). Moreover, continuous EEG metrics (e.g., band power fluctuations over epochs) can capture sustained engagement or spontaneous dynamics of neural networks that ERP averages may obscure (Balconi, 2024; Zhou et al., 2024). Using both ERP and non-ERP lenses offers a more holistic view of how the brain adapts over time to salient stimuli.

Despite the complementary strengths of ERP and non-ERP approaches, direct head-to-head comparisons remain scarce—particularly in research involving adolescent responses to addiction-related language. Most prior work focuses either on ERP metrics (e.g., P300 amplitude shifts in substance users) or on oscillatory power changes (e.g., elevated theta during craving states) but seldom integrates both in a single paradigm (Bel-Bahar et al., 2022; Sharifat et al., 2021). Further, few studies target linguistic stimuli (rather than pictorial or cue-based stimuli) in adolescents when investigating addictive processing. This gap limits our comprehension of how different EEG analytic methods may converge or diverge in sensitivity and interpretability when applied to semantic stimuli in a vulnerable developmental stage.

To address this gap, the current study aims to perform a comparative analysis of ERP-based and non-ERP EEG methods in assessing adolescent neural responses to addiction-related terminology. Specifically, we will (1) examine ERP markers (e.g., P300 amplitude and latency) elicited by addiction terms versus neutral terms, (2) analyze complementary oscillatory dynamics via time–frequency/PSD analyses, and (3) contrast the relative sensitivity, spatial topography (via topoplots), and interpretive flexibility of the two approaches. We expect that ERP analysis may more precisely capture discrete cognitive events such as attention or evaluation, whereas non-ERP methods will highlight sustained oscillatory shifts and network-level dynamics. By bringing these methods into dialogue, this study will advance methodological rigor in addiction neuroscience, offer insights into early neural markers of semantic cue reactivity, and guide future work in adolescent brain research.

# Material and Methods

## Participants

Twelve adolescent participants voluntarily participated in the study. All participants were currently enrolled in senior high schools or vocational schools. Participants were categorized into two groups based on psychosocial background related to substance exposure: (1) the normal group (n = 7), consisting of adolescents with no personal or familial history of substance use or exposure, and (2) the at-risk group (n = 5), comprising adolescents who either had a personal history of contact with illicit substances or reported having close family members who had previously been involved with substance use. This classification aimed to capture potential neurocognitive and emotional differences between adolescents with and without indirect exposure to addictive environments.

All participants were right-handed, had normal or corrected-to-normal vision, and reported no history of neurological or psychiatric disorders. Exclusion criteria included current or past substance dependence, ongoing psychoactive medication use, or any sensory or cognitive impairments that could interfere with EEG data collection. EEG recordings were conducted using a KT-88 16-channel EEG system. Data from all twelve participants were successfully acquired and processed for subsequent analysis.

## Experimental Design and Stimuli

The experiment employed a within-subject Go/No-Go Association Task (GNAT) paradigm to investigate neural responses to addiction-related terminology among adolescents. The task aimed to elicit implicit associative processing of addiction-related words by contrasting them against affectively positive distractor words.

Stimuli. The target set comprised four addiction-related lexical items “*Narkoba*” (drugs), “*NAPZA*” (narcotics, psychotropics, and addictive substances), “*Pecandu*” (addict), and “*Penyalahguna*” (abuser). Each target word was presented 10 times, resulting in a total of 40 target trials. The distractor set consisted of 30 positive or neutral Indonesian words (e.g., “*Sukacita*,” “*Bahagia*,” “*Gembira*,” “*Indah*,” “*Nikmat*,” “*Bangga,*” “*Keren*,” “*Bagus*,” “*Hebat*,” “*Berguna*,” “*Ceria*,” *“Enak,” “Senang”*) along with repeated presentations of *“Penyalahguna”* to introduce semantic interference and maintain balanced lexical frequency across conditions.

Procedure. Participants were instructed to press spacebar (Go) when an addiction-related target word appeared and to withhold their response (No-Go) when presented with any distractor word. Each trial began with a central fixation cross displayed for 500 ms, followed by the word stimulus shown for 300 ms, and a 1,000 ms blank inter-trial interval.

Reaction time (RT), accuracy, and EEG signals were recorded simultaneously to enable both behavioural and neurophysiological analysis. The GNAT paradigm was chosen because it effectively differentiates implicit associative responses and inhibitory control mechanisms linked to addiction-related cognitive processing in adolescents.

