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Event-related EEG microstate complexity reveals specific brain network connectivity during aesthetic perception in depression

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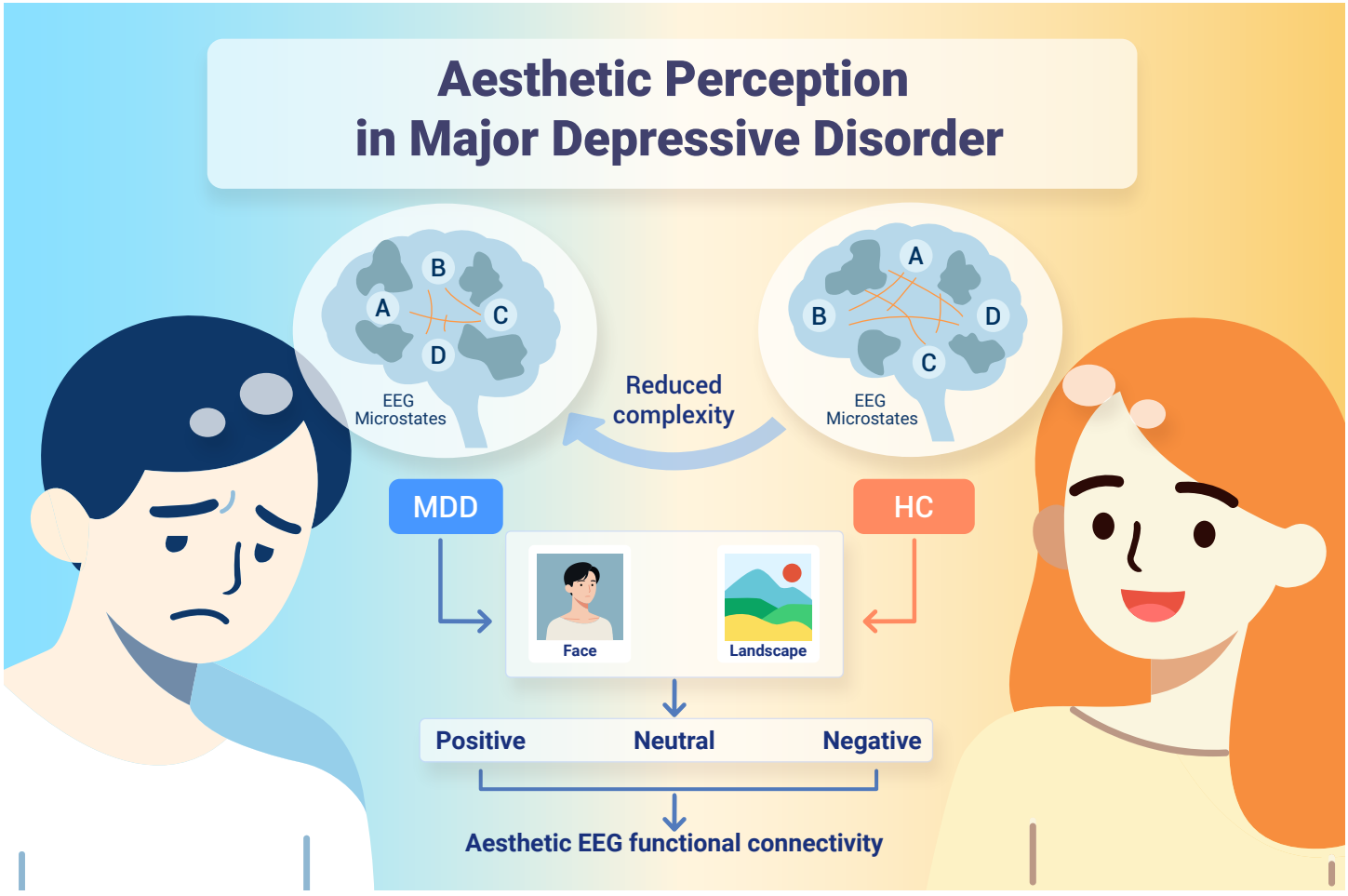
Received: January 17, 2025; Accepted: January 7, 2026; Published Online: January 16, 2026; https://doi.org/10.59717/j.xinn-life.2026.100192

GRAPHICAL ABSTRACT



PUBLIC SUMMARY

- Patients with major depressive disorder (MDD) show altered brain activity patterns during visual aesthetics.
- Electroencephalography (EEG) microstates reveal reduced frontal control and increased posterior activity in MDD.
- MDD shows abnormal timing and complexity of brain states, suggesting reduced flexibility in processing images.
- These EEG features may help identify depression and support treatment monitoring in the future.

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Event-related EEG microstate complexity reveals specific brain network connectivity during aesthetic perception in depression

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Received: January 17, 2025; Accepted: January 7, 2026; Published Online: January 16, 2026; https://doi.org/10.59717/j.xinn-life.2026.100192

Citation: Ma X., Ye J., Ding Y., et al. (2026). Event-related EEG microstate complexity reveals specific brain network connectivity during aesthetic perception in depression. *The Innovation Life* **4**:100192.

Visual aesthetic experience recruits distributed brain networks encompassing perceptual, emotional, and cognitive processes. Individuals with major depressive disorder (MDD) often exhibit altered aesthetic preferences, typically biased toward negative stimuli, yet the underlying neural dynamics remain poorly understood. In this study, 25 patients with MDD and 27 healthy controls (HCs) were recruited and performed image-based aesthetic processing tasks while the EEG signals were collected using a 32-channel system. EEG microstate was obtained by iterative clustering and the duration, occurrence, coverage, Lempel-Ziv complexity, and functional connectivity were calculated and analyzed. Significant alterations in both the spatial and temporal characteristics of EEG microstates were observed in the MDD group. Specifically, individuals with MDD showed increased occurrence and coverage of microstates associated with posterior visual processing, and reduced coverage and duration of those linked to right prefrontal executive control networks. These findings suggest a general functional shift from higher-order cognitive regulation toward lower-level sensory processing across stimulus types. Notably, microstate transitions were less dynamic in individuals with MDD, indicating lower information entropy and a decreased frequency of microstate switching. Moreover, MDD patients exhibited prolonged engagement of anterior microstates, potentially reflecting sustained activation of self-referential and affective regulatory circuits, including the anterior cingulate cortex (ACC), independent of executive-control-associated networks. Functional connectivity analysis further revealed altered anterior–posterior coupling and disrupted integration within the fronto-central regions, which are considered critical for emotional appraisal. These findings suggest that MDD alters the balance between perceptual and regulatory networks during aesthetic processing, which may underlie the negative aesthetic preferences often observed in depression. Our study highlights EEG microstate analysis as a sensitive tool for capturing neural signatures of aesthetic experience and offers new insights into the dysfunctional brain dynamics associated with MDD. These results provide a foundation for developing neurophysiological markers and targeted interventions to modulate aesthetic-related brain activity in depressive disorders.

