Doctoral (PhD) Thesis Booklet

EEG analysis of naturalistic viewing: From connectivity analysis to reliable extraction of neural components

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Introduction

Aesthetic perception involves a rapid interplay of perceptual, cognitive and affective processes that unfold as viewers explore complex visual stimuli. Neuroaesthetics, as an interdisciplinary field, seeks to understand how these processes are supported by distributed neural systems and how they contribute to the experience of viewing artworks. Aesthetic experience extends beyond the evaluation of beauty; it involves the perceptual analysis, semantic interpretation and evaluative judgements that occur as viewers extract meaning from visual input [1], [2]. Because these processes unfold within the first few hundred milliseconds of viewing, understanding them requires methods capable of capturing fast neural dynamics [3].

Neural oscillations provide one mechanism through which the brain coordinates information across distributed regions during perception, memory and decision-making. Oscillatory activity reflects rhythmic fluctuations in neuronal excitability and regulates the timing of neuronal firing, shaping communication between distant cortical areas [4], [5], [6], [7]. Different frequency bands have been associated with distinct cognitive functions such as theta rhythms with memory encoding [8], [9], alpha rhythms with attentional control and sensory inhibition [10], [11], beta rhythms with sensorimotor integration [12] and gamma rhythms with perceptual binding [13]. These oscillatory interactions reorganise dynamically depending on task demands, forming transient networks that reflect moment-to-moment changes in cognitive processing [14], [15]. Because many of these dynamics are not strictly time-locked to external events, they may remain undetected in traditional event-related approaches. Understanding how oscillatory networks support perception therefore requires methods that can resolve fast temporal changes.

Electroencephalography (EEG) is well suited for this purpose. It records neural activity with millisecond precision and can reveal how oscillatory patterns evolve during perception, memory and evaluative processing [16], [17], [18]. However, interpreting EEG signals is challenging. Scalp recordings reflect mixtures of multiple neural and non-neural sources, and the effects of volume conduction can create the appearance of coordinated activity even when no true interaction exists [19], [20]. These issues complicate analyses that rely on sensor-level signals, particularly when studying functional connectivity.

Functional connectivity provides a framework for examining how neural signals vary or synchronise over time, offering insight into how distributed regions interact during cognitive tasks [21], [22], [23]. In the context of aesthetic perception, connectivity approaches have the potential to reveal how visual, emotional and semantic processes are integrated when viewing different artistic styles [24], [25], [26], [27]. Yet, despite their promise, connectivity analyses in EEG remain sensitive to preprocessing choices and to the spatial mixing inherent in scalp recordings [28], [29], [30]. These limitations highlight the need for analysis approaches that can better separate overlapping activity and improve the interpretability of connectivity estimates.

Source-separation methods such as Independent Component Analysis (ICA) offer one way to address these challenges. ICA attempts to unmix EEG signals into statistically independent components, isolating both artefactual and neural processes [31], [32], [33]. Although ICA is widely used for artefact removal, it can also extract physiologically meaningful neural components [34], [35]. However, its performance depends strongly on preprocessing decisions, data quality and algorithm parameters [36], [37]. These factors can substantially influence the number, quality and interpretability of the resulting components. Despite ICA's widespread use, there is limited systematic evidence demonstrating how consistently it can recover meaningful neural activity across different preprocessing pipelines, especially in naturalistic viewing conditions where frequent saccades and variable fixation timing introduce additional complexity [38].

A second challenge arises from the structure of natural viewing itself. During free exploration of artworks, perception unfolds across a rapid sequence of fixations, each providing a brief window for visual processing. Fixation-locked neural activity, involving the lambda response [39], [40], [41], [42], offers a potential physiological marker for studying these early stages. However, most existing knowledge about fixation-related signals comes from highly controlled paradigms with constrained eye movements. It remains unclear how reliably such activity can be identified during naturalistic viewing of complex stimuli, where fixations vary widely in duration, content and cognitive demands.

These considerations motivate the work presented in this thesis. The first study examines functional connectivity during the perception of abstract and figurative paintings, using a connectivity metric designed to mitigate the effects of volume conduction. This study characterises how connectivity patterns evolve across time and frequency during aesthetic perception and highlights the limitations of sensor-space analyses.