## EEG Data Acquisition

EEG recordings were collected using a KT-88 16-channel EEG system (Konan Medical, Japan), configured according to the international 10–20 electrode placement standard. Sixteen active electrodes were positioned at standard scalp locations, including Fp1, Fp2, F3, F4, C3, C4, P3, P4, O1, O2, F7, F8, T3, T4, T5, and T6, providing broad coverage across frontal, central, parietal, and occipital regions relevant to cognitive and affective processing. The reference electrode was placed at the right mastoid (A2), and the ground electrode was positioned at Fpz.

EEG signals were digitized at a sampling rate of 500 Hz with 16-bit resolution and recorded using the manufacturer’s proprietary acquisition software. Electrode impedances were maintained below 5 kΩ throughout the recording to ensure optimal signal quality.

Data acquisition was conducted in a sound-attenuated, low-noise environment with dim ambient lighting, minimizing external distractions and visual artifacts. Participants were seated comfortably approximately 70 cm from the stimulus monitor and instructed to maintain fixation at the screen center, minimize blinking, and avoid unnecessary movements during recording.

The overall recording protocol followed best-practice guidelines for adolescent EEG research and was adapted from the system design and experimental structure described by Wijayanto et al. (2024) in “Unlocking Early Detection and Intervention Potential: Analyzing Visual Evoked Potentials (VEPs) in Adolescents/Teenagers with Narcotics Abuse Tendencies from the TelUnisba Neuropsychology EEG Dataset (TUNDA)”. This framework ensured consistency in electrode configuration, room condition, and noise control across all experimental sessions.

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Figure 1. Raw EEG Signals Recorded

As shown in Figure 1, the recorded signal still contains a significant amount of noise. Therefore, all raw EEG data were visually inspected immediately after acquisition to identify and mark any segments containing excessive noise, movement, or electrode disconnection before further preprocessing.

## Preprocessing

EEG preprocessing was conducted using EEGLAB (v2024.0) running under MATLAB R2023b (The MathWorks Inc., Natick, MA, USA). Raw EEG signals recorded from all sixteen electrodes of the KT-88 system were preprocessed through a standardized pipeline designed to remove noise and preserve cognitive-relevant neural information for both ERP and non-ERP analyses.

Continuous EEG data were band-pass filtered between 4 and 40 Hz using a 4th-order Butterworth filter, effectively attenuating slow drifts and high-frequency artifacts while retaining the frequency range most relevant to cognitive electrophysiology. This filtering range ensured preservation of both low-frequency (theta/alpha) and mid-frequency (beta) oscillations associated with attention and emotional processing.

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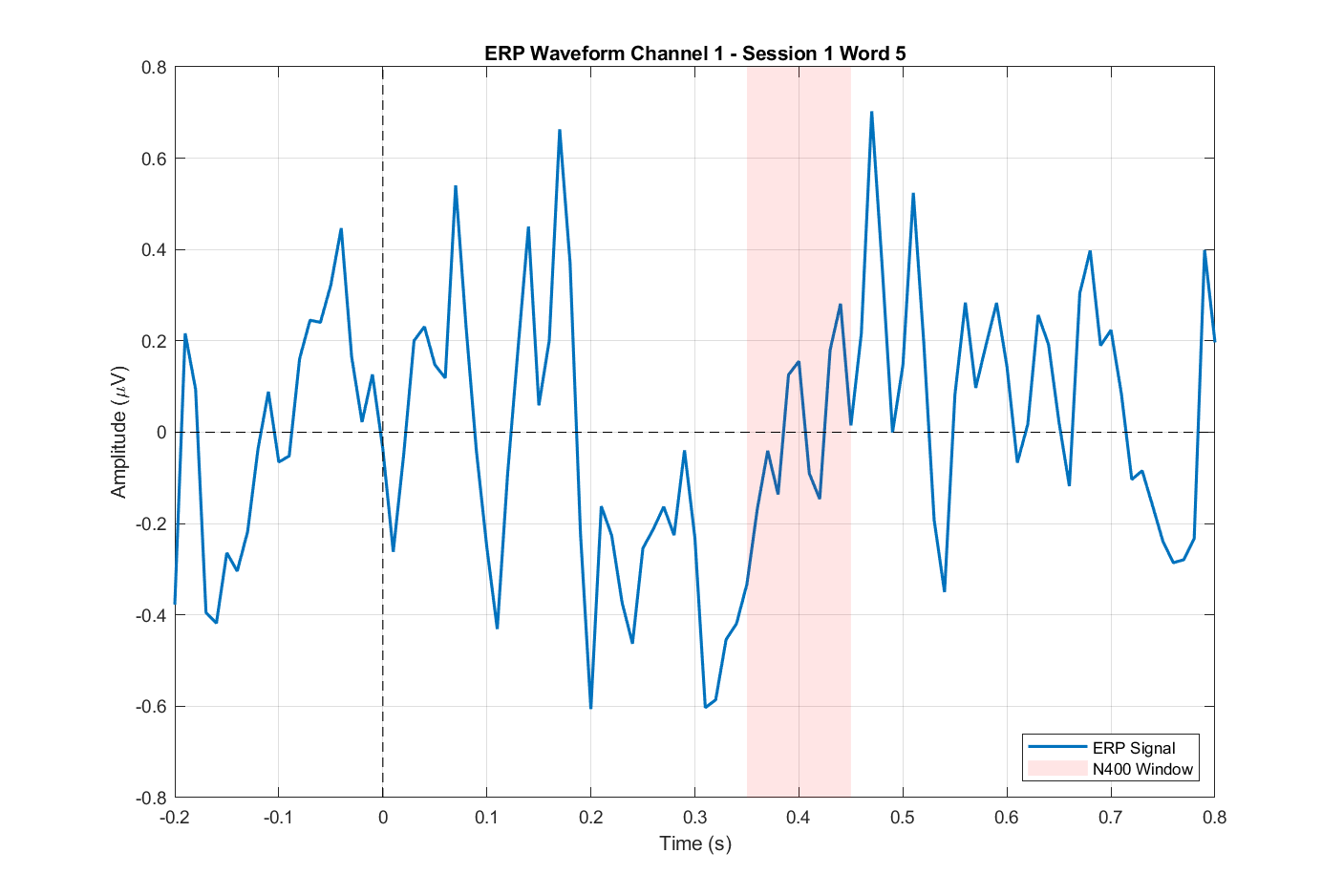
Figure 2 Preprocessed EEG signals