INTRODUCTION

Characterized by persistent low mood, loss of interest, and cognitive impairments, major depressive disorder (MDD) has emerged as the foremost cause of disability worldwide.[1] Among its core symptoms, anhedonia—the diminished capacity to experience pleasure from typically rewarding activities—not only serves as a diagnostic hallmark but also predicts poor treatment response and functional outcomes.[2] As such, elucidating the neural substrates of anhedonia is critical for advancing both diagnostic precision and therapeutic strategies.

One promising avenue for probing anhedonia involves examining the aesthetic experience, commonly defined as the perceptual and evaluative engagement with external stimuli that elicit sensory pleasure or emotional resonance. Aesthetic experience represents a fundamental and nearly universal aspect of human cognition,[3] engaging affective, sensory, and evaluative processes. While research on healthy individuals has highlighted the involvement of brain regions like the orbitofrontal cortex (OFC) and anterior insula in aesthetic processing, studies show that these mechanisms are disrupted in depression, leading to altered aesthetic preferences and emotional engagement. Individuals with MDD frequently exhibit atypical aesthetic responses, marked by a cognitive bias toward negative stimuli and a blunted sensitivity to positive or rewarding input.[4,5] These alterations suggest that aesthetic processing may be disrupted in depression, reflecting broader impairments in reward-related neural circuits, and underscoring the need to understand its neural basis in this population.

To understand these impairments in MDD, it is first essential to consider the neural basis of aesthetic experience in the healthy population. Early studies in the field of neuroaesthetics have consistently identified overlapping neural substrates between aesthetic liking and reward processing. For instance, activity in the ventromedial prefrontal cortex and the ventral striatum—regions well-established in the reward literature—has been observed during the appreciation of visual art and music.[6,7] These findings support the notion that stimuli capable of evoking aesthetic pleasure are processed via similar neural mechanisms as primary or secondary rewards such as money, taste, or odor. Further supporting this convergence, research in the reward domain suggests that the medial prefrontal cortex encodes the value of diverse rewards in a domain-general fashion, consistent with the implementation of a "common currency" for reward valuation.[8] Intriguingly, this same region appears to represent subjective aesthetic preferences across a broad range of stimuli,[9] reinforcing the view that aesthetic experience is deeply intertwined with core reward systems.

A central goal of neuroaesthetics is to identify the brain areas and networks involved in processing aesthetic responses.[10] Visual aesthetic information, for example, is first captured by the retina and relayed through the visual system, ultimately influencing a wide range of cognitive and emotional processes. Functional neuroimaging studies have repeatedly shown that aesthetic appreciation engages regions such as the orbitofrontal cortex, anterior insula (AI), and ACC.[6,11–13] Nadal and Pearce proposed a theory emphasizing the reward circuit's central role in the appreciation of visual art, music, and dance. This circuit includes cortical regions (OFC, ACC, and ventromedial prefrontal cortex) and subcortical structures, along with modulatory regions such as the amygdala, thalamus, and hippocampus.[14,15] Further support for the involvement of higher-order networks comes from studies implicating the default mode network (DMN) in aesthetic appreciation. For instance, Vessel et al. found positive activation in the medial prefrontal cortex—a hub of the DMN—during the aesthetic viewing of visual art,[16] and subsequent work confirmed widespread DMN involvement in aesthetic experiences.[17] A recent meta-analysis by Skov et al. further revealed activation in visual (occipital lobe), emotional (anterior insula), and self-referential (posterior

cingulate cortex) areas during painting viewing,[18] supporting the integrative nature of aesthetic responses. These regions not only support early and intermediate visual processing but also contribute to emotional salience and introspective valuation.[19]

Given this rich characterization of aesthetic networks in healthy individuals, and the behavioral evidence of neural impairments in MDD, it becomes critical to ask how these processes may be disrupted in the MDD population. Understanding how these systems function abnormally in MDD, particularly in response to affectively salient, aesthetically rich stimuli may therefore yield novel insights into the pathophysiology of anhedonia.

Furthermore, exploring the neural basis of aesthetic stimulation in MDD opens promising avenues for non-pharmacological interventions. Emerging modalities such as art therapy, music therapy, and aesthetic-based neuromodulation have shown potential in alleviating depressive symptoms by harnessing emotional and sensory engagement.[20-23] These approaches not only enhance quality of life but also offer culturally adaptable, low-barrier, and scalable strategies to complement traditional treatments, particularly valuable given the global burden of depression.

Our study addresses this gap by focusing on EEG microstates, brief periods of stable brain activity with high temporal resolution that capture rapid and transient changes reflecting distinct cognitive processes. Through topographic mapping, microstates enable the tracking of dynamic shifts in global brain states and can reveal subtle disruptions in cognitive and emotional processing associated with MDD.[24] By examining EEG signals from 25 patients with MDD and 27 healthy controls, we aim to elucidate the alterations in microstate features sequence complexity and brain network connectivity during aesthetic perception. This approach offers theoretical insights into how aesthetic processing engages altered brain circuits in MDD and carries potential therapeutic implications. Identifying disruptions in large-scale brain networks, such as the reward circuitry and the default mode network, may advance understanding of the neurobiological mechanisms of depression, contribute to the development of objective biomarkers for early detection and stratification, and inform aesthetic-based interventions that leverage residual reward sensitivity as adjunctive strategies to conventional treatments.

MATERIALS AND METHODS

Participants

The study sample was derived from an EEG dataset comprising patients with depression and healthy controls. Following quality assessment, we included 25 patients with depression and 27 healthy controls in the final analysis (Table S1). Patients were recruited from the outpatient clinics of the Fourth People's Hospital of Wuhu. Diagnoses were conducted by licensed psychiatrists using structured interviews based on the DSM-V criteria.[25] Inclusion criteria required patients to meet the DSM-V criteria for depression. Exclusion criteria included a primary diagnosis of schizophrenia, schizoaffective disorder, bipolar disorder, or anxiety disorder. Additionally, the study excluded patients aged outside the range of 18–40 years. Healthy controls were recruited through internet-based advertisements and were screened for both current and historical psychiatric and neurological disorders. All participants had normal or corrected-to-normal vision. Prior to the experiment, both groups completed the 21-item Beck Depression Inventory.[26]

Microstate analysis

Microstate clustering was performed using the EEGLAB toolbox following the standard procedure. For EEG data with a frequency band of 1 to 45 Hz, the L1-norm was used to calculate the global field power, from which the time series of GFP were obtained. The peak (local maximum) was then extracted from the GFP time series and sent to the k-means clustering algorithm, and the final microstate topographic map was obtained by iterative clustering. Microstate segmentation was conducted on a spatial scale. In addition, the GFP time series were back-fitted according to the classified microstates to obtain the EEG microstate sequences.