The second study investigates whether reliable fixation-locked neural activity can be identified during free-viewing of paintings. By characterising the temporal and spatial properties of fixation-locked responses, this study provides a physiological basis for understanding how perceptual processing unfolds across the rapid sequence of fixations that structure naturalistic viewing.

The third study evaluates how preprocessing choices influence the stability and reproducibility of ICA decompositions. By systematically varying filtering, sampling rate and data length parameters, this study provides evidence-based guidance for component-level analyses in naturalistic EEG and clarifies the conditions under which ICA can be trusted to isolate meaningful neural activity.

Together, these studies address key methodological challenges in interpreting EEG signals during naturalistic cognitive tasks. By examining connectivity, fixation-locked activity and ICA reliability within a unified framework, the thesis contributes to a clearer understanding of how neural interactions can be studied in settings that more closely reflect real visual behaviour. The work also provides practical recommendations for improving the robustness and interpretability of EEG analyses in neuroaesthetics and related fields.

Overview of Methods and Study Design

The work presented in this thesis is based on EEG recordings collected during the viewing of paintings, with the broader aim of understanding how neural activity unfolds during aesthetic perception and how methodological choices influence the interpretability of EEG signals in naturalistic cognitive tasks. Although the three studies address separate research questions, they are conceptually linked and build on a shared dataset, allowing the findings to be interpreted within a coherent methodological framework.

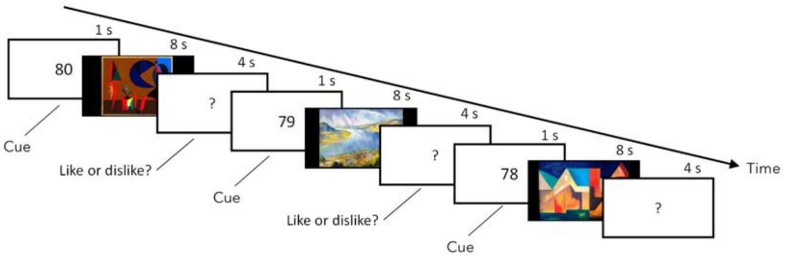

Figure 1. Experimental protocol showing the sequence of events in each trial: numeric cue (1 second), painting presentation (8 seconds) and response period (4 seconds).

The EEG data were recorded while participants viewed a series of abstract and figurative paintings as shown in Figure 1. This paradigm was chosen because it captures the perceptual and evaluative processes central to aesthetic experience while maintaining experimental control over stimulus presentation. Participants viewed each painting freely for 8 seconds and then provided their ‘Like/Dislike’ response, allowing the EEG analysis to focus specifically during the viewing period. The EEG recordings were acquired using a high-density system (128 channels), providing sufficient spatial coverage for connectivity analysis, fixation-locked responses and component-level decomposition. Preprocessing procedures included filtering, artefact removal and referencing, following established practices in cognitive EEG research. Importantly, for the first two studies, preprocessing was kept consistent, ensuring that any observed effects reflected neural processes rather than methodological variation. Only the third study systematically varied preprocessing parameters, as its explicit aim was to evaluate how such choices influence ICA reliability.

The first study examined functional connectivity during aesthetic perception. Connectivity was computed in sensor-space using debiased weighted Phase-Lag Index (dwPLI) to mitigate the influence of volume conduction, addressing one of the central challenges in interpreting EEG connectivity. Time-resolved and frequency-specific connectivity patterns were analysed to characterise how distributed neural interactions evolve during the viewing of abstract and figurative artworks. This study provided details into the temporal organisation of connectivity during aesthetic perception and highlighted the limitations of sensor-space analyses, particularly in relation to spatial mixing and interpretability. Because the goal was to assess the feasibility of connectivity analysis in a higher-order cognitive task, preprocessing was intentionally kept constant to avoid introducing variability unrelated to the cognitive processes of interest.

The second study focused on fixation-locked neural activity during naturalistic viewing. Eye-tracking data were incorporated to identify fixation onsets, allowing EEG epochs to be aligned to the rapid sequence of fixations that structure visual exploration. This approach enabled the investigation of neural responses that occur immediately after each fixation, known as the lambda response, a well-known early visual component. The analysis examined whether reliable fixation-locked activity could be extracted under naturalistic conditions and characterised its temporal and spatial properties. Because the aim of this study was to establish the physiological basis of fixation-locked responses during free-viewing, preprocessing was again kept consistent. This ensured that the observed neural patterns reflected genuine perceptual processes rather than differences introduced by methodological choices. The findings from this study provided a physiological marker for understanding how perception unfolds across successive fixations during the viewing of complex artworks.