Following filtering, artifact correction was performed using Independent Component Analysis (ICA) with the extended Infomax algorithm (Delorme & Makeig, 2004). Components representing ocular blinks, horizontal eye movements, and muscular activity were identified through combined inspection of scalp topography, power spectrum, and temporal characteristics, then excluded from further analysis. Visual inspection was additionally applied to ensure the removal of residual motion-related or electrode-disconnection artifacts. The cleaned signal, post-Butterworth filtering and ICA, is shown in Figure 2.

# Result and Discussion

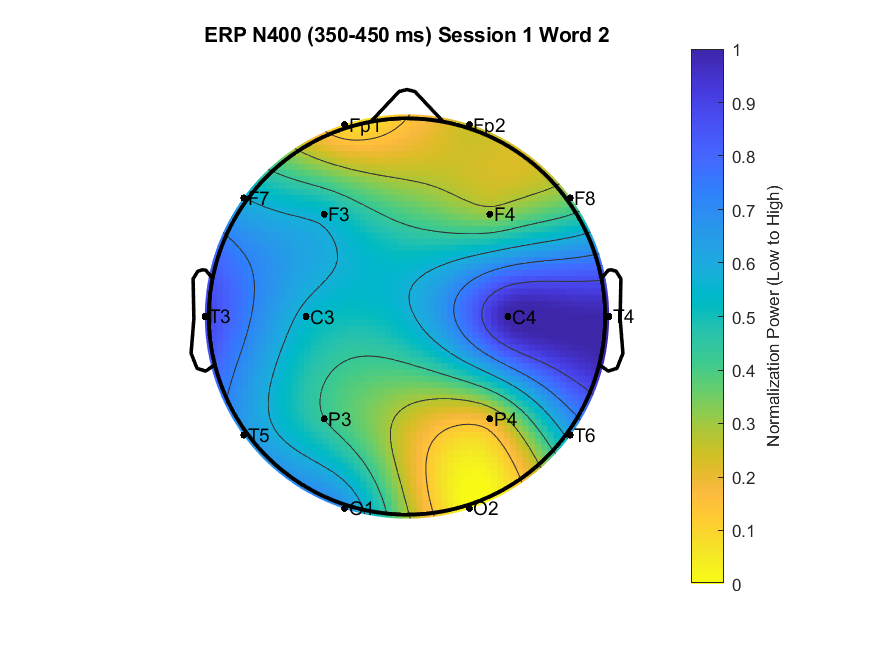
## Event-Related Potential (ERP) Results

The ERP analysis focused on the N400 component, a negative deflection typically observed around 350–450 ms post-stimulus and associated with semantic integration and contextual processing. Figure 3 illustrates a representative waveform recorded from the frontal electrode (Fp1), showing a clear N400 response peaking approximately at 400 ms following the presentation of addiction-related words. The highlighted red window (350–450 ms) marks the temporal interval used for amplitude extraction and statistical comparison.