After obtaining microstates of each subject, we assessed the following three conventional parameters of the EEG microstates: (1) duration, (2) occurrence, and (3) coverage. The coverage reflects the involvement of different brain regions in the underlying neural processes. Occurrence reflects the prevalence of the microstate in the EEG data and is often used as a measure of the stability of the underlying neural process. Duration reflects the temporal dynamics of the underlying neural processes and is thought to be related to the time course of cognitive and perceptual processes. Detailed descriptions of these methods are provided below:

$$Dur(m) = \frac{\sum_{x=1}^{x=N_c} C(x) \cdot sgn(M(x))}{\sum_{x=1}^{x=N_c} sgn(M(x))} \cdot \frac{1000}{F_s} \quad (1)$$

where $sgn(M(x))$ is the sign function. N_c is the length of C. F_s is the sampling rate.

$$Occ(m) = \frac{\left(\sum_{x=1}^{x=N_c} sgn(M(x))\right) \cdot F_s}{N_L} \quad (2)$$

where N_L is the length of L. The unit of Occ is number per second.

$$Cov(m) = \frac{Dur(m) \cdot Occ(m)}{1000} \quad (3)$$

EEG microstate complexity

Lempel-Ziv complexity is a widely used method for calculating the spatiotemporal complexity of EEG. To calculate the conventional Lempel-Ziv complexity, it is necessary to binarize and detrend the time series. In the binarization process, some information can be lost, leading to a loss of information in the resulting microstate sequence. The Lempel-Ziv complexity value is obtained by normalizing the size of the dictionary. The expression for Lempel-Ziv complexity is as follows:

$$LZC = \frac{length(dic_{x_{ms}})}{length(dic_{x_{rand}})} \quad (4)$$

Where $length(dic_{x_{ms}})$ denotes the dictionary length of microstate sequence x_{ms}; $length(dic_{x_{rand}})$ is the dictionary length of the sequence, x_{rand} which is obtained by randomly reordering the microstate sequence x_{ms}, LZC: Lempel-Ziv complexity. The Lempel-Ziv complexity increased with a high degree of randomness in the EEG time series. In this study, we analyzed the Lempel-Ziv complexity of the microstate sequence and termed the EEG microstate complexity based on the Lempel-Ziv complexity as microstate-LZC (Ms-LZC).

Functional connectivity analysis

Coherence (Coh) measures the linear relationship between two EEG channels at a given frequency, and this method has been widely used to calculate the FC matrix.[27] The imaginary part of coherence (iCoh) is calculated by dividing the imaginary part of the cross-spectrum of the electrodes by the square root of the product of the power spectra of the individual electrodes.[28] Compared to Coh, iCoh reduces the effect of bulk conductivity and electrode reference.[29] The iCoh is calculated as follows.

$$C_{xy}(f) = \frac{P_{xy}(f)}{\sqrt{P_{xx}(f)P_{yy}(f)}} = Real\{C_{xy}(f)\} + Imag\{C_{xy}(f)\} \quad (5)$$

$$iCoh_{xy}(f) = Imag\{C_{xy}(f)\} \quad (6)$$

where $P_{xy}(f)$ represents the crossover power spectral density between electrode signal x and electrode signal y at frequency f, and $P_{xx}(f)$ and $P_{yy}(f)$ represent the power spectral density of electrode signal x and electrode signal y, respectively, at frequency f. iCoh is defined as the imaginary part of the complex coherence.

On these bases, all adjacency matrices for each subject were calculated by superimposing averages separately to obtain the adjacency matrix for each subject. The adjacency matrices of the groups were then obtained by superimposing and averaging all subjects by the group. This study used the BrainNet Viewer toolbox for 3D display.[30]

The phase-locking value (PLV) is another widely used metric to estimate functional connectivity based on the consistency of phase differences between EEG signals. To compute PLV, the instantaneous phase of each EEG signal was first extracted using the Hilbert transform. For each electrode pair x and y, the phase difference $\Delta\varnothing_{xy}(t) = \varnothing_x(t) - \varnothing_y(t)$ at time t was calculated,

and PLV was defined as:

$$PLV_{xy} = |\frac{1}{N}\sum_{t=1}^{N} e^{i(\varnothing_x(t)-\varnothing_y(t))}|$$

where N is the number of time points, and $\varnothing_x(t)$ and $\varnothing_y(t)$ are the instantaneous phases of electrodes x and y, respectively. The resulting PLV values range from 0 (no phase synchronization) to 1 (perfect synchronization).

To examine the directionality of information flow between cortical regions during the aesthetic evaluation process, we employed Transfer Entropy (TE), a model-free, information-theoretic measure that quantifies the directed transfer of information between time series.

Statistical analysis

Statistical analyses were conducted using R (version 4.1.2). For each participant, a single value was obtained for each parameter before statistical testing. Group effects were tested using repeated-measures ANOVA, followed by independent samples t-tests for post hoc comparisons. To control for Type I error arising from multiple comparisons, Bonferroni correction was applied where appropriate. An alpha level of 0.05 was used as the primary threshold, and adjusted alpha values were computed based on the number of comparisons (adjusted $\alpha = 0.05/N$). Results are presented with corrected p-values and 95% confidence intervals (CI) of the mean differences. Statistical significance is indicated as follows: $p < 0.05$, $p < 0.01$, and $p < 0.001$. Additionally, Cohen's d was calculated to estimate effect sizes. For findings with marginal significance (e.g., p-values slightly above corrected thresholds), results are reported but interpreted with caution.

RESULTS

Abnormal spatial topography and conventional parameters of EEG microstate in depressed patients during aesthetic perception

The demographic and clinical characteristics of the participants are summarized in Table S1. No significant differences were observed between the MDD and HC groups in terms of age, gender distribution, and years of education. However, medication status and Beck Depression Inventory II (BDI-II) scores differed significantly between the groups. In the MDD group, 23 participants were on medication while 2 were not, compared to the HC group where no participants were on medication (Chi-square tests, $\chi^2 = 23.12$, $P < 0.001$). The BDI-II scores, which measure the severity of depressive symptoms, were significantly higher in the MDD group (24.32 ± 10.30) compared to the HC group (6.37 ± 5.32) (Independent-samples t-tests, $t = 3.85$, $P < 0.001$).

The analysis of EEG microstates was conducted to investigate differences between HC and MDD participants as they viewed images of positive, neutral and negative valence faces and landscapes. Figure S3 illustrates the topological maps for three to eight microstates during the aesthetic evaluation of these images. To determine the optimal number of microstates for EEG analysis, we employed a polarity-invariant cross-validation criterion and global explained variance. The cross-validation index reached its minimum at four microstates, consistent with the method introduced by Pascual-Marqui et al.[20] This approach has been validated in large cohorts, explaining approximately 79% of variance in resting-state EEG across 496 healthy individuals.[20] Similarly, during task conditions, Seitzman et al.[21] reported that four archetypal microstates accounted for over 60% of the variance. Given the robustness and widespread adoption of this model, all analyses in the present study were conducted using four microstates.