The third study evaluated the stability and reproducibility of ICA decompositions across different preprocessing pipelines. ICA is widely used in EEG research for artefact removal and for isolating neural components that reflect meaningful cognitive processes. However, its performance depends strongly on preprocessing decisions, including filtering parameters, sampling frequency and data length. To address this, I systematically varied these parameters and applied ICA to each resulting dataset. The components were then compared to assess how preprocessing choices influence component quality, stability and the recovery of meaningful cognitive signals. This analysis provided evidence-based guidance for selecting preprocessing strategies that support reliable component-level analyses in naturalistic EEG tasks. By identifying which preprocessing combinations consistently produce stable and interpretable components, the study contributes to improving the reproducibility of ICA-based research.

Across all three studies, the analyses were implemented using established EEG processing toolboxes (e.g. MATLAB, EEGLAB and FieldTrip) and custom scripts developed for evaluating connectivity, fixation-locked activity and ICA stability. The shared dataset and consistent analysis framework linked the studies into a coherent set of findings: the connectivity analysis highlighted the limitations of sensor-space approaches, the fixation-locked analysis provided a physiological marker for early perceptual processing and the ICA reliability study clarified the conditions under which component-level analyses can be trusted. Simultaneously, these methods form a unified approach for examining neural dynamics in aesthetic perception and for addressing the methodological challenges associated with interpreting EEG signals in naturalistic cognitive paradigms.

New Scientific Results

The research presented in this thesis advances understanding in three areas: the organisation of functional connectivity during aesthetic perception, the physiological basis of fixation-locked neural activity during naturalistic viewing and the methodological factors that influence the stability of ICA decompositions in EEG. Together, these studies provide new insights into how neural activity unfolds during the viewing of artworks and clarify the methodological conditions under which EEG signals can be interpreted reliably. The main scientific results are summarised below.

Thesis I. *I proposed a method to identify large-scale neural networks engaged during the viewing of abstract and figurative paintings, and demonstrated that aesthetic perception involves dynamic, frequency- and style-specific patterns of connectivity.*

Publication related to this thesis: [J1], [C3], [C4], [C5], [C7].

I used high-density EEG, time-frequency analysis and the debiased weighted Phase-Lag Index (dwPLI) to track how oscillatory interactions evolve across delta, theta, alpha, beta and gamma bands during the viewing of abstract and figurative paintings. By analysing connectivity across multiple time windows, I showed that connectivity patterns change systematically over the course of viewing and differ between stimulus categories, indicating that abstract and figurative artworks engage distinct perceptual and interpretive processes. I further applied graph theory metrics to identify the functional roles of occipital and parietal hubs, demonstrating that aesthetic perception relies on distributed, frequency-specific networks rather than isolated regions. Through this approach, I provided a methodologically rigorous sensor space framework for studying functional connectivity in neuroaesthetics, using metrics specifically designed to minimise the influence of volume conduction and clarifying what can and cannot be inferred from sensor-level connectivity in higher order cognitive tasks.

Thesis II. *I demonstrated that ICA can reliably extract the lambda response as a fixation-locked neural component during naturalistic art viewing, indicating that perception is based on the sequence of discrete visual processing cycles.*

Publication related to this thesis: [J2], [C2], [C6].

By combining EEG with eye-tracking, I demonstrated that ICA can isolate fixation-locked neural activity, comprising the lambda response, which can be extracted even under naturalistic conditions despite variability in fixation timing, stimulus complexity and viewing behaviour. The extracted components exhibited consistent timing relative to saccade onset and offset, showed the expected occipital topography and waveform morphology, and remained stable across different artworks and viewing conditions. I validated the temporal precision of these components using saccade aligned information and demonstrated that their characteristics reflect discrete cycles of early visual processing. This work provides systematic evidence that aesthetic perception unfolds through a sequence of fixation-locked neural events, extending findings from controlled paradigms and showing that naturalistic viewing does not exclude the identification of reliable early visual components.