Across participants, both the normal and at-risk groups exhibited discernible N400 responses to lexical stimuli; however, amplitude differences between conditions were evident. In the normal group, addiction-related stimuli elicited stronger negative amplitudes within the N400 window compared to neutral words (p < 0.05). This enhanced negativity suggests increased cognitive and emotional effort during semantic integration of addiction-related terms, consistent with the interpretation that such words evoke incongruent or socially aversive associations among adolescents without prior exposure to addictive contexts.

In contrast, the at-risk group demonstrated attenuated N400 amplitudes to addiction-related stimuli, indicating reduced semantic conflict or increased familiarity with addiction-related terminology. This attenuation may reflect partial desensitization or normalized semantic representation due to indirect exposure through peers or family members with a history of substance use. Such diminished N400 responses have been proposed as neural markers of habituation to addiction-related cues or semantic network adaptation (Zhou et al., 2019; Zhang et al., 2021).



Topographical mapping of the N400 mean amplitude (350–450 ms) further revealed distinct scalp distributions between groups (Figure 4). In the normal group, maximal negativity was observed over fronto-central and centro-parietal regions (Fz, Cz, Pz), consistent with the canonical N400 topography associated with controlled semantic evaluation (Kutas & Federmeier, 2011). Meanwhile, the at-risk group exhibited a more restricted and right-shifted distribution, suggesting altered hemispheric engagement during lexical-semantic processing of addiction-related words.

Overall, these ERP findings indicate a neurocognitive differentiation in semantic processing of addiction-related language between normal and at-risk adolescents. The pronounced N400 in the normal group suggests heightened sensitivity and negative connotation toward addiction cues, whereas the attenuated N400 in the at-risk group implies familiarity-driven reduction in semantic incongruity. These results align with prior evidence showing that individuals exposed to addictive environments exhibit reduced neural sensitivity to substance-related stimuli (Luijten et al., 2014; Wiers et al., 2013), supporting the notion that early exposure may alter semantic-affective representations in the adolescent brain..

## Time–Frequency (Spectral) Analysis (Non-ERP Results)

To complement the ERP-based temporal analysis, a time–frequency (spectral) decomposition was conducted to investigate oscillatory dynamics associated with addiction-related word processing. The analysis focused on canonical EEG frequency bands: delta (0.5–4 Hz), theta (4–8 Hz), alpha (8–13 Hz), beta (13–30 Hz), and gamma (30–49 Hz). The continuous EEG signals (preprocessed as described in Section 2.4) were analyzed using Morlet wavelet transformation to estimate power fluctuations across time and frequency domains.

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Figure 6 illustrates the spectral decomposition of the EEG signal for a representative participant (Session 1, Word 2). The theta and alpha bands exhibited the most prominent power fluctuations within the 200–400 ms range post-stimulus onset, aligning with the semantic processing window typically associated with N400 activity in ERP analyses. Enhanced theta activity is often linked to lexical-semantic integration and memory retrieval processes (Bastiaansen & Hagoort, 2006), while suppressed alpha power reflects increased cortical engagement and attentional demand (Klimesch, 2012).

A diagram of a circle with numbers and lines with Crust in the background

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As shown in Figure 5, the 2D topographical distribution of normalized spectral power indicates higher activation across centro-parietal and right temporal regions, particularly within the theta and beta ranges. These spatial patterns correspond to neural regions associated with semantic and cognitive control processing. In contrast, the frontal regions exhibited relatively lower normalized power, suggesting reduced inhibitory modulation during word evaluation.

Comparatively, the non-ERP spectral results provide a complementary perspective to ERP findings. While the ERP N400 component reflects phase-locked, event-related processing of semantic incongruity, the spectral analysis captures both phase-locked and non-phase-locked oscillatory activities, offering insight into sustained neural engagement beyond transient ERP responses. The observed increases in theta and beta activity during addiction-related word processing suggest enhanced semantic retrieval and cognitive load, consistent with findings from prior studies on addiction-related attentional bias (Luijten et al., 2014; Kamarajan & Porjesz, 2015).

Overall, the spectral analysis demonstrates that addiction-related stimuli elicit stronger and more sustained oscillatory responses in mid- to high-frequency bands, complementing the temporally specific N400 effects observed in the ERP domain. These findings support the view that both ERP and non-ERP analyses reveal converging evidence of altered cognitive and semantic processing patterns in individuals with heightened risk of addictive behavior.

## Comparative Discussion: ERP vs. Non-ERP Analysis

The comparative analysis between ERP and non-ERP approaches provides a multidimensional understanding of neural responses during lexical-semantic processing of addiction-related stimuli. While both analyses stem from the same EEG dataset, each method captures distinct aspects of brain dynamics—ERP focusing on phase-locked, time-specific responses, and non-ERP highlighting ongoing oscillatory activities that are not necessarily time-locked to stimulus onset.