Microstate clustering was performed separately for the aesthetic evaluation of facial and landscape images. The spatial configurations of microstates were largely consistent across all valence categories (positive, neutral and negative valence). Stimuli were presented at the 1-second mark, and EEG signals were recorded over a 3-second interval, encompassing 1 second before and 2 seconds after stimulus onset (Figure S1).

In both facial and landscape aesthetic evaluations (Figures 1 & 2), the four microstates alternately dominate over a period of time before the onset and after the cessation of the visual stimuli. However, during the aesthetic stimuli, the predominant microstate patterns are similar across different types of aesthetic images yet show significant differences between the MDD and HC groups.

Aesthetic perception of facial images

For the facial aesthetic evaluation, four predominant topographic maps were identified, corresponding to microstate A (i.e., posterior pattern), microstate B (i.e., central-posterior pattern), microstate C (i.e., anterior pattern), and microstate D (i.e., prefrontal pattern). For clarity, these will be referred to as MS-A-F through MS-D-F in subsequent descriptions. Figures 1A–C illustrate the EEG microstate analysis results for the aesthetic perception of facial images across the three valence categories, along with microstate segmentation visualizations.

During the facial aesthetic evaluation (Figure 1), the four microstates exhibited alternating dominance before and after stimulus onset. Although the dominant patterns remained generally consistent across different emotional valences, distinct group differences emerged, suggesting that depression may modulate the temporal dynamics of aesthetic processing.

Specifically, during the aesthetic evaluation of facial images, the HC group was predominantly characterized by microstate MS-D-F (i.e., prefrontal pattern), with brief peaks in microstates MS-A-F (i.e., posterior pattern) and MS-C-F (i.e., anterior pattern), and subsequent dominance of microstates MS-B-F (i.e., central-posterior pattern), MS-C-F (i.e., anterior pattern), and MS-D-F (i.e., prefrontal pattern). In comparison, the MDD group was primarily dominated by microstate MS-C-F (i.e., prefrontal pattern), with short peaks in microstates MS-A-F (i.e., posterior pattern) and MS-D-F (i.e., anterior pattern), followed by the predominance of microstates MS-C-F (i.e., prefrontal pattern) and MS-B-F (i.e., central-posterior pattern). The altered sequence and predominance of microstates in the MDD group suggest a functional reorganization of neural circuits underlying facial aesthetic perception.

Quantitative comparisons revealed that the MDD group exhibited significantly greater coverage of MS-A–F and significantly or marginally reduced coverage of MS-D–F across all valence categories (Figure 3 & Table 1). To control Type I error due to multiple comparisons, Bonferroni correction was applied (adjusted $\alpha = 0.05/N$). Results with p-values below the corrected threshold were considered statistically significant, whereas those between the uncorrected and corrected thresholds were reported as marginally significant and interpreted with caution. Post-hoc comparisons further confirmed that these differences were consistent across positive, neutral, and negative valence conditions (Table 1 & S2 for full statistics). This pattern suggests a functional shift from higher-order prefrontal networks, which support affective evaluation and integration, toward posterior regions associated with lower-level perceptual processing.

Functionally, the increased coverage of MS-A-F may reflect an over-reliance on perceptual analysis at the expense of integrative emotional evaluation in MDD patients. Conversely, the reduced coverage of MS-D-F suggests diminished engagement of prefrontal circuits essential for the appraisal and contextualization of facial aesthetics. These findings align with prior reports of prefrontal hypoactivity during emotional tasks in depression, highlighting impaired top-down modulation during aesthetic judgment.

Further analysis of occurrence and duration metrics corroborated these observations. The MDD group demonstrated significantly higher occurrence rates of MS-A-F for both positive and negative images, though no significant difference was observed for neutral face images. The group also showed significantly shorter durations of microstate MS-D-F in the same conditions. These results indicate that depressed individuals experience more frequent but briefer activations of posterior-dominant microstates, whereas prefrontal-dominant microstates are less stable and persistent. Such instability in prefrontal engagement may underlie the difficulties in sustained aesthetic appraisal and emotional experience frequently reported in depression.

Additionally, correlation analyses revealed strong associations between BDI-II scores and the coverage of MS-A-F and MS-D-F, as well as the duration of MS-D-F, underscoring the clinical relevance of these neural alterations (Figure 3D).

Aesthetic perception of landscape images

For the aesthetic perception of landscape images, four dominant topographic maps were similarly identified: microstate A (posterior pattern), microstate B (central-posterior pattern), microstate C (prefrontal pattern), and microstate D (right prefrontal pattern), referred to as MS-A-L through MS-D-L.