Thesis III. *I investigated the reliability of ICA for extracting meaningful neural components from free-viewing EEG data by examining how different preprocessing choices affect the stability and reproducibility of ICA decompositions, and identified the conditions under which ICA can consistently isolate meaningful neural signals.*

Publication related to this thesis: [J2], [C1].

I developed a multi layered validation framework to assess ICA component quality using waveform morphology, latency distributions, saccade-locked alignment and single-trial detectability. By systematically varying filtering parameters, sampling rate and data length, I identified preprocessing configurations that consistently improve lambda component extraction and demonstrated that some pipelines produce stable, physiologically interpretable components, whereas others produce unstable decompositions. I showed that these differences are systematic rather than random, indicating that preprocessing decisions exert a strong and predictable influence on ICA outcomes. I also demonstrated that ICA can recover meaningful neural activity at the single-trial level, revealing fine-grained visual dynamics that are typically obscured in averaged ERPs. This contribution provides evidence-based guidance for selecting preprocessing strategies that support robust ICA performance and establishes a methodological foundation for future component-space connectivity analyses in naturalistic EEG research.

Publications list

List of journal articles

[J1] **I. S. Suhaili**, Z. Nagy, and Z. Juhász, "Functional Connectivity Differences in the Perception of Abstract and Figurative Paintings," Applied Sciences, vol. 14, no. 20, 2024, doi: 10.3390/app14209284.

[J2] **I. S. binti Suhaili,** B. Tóth, Z. Nagy, and Z. Juhász, "Reliable Single-trial Detection of Saccade-related Lambda Responses with Independent Component Analysis," ENEURO, vol. 12, no. 11, 2025, doi: 10.1523/ENEURO.0270-25.2025.

List of conference publications

[C1] **I. S. Suhaili**, Z. Nagy, and Z. Juhász, "Single-trial detection of lambda responses in free-viewing EEG measurements," in 34th Annual Computational Neuroscience Meeting (CNS*2025), Florence, Italy, Jul. 2025, J. Comput. Neurosci., vol. 54, suppl. 1, p. 315, 2026, doi: 10.1007/s10827-025-00915-4.

[C2] **I. S. Suhaili**, Z. Nagy, and Z. Juhász, "Single-trial source-resolved EEG analysis of a free-viewing neuroaesthetic task with independent component analysis," in International Neuroscience Conference (INC) 2026, Budapest, Hungary, Jan. 2026, Abstract Book, Poster PS06.22.

[C3] **I. S. binti Suhaili**, Z. Nagy, and Z. Juhasz, "Comparing Brain Responses to Abstract and Representational Style Paintings: A High-Density EEG Connectivity Study," in The Federation of European Neuroscience Societies (FENS)

Forum 2024, Vienna, Austria, Jun. 2024, Poster PS03-27AM-536.

[C4] **I. S. Suhaili**, Z. Juhász, and Z. Nagy, "On the perception of paintings: A high-density EEG study," in IBRO World Congress 2023, Granada, Spain, Sep. 2023, IBRO Neurosci. Rep., vol. 15, pp. S900 – S901, 2023, doi: 10.1016/j.ibneur.2023.08.1888.

[C5] **I. S. Suhaili**, Z. Nagy, and Z. Juhász, "The modulation effect of art painting content on saccade-evoked perceptual processes: A high-density EEG Study," in Annual Meeting of the Hungarian Neuroscience Society, MITT 2025, Debrecen, Hungary, Jan. 2025, Abstract Book, 2025, p. 45.

[C6] **I. S. binti Suhaili** and Z. Juhasz, "Uncovering Neural Saccadic Responses using Electroencephalogram (EEG) during Natural Viewing of Paintings," in 7th Hungarian Neuroscience Doctoral Conference for Undergraduate Students, Graduate Students and Junior Post-Docs (HUNDOC), Pécs, Hungary, Jan. 2024, Abstract Booklet, p. 98.

[C7] **I. S. binti Suhaili**, Z. Juhasz, Z. Wang, F. I. Mohamed, Cs. Borbely, and Z. Nagy, "Aesthetic experiences registered by high density EEG: a functional connectivity study," in XXXV Neumann Colloquium Conference, Szeged, Hungary, Nov. 2022, Az egészségügyi informatika COVID előtt és COVID után - A XXXV. Neumann Kollokvium konferencia kiadványa, pp. 82–89, ISBN 978-615-5036-22-4.

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