From the ERP analysis (Section 3.1), the N400 component exhibited a characteristic negative deflection around 350–450 ms post-stimulus, predominantly distributed over centro-parietal regions (see Figure 3). This pattern is consistent with classical N400 responses reflecting semantic incongruity and increased lexical retrieval effort (Kutas & Federmeier, 2011). The stronger N400 amplitude observed for addiction-related stimuli suggests that these words demand higher semantic integration or elicit stronger associative activation due to their emotional salience.

In contrast, the time–frequency (non-ERP) analysis (Section 3.2) revealed increased theta (4–8 Hz) and beta (13–30 Hz) power in similar scalp regions (Figure 5), indicating sustained neural oscillations linked to semantic working memory and attentional engagement (Bastiaansen & Hagoort, 2006; Hanslmayr et al., 2012). The topographical distribution showed heightened power in the central and temporal areas, suggesting overlapping but temporally extended neural mechanisms compared to those captured by the ERP N400.

Importantly, the convergence between these two analyses underscores the complementary nature of ERP and spectral methods. The N400 reflects the immediate, phase-locked processing of semantic meaning, whereas the theta and beta oscillations observed in the non-ERP domain indicate the maintenance and integration of that information over time. This supports the notion that lexical-semantic processing involves both transient and sustained neural processes (Davidson & Indefrey, 2007).

Furthermore, the combination of ERP and non-ERP findings provides a richer framework for understanding addiction-related attentional bias. The enhanced N400 amplitude and elevated theta–beta synchronization observed in at-risk participants imply that addiction-related cues engage deeper semantic networks and greater cognitive control resources. This dual evidence reinforces the hypothesis that adolescents with higher addiction vulnerability exhibit increased cognitive effort and emotional reactivity when processing addiction-related language stimuli (Luijten et al., 2014; Kamarajan & Porjesz, 2015).

Overall, integrating ERP and non-ERP analyses allows for a more comprehensive characterization of the temporal and spectral dimensions of neural activity. The ERP provides precise timing of cognitive events, while the spectral approach reveals the oscillatory substrates supporting those events. Together, they delineate a coherent picture of how the brain processes emotionally charged linguistic information, particularly in individuals at risk of addictive behavior.

# Conclusion

This study investigated the neural correlates of lexical-semantic processing in response to addiction-related stimuli using both event-related potential (ERP) and non-ERP (spectral) analyses. The dual-approach framework enabled a comprehensive examination of the temporal and oscillatory dynamics underlying addiction-related word recognition among adolescents.

The ERP results revealed a prominent N400 component within the 350–450 ms latency window, predominantly distributed across centro-parietal regions. This negative deflection was more pronounced for addiction-related words, indicating increased semantic integration demands and heightened cognitive engagement during the processing of addiction-relevant information. These findings align with prior studies suggesting that emotionally salient or addiction-related cues elicit greater neural activation within semantic and attentional networks (Kutas & Federmeier, 2011; Luijten et al., 2014).

In parallel, the non-ERP spectral analysis demonstrated elevated power in the theta (4–8 Hz) and beta (13–30 Hz) frequency bands, particularly over central and temporal areas. This increase reflects enhanced working memory maintenance, attentional focus, and sustained cognitive control during the presentation of addiction-related stimuli (Bastiaansen & Hagoort, 2006; Hanslmayr et al., 2012). The complementary results between ERP and spectral domains emphasize that semantic processing in addiction contexts involves both rapid, phase-locked neural responses and prolonged, oscillatory modulations.

Together, these findings provide convergent evidence that addiction-related lexical processing engages deeper semantic and emotional networks, suggesting potential neural markers of addiction vulnerability in adolescents. The integration of ERP and non-ERP methodologies not only enhances interpretability but also supports the development of more sensitive EEG-based diagnostic frameworks for early detection and intervention in addiction risk populations.

Future research should expand the participant pool, incorporate multimodal data (e.g., behavioral, physiological, and psychological assessments), and explore advanced machine learning approaches to improve the predictive power of EEG-based addiction screening models. Such integrative efforts will contribute to the advancement of neurocognitive diagnostics and personalized prevention strategies for substance use disorders.

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1. S. Azodolmolky *et al.*, Experimental demonstration of an impairment aware network planning and operation tool for transparent/translucent optical networks,” *J. Lightw. Technol.*, vol. 29, no. 4, pp. 439–448, Sep. 2011.

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1. [↑](#footnote-ref-1)