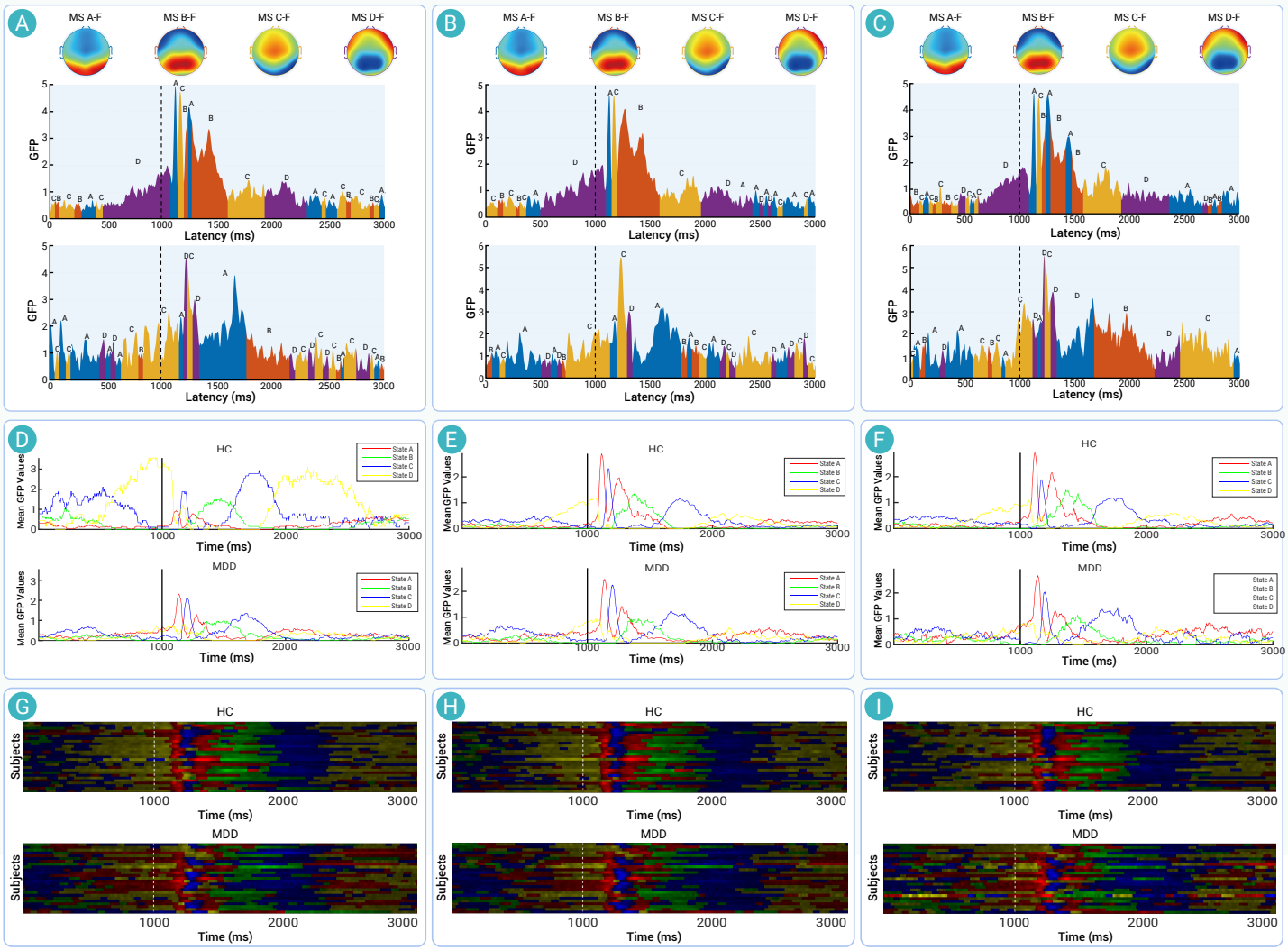

Figure 1. State classification of the back-fitting of the original EEG sequence by the microstate prototype during aesthetic perception of face images (A-C) EEG topographic maps representing different microstates (MS-A-F to MS-D-F) during face aesthetic perception under positive, neutral, and negative valence images, respectively. The upper row corresponds to the Healthy Control (HC) group, and the lower row corresponds to the Major Depressive Disorder (MDD) group. Each microstate reflects distinct functional brain networks: MS-A-F: Microstate A, associated with posterior visual processing regions. MS-B-F: Microstate B, linked to central-posterior sensorimotor areas. MS-C-F: Microstate C, related to anterior cingulate and limbic areas. MS-D-F: Microstate D, reflecting prefrontal executive and attentional control. (D-F) Time course (0 to 3 s) of changes in the average Global Field Power (GFP) for the four microstates during face aesthetic perception across positive, neutral, and negative valence images, respectively. (G-I) Heatmaps illustrate the temporal dynamics (0 to 3 s) of average GFP for each microstate during aesthetic evaluation of positive, neutral, and negative valence face images. Different colors represent different microstates, with labels corresponding to MS-A-F, MS-B-F, MS-C-F, and MS-D-F as defined above. The letters on the figure indicate the microstate classification of each data segment. The vertical line at 1 s marks stimulus onset.

Figures 2A–C present the microstate analysis results for the three categories of landscape images, along with EEG microstate segmentation visualizations.

As with facial aesthetics, landscape aesthetic processing exhibited alternating dominance of microstates before and after stimulus presentation. However, notable group differences emerged during the stimulus engagement period.

In the HC group, a progression from MS-C-L (i.e., prefrontal pattern) to MS-B-L (i.e., central-posterior pattern), then to MS-A-L (i.e., posterior pattern), and back to MS-C-L (i.e., prefrontal pattern) was observed respectively. This progression suggests an integrated sequence involving initial cognitive appraisal (prefrontal engagement), sensory processing (central-posterior activity), and subsequent affective evaluation (prefrontal re-engagement). In contrast, the MDD group exhibited a disrupted progression, characterized by disorganized transitions among MS-C-L (i.e., prefrontal pattern), MS-A-L (i.e., posterior pattern), and MS-B-L (i.e., central-posterior pattern) respectively, indicating a less structured and less hierarchically organized aesthetic processing strategy.

Quantitatively, the MDD group exhibited significantly higher coverage of MS-A-L and lower coverage of microstate MS-C-L across all stimulus types. These results again point to a functional shift toward greater posterior (perceptual) dominance and reduced prefrontal (evaluative) engagement (Table 2 & S3 for full statistics).

Reduced prefrontal microstate coverage (MS-C-L) alongside increased posterior coverage (MS-A-L) likely reflects deficits in the affective-cognitive integration necessary for holistic landscape appreciation. Depressed individuals may remain fixated at the level of sensory analysis, failing to engage evaluative and emotionally enriching processes typically mediated by prefrontal networks.

Unlike the facial aesthetic task, no significant group differences were observed in occurrence rates for landscape images. However, the duration of microstate MS-C-L was significantly prolonged in the MDD group. This prolonged but less frequent engagement of prefrontal microstates may reflect inefficient or maladaptive recruitment of prefrontal regions during landscape aesthetic evaluation.

Consistently, the coverage values of MS-A-L and MS-C-L exhibited strong correlations with BDI-II scores, irrespective of the image types (positive/neutral/negative valence), further highlighting the association between altered microstate dynamics and depression severity (Figure 3H).

Notably, the increased coverage of microstate MS-A-L indicates prolonged activation of occipital areas associated with early sensory and perceptual processing of visual stimuli.[24,31] This may reflect an over-engagement of low-

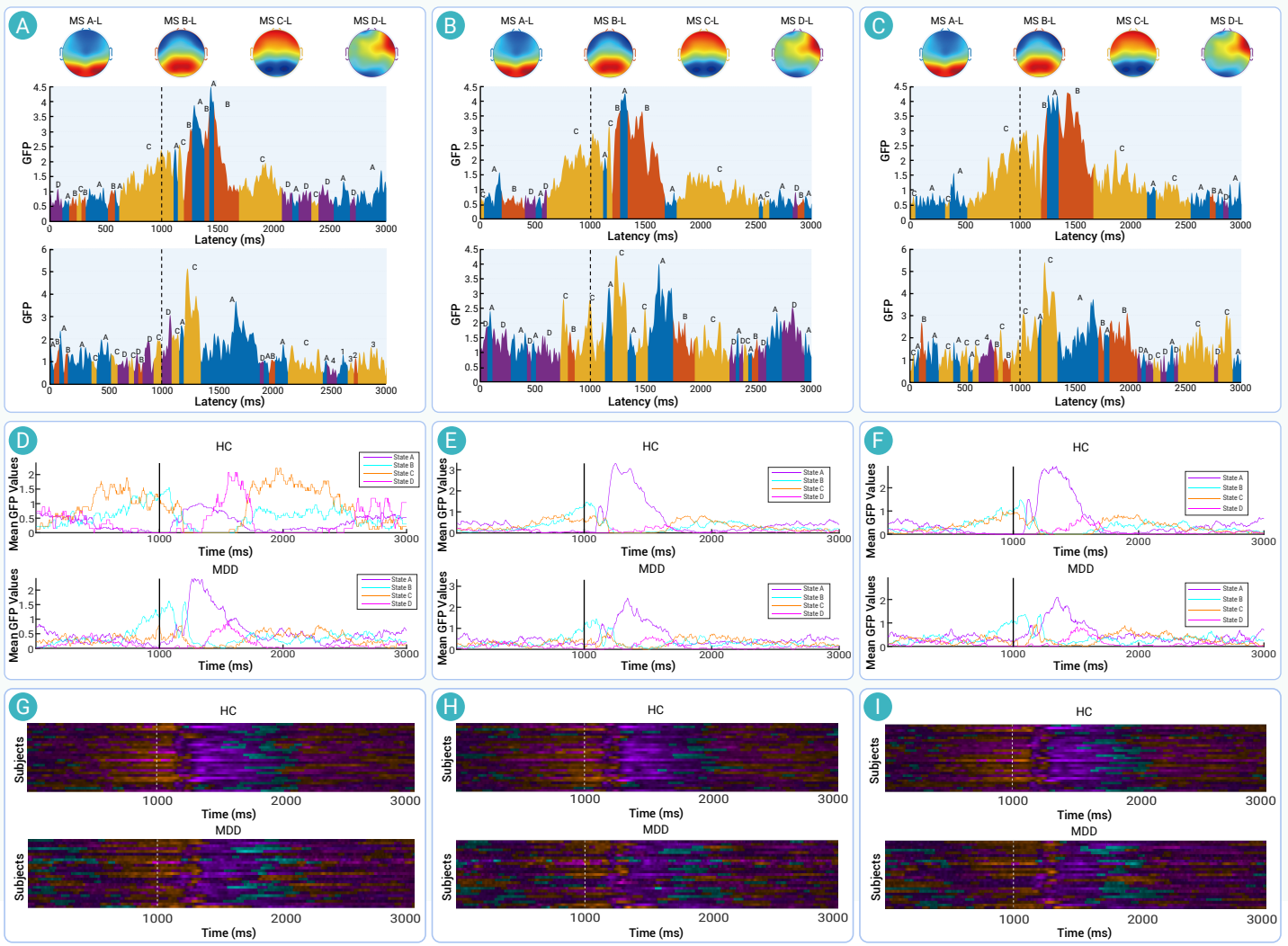

Figure 2. State classification of the back-fitting of the original EEG sequence by the microstate prototype during aesthetic perception of landscape images (A-C) EEG topographic maps corresponding to different microstates (MS-A-L to MS-D-L) during landscape aesthetic perception under positive, neutral, and negative valence images, respectively. The upper row shows the Healthy Control (HC) group, and the lower row shows the Major Depressive Disorder (MDD) group. The four microstates represent: MS-A-L: Microstate A (posterior pattern, related to visual processing). MS-B-L: Microstate B (central-posterior pattern, sensorimotor-related). MS-C-L: Microstate C (anterior pattern, associated with anterior cingulate and limbic functions). MS-D-L: Microstate D (prefrontal pattern, linked to executive control and attentional networks). (D-F) Time courses (0 to 3 s) of changes in average Global Field Power (GFP) for the four microstates during landscape aesthetic perception under positive, neutral, and negative valence images, respectively. (G-I) Heatmaps depicting changes (0 to 3 s) in average GFP of the four microstates during landscape aesthetic perception across the three valence conditions. Different microstates are represented by different colors in the figure. The letters indicate the microstate classification of each data segment. Note: GFP = Global Field Power. The vertical line at 1 s denotes stimulus onset.

level visual processing in individuals with MDD, which could limit the transition to higher-order evaluative stages of aesthetic experience.

Conversely, the reduced coverage and duration of prefrontal MS-D-F for facial stimuli and MS-C-L for landscape stimuli suggest a weakened engagement of neural networks involved in cognitive-affective evaluation, reward, and self-referential processing.[32,33] These alterations may indicate a reduced ability to integrate perceptual input with emotional value and subjective meaning during aesthetic appraisal.

Furthermore, a significant negative correlation between posterior (MS-A-L) and prefrontal (MS-C-L/D-F) microstates suggests a functional imbalance in MDD, possibly reflecting a disrupted coordination between early sensory encoding and higher-level evaluative integration.[24]

Taken together, these results reveal a distinct pattern of altered microstate dynamics in MDD during aesthetic evaluation, characterized by enhanced occipital engagement and attenuated prefrontal involvement—highlighting potential neurophysiological markers of impaired aesthetic perception in depression.

Abnormal temporal dynamics of microstate GFP and complexity in depressed patients during aesthetic perception

We initially conducted a statistical analysis to examine the differences in GFP values across all microstates between different groups. A three-way repeated measures ANOVA was performed with mean total GFP (A/B/C/D) values as the dependent variable; subject type (MDD/HC) as a between-subject factor, image type (positive/neutral/negative valence), and aesthetic type (face/landscape) as within-subject factors. The analysis revealed a significant main effect of aesthetic type ($F_{(1, 50)} = 72.118$, $p < 0.001$, partial $\eta^2 = 0.750$), and a significant main effect of image type ($F_{(2, 100)} = 6.366$, $p = 0.004$, partial $\eta^2 = 0.210$). However, the main effect of subject type was not significant ($F_{(1, 50)} = 2.681$, $p = 0.115$, partial $\eta^2 = 0.100$), indicating a clear impact of aesthetic type and image type on GFP values.

Next, we averaged the GFP values (A/B/C/D) over time across subjects within each group. Figures 1D-I, Figures 2D-I show the mean GFP (A/B/C/D) curves for both HC individuals and MDD during the aesthetic perception of face and landscape images, respectively. It is evident that for face aesthetics, the sequence patterns of GFP peaks during the evaluation of neutral and negative images are the same, following the order of MS-A-F (posterior pattern), MS-C-F (anterior pattern), MS-A-F (posterior pattern), MS-B-F (central-posterior pattern), and MS-C-F (anterior pattern). However, in the MDD group, during the evaluation of positive face images, there is a noticeable appearance of the MS-D-F (prefrontal pattern) both at the beginning and

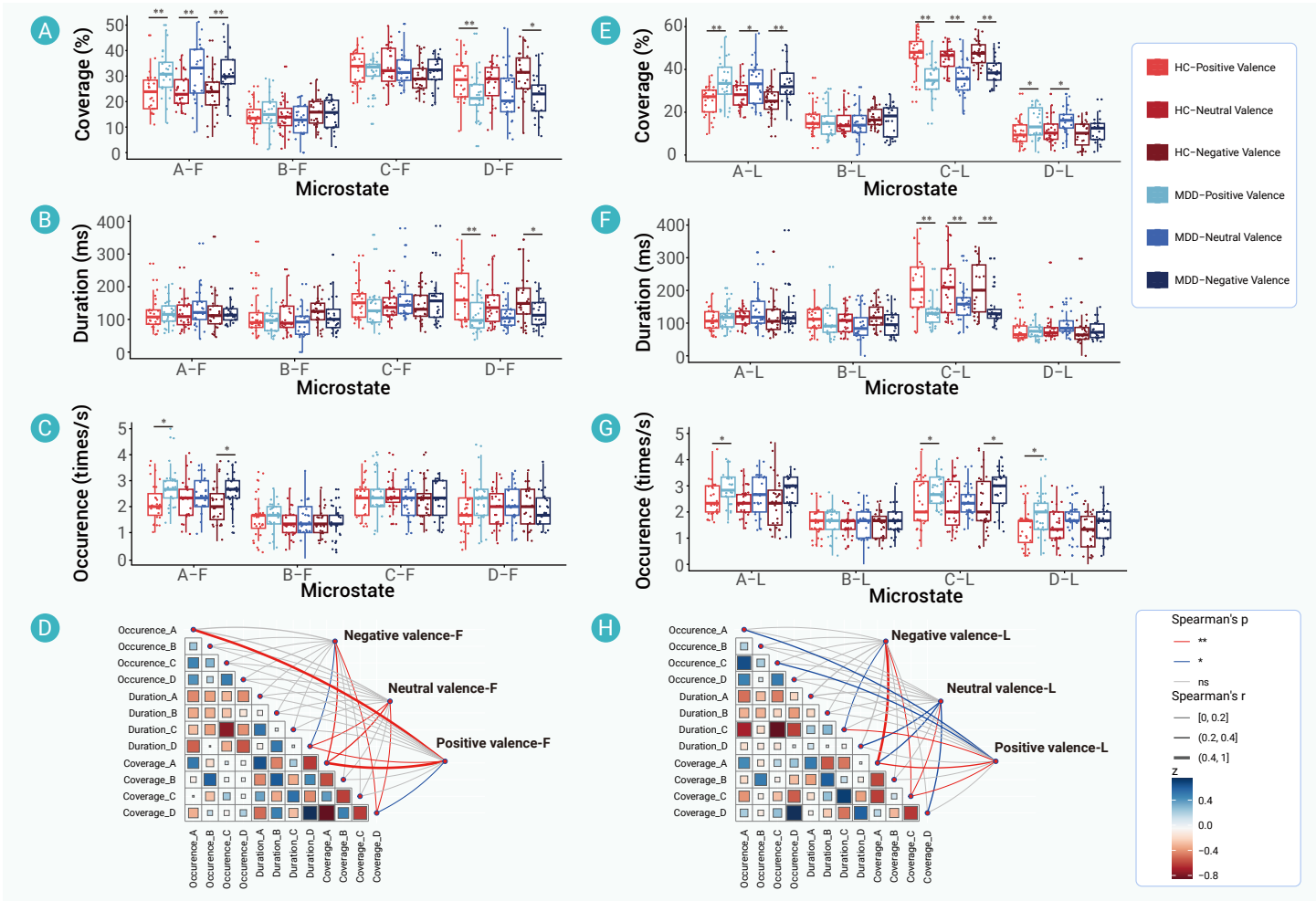

Figure 3. Box plot of occurrence, duration, and coverage of microstates and their correlations with BDI-2 scores (A-C) Distribution of coverage, duration, and occurrence parameters during face aesthetic perception. (E-G) Distribution of coverage, duration, and occurrence parameters during landscape aesthetic perception. (D-H) Correlation analysis between BDI-2 scores and microstate parameters during face (D) and landscape (H) aesthetic perception. Pairwise comparisons are displayed with a color gradient denoting Spearman's correlation coefficients corrected by Fisher's z transformation. The line color and thickness represent the p-value and coefficients of Spearman's correlation, respectively. *P < 0.05, **P < 0.01, ***P < 0.001.

end of the aesthetic perception process, accompanied by a reduction in the amplitude of the MS-A-F (posterior pattern) peak. This observation aligns with the negative attentional bias often observed in depression, where patients show a reduced responsiveness to positive stimuli and increased attention to negative or emotionally neutral content.[34]

In contrast, during the aesthetic evaluation of landscape images, fewer common peaks were observed compared to face images, with only two MS-B-L (central-posterior pattern) peaks and a MS-A-L (posterior pattern) peak appearing, respectively. Similarly, in the MDD group, during the evaluation of positive landscape images, a MS-A-L (posterior pattern) GFP peak was observed at both the beginning and end of the aesthetic process. This difference suggests that landscape aesthetics may engage less complex neural dynamics than face stimuli, which might be attributed to different processing mechanisms for these two types of stimuli.[35]

To assess temporal microstate complexity, we computed Lempel-Ziv complexity (Ms-LZC) using sliding windows of 200 ms, 300 ms, and 500 ms. Figures 4A-F illustrates the average Ms-LZC time courses across all participants during aesthetic evaluation of facial and landscape images.

With 200 ms and 300 ms windows, the HC group exhibited two distinct complexity peaks at approximately 1000 ms (stimulus onset) and 1500 ms (decision period), indicating enhanced neural flexibility and dynamic engagement during aesthetic judgment. In contrast, the MDD group displayed only an early peak around 1000 ms, with the second peak either attenuated or delayed, suggesting reduced neural adaptability.

To statistically evaluate group differences in Ms-LZC, we performed nonparametric cluster-based permutation tests (5,000 permutations; cluster-forming threshold $p < 0.05$). Statistical analyses were restricted to a predefined 300-ms window. A significant negative cluster was identified between 1000 ms and 1500 ms for both facial and landscape conditions. Within this interval, the MDD group exhibited a significantly attenuated change in Ms-LZC compared to the HC group (facial stimuli: $p = 0.023$, Cohen's $d = 0.84$; landscape stimuli: $p = 0.041$, Cohen's $d = 0.77$; FWE-corrected), suggesting reduced temporal entropy modulation and fewer microstate transitions during active aesthetic appraisal.

No significant differences were observed outside the 1000–1500 ms window or during rest (all $p > 0.10$). Additionally, around 1200 ms, the HC group showed a significant trough in complexity, while the MDD group's trough was significantly shallower. To quantify this, we extracted the minimum Ms-LZC values within the 1150–1250 ms window for each subject and conducted a between-group comparison using the Wilcoxon rank-sum test, which revealed a significant difference ($p = 0.031$), further highlighting altered dynamic transitions. Given that aesthetic judgments generally peak around 1600–1700 ms, later peaks were not included.

These findings suggest that Ms-LZC effectively captures group-specific differences in temporal brain dynamics during aesthetic processing. The increased distinctiveness and decreased randomness in the information integration of EEG spatiotemporal microstates may reflect the neural correlates of aesthetic signal reception and aesthetic judgment. These abnormalities observed in the MDD group suggest a more rigid and less flexible neural network during aesthetic evaluation, consistent with the cognitive inflexibility often associated with depression.[32,36] Moreover, the significant differences in these patterns among patients with depression further underscore the potential

Table 1. Three conventional microstate parameters (Coverage, Occurrence, and Duration) of different image types (positive/neutral/negative valence) during face aesthetic perception (values are mean ± SD). And detailed statistical metrics, including P values, t values, and effect size (Cohen's d) for post hoc comparisons of the three conventional parameters during face aesthetic processing (HC vs MDD).

Parameters (Face)	Microstate	Positive		Neutral		Negative	
		HC	MDD	HC	MDD	HC	MDD
Coverage (%)	A	23.33±8.63	31.23±8.51	24.30±6.63	31.39±11.2	23.63±7.76	31.50±9.13
	B	15.87±5.92	15.14±5.93	14.06±6.64	12.72±6.18	14.25±5.39	15.67±6.92
	C	29.64±6.02	31.75±6.22	34.06±7.69	32.92±6.61	33.41±6.56	30.79±6.75
	D	31.16±8.90	21.89±8.58	27.58±7.50	22.97±10.23	28.71±8.31	22.04±8.95
Occurrence (times/s)	A	2.09±0.73	2.60±0.67	2.27±0.78	2.44±0.64	2.17±0.72	2.76±0.83
	B	1.37±0.53	1.47±0.59	1.37±0.53	1.47±0.75	1.52±0.72	1.64±0.55
	C	2.26±0.71	2.27±0.74	2.46±0.59	2.21±0.64	2.32±0.68	2.47±0.83
	D	1.99±0.75	1.91±0.67	1.96±0.71	2.00±0.76	1.83±0.80	2.15±0.88
Duration (ms)	A	121.72±61.70	129.14±65.71	117.29±45.72	136.11±62.19	117.96±50.79	119.83±39.81
	B	123.49±41.39	115.37±59.38	108.40±53.75	87.00±47.13	113.16±68.73	95.79±36.33
	C	142.61±47.31	160.41±76.30	144.85±42.94	164.59±72.02	156.61±56.56	140.04±68.33
	D	188.14±110.40	120.18±45.15	168.60±110.29	124.81±78.21	197.06±122.80	111.21±48.63

Statistical value (Face)	Microstate	Positive HC VS MDD			Neutral HC VS MDD			Negative HC VS MDD		
		t value	P value	Cohen's d	t value	P value	Cohen's d	t value	P value	Cohen's d
Coverage (%)	A	-3.323	0.002	0.921	-2.732	0.009	0.233	-3.336	0.001	0.932
	B	0.444	0.658	0.123	0.753	0.454	0.149	-0.822	0.415	0.231
	C	-1.238	0.221	0.344	0.574	0.568	0.396	1.417	0.162	0.393
	D	3.827	0.0003	1.061	1.840	0.072	0.050	2.779	0.007	0.773
Occurrence (times/s)	A	-2.648	0.010	0.732	-0.848	0.400	0.773	-2.718	0.009	0.758
	B	-0.613	0.542	0.171	-0.531	0.598	0.208	-0.683	0.497	0.187
	C	-0.036	0.971	0.010	1.421	0.161	0.158	-0.688	0.494	0.192
	D	0.410	0.683	0.113	-0.180	0.857	0.517	-1.362	0.179	0.379
Duration (ms)	A	-0.418	0.677	0.116	-1.234	0.223	0.346	-0.148	0.882	0.041
	B	0.567	0.573	0.159	1.529	0.132	0.422	1.150	0.256	0.312
	C	-1.001	0.322	0.282	-1.188	0.241	0.336	0.948	0.347	0.265
	D	2.943	0.005	0.794	1.660	0.103	0.454	3.359	0.002	0.906

clinical relevance of Ms-LZC as a biomarker for aberrant neural processing in aesthetic perception.

Abnormal brain functional connectivity in depressed patients during aesthetic perception

Previous studies have linked typical microstates to specific functional networks.[31,37] Although microstates share neural generators, they retain distinct network properties.[32] In our study, we identified that the interval between 1000-1500ms is a critical period for aesthetic perception, exhibiting significant differences between MDD and HC groups in terms of microstate complexity. Therefore, we calculated and compared the adjacency matrices of each group within this timeframe.

Our findings (shown in Figures 5A-F) reveal that, during aesthetic perception, the strongest brain functional connectivity (FC) in both groups was observed in the occipital region electrodes (O1-O2-O_Z) and frontal/fronto-central region electrodes (F_Z-FC1-FC2).

Regional FC strength was defined as the mean of z-transformed connectivity values between electrode pairs within predefined cortical regions. Specifically, occipital region electrodes FC were calculated based on the average connectivity among electrodes O1, O2, and Oz, while frontal/fronto-central region electrodes FC were derived from Fz, FC1, and FC2. Two complementary measures of connectivity were employed: coherence (COH), representing linear synchronization, and phase-locking value (PLV), reflecting phase consistency of neural oscillations. Since our primary interest was in group differences in functional connectivity during aesthetic processing, we first examined whether stimulus type (face vs. landscape) affected connectivity measures. Finding no significant stimulus-specific effects on connectivity patterns (all $p > 0.20$), we averaged across both stimulus types to maximize statistical power for between-group comparisons.

Between-group comparisons were performed using two-tailed independent samples t-tests, with multiple comparisons corrected using the Bonferroni method. In the frontal/fronto-central region, MDD patients exhibited significantly higher FC than healthy controls across both metrics. For COH, the MDD group showed a mean (± SD) of 0.473 ± 0.108, compared to 0.391 ± 0.095 in the HC group ($t_{50} = 3.19$, $p = 0.0126$, Bonferroni-corrected). Similarly, PLV was elevated in the MDD group (0.521 ± 0.094) relative to controls (0.444 ± 0.086; $t_{50} = 3.45$, $p = 0.0066$, Bonferroni-corrected).

In contrast, anterior–posterior region FC, computed as the mean connectivity between all frontal (Fz, FC1, FC2) and occipital (O1, O2, Oz) electrode pairs, was significantly reduced in the MDD group. For COH, MDD patients had a mean value of 0.276 ± 0.083, compared to 0.351 ± 0.079 in controls ($t_{50} = -3.29$, $p = 0.0102$, Bonferroni-corrected). For PLV, the MDD group

Table 2. Three conventional microstate parameters (Coverage, Occurrence, and Duration) of different image types (positive/neutral/negative valence) during landscape aesthetic perception (values are mean ± SD). And detailed statistical metrics, including P values, t values, and effect size (Cohen's d) for post hoc comparisons of the three conventional parameters during face aesthetic processing (HC vs MDD).

Parameters (Landscape)	Microstate	Positive		Neutral		Negative	
		HC	MDD	HC	MDD	HC	MDD
Coverage (%)	A	25.54±6.87	33.97±10.33	27.94±6.37	33.68±9.96	25.05±6.60	33.16±8.52
	B	16.55±6.77	15.75±7.31	15.14±5.90	14.60±7.21	17.50±4.62	16.25±7.46
	C	47.69±9.11	35.45±8.43	45.20±6.10	35.82±8.31	47.47±5.90	39.01±6.74
	D	10.23±5.91	14.83±7.33	11.72±6.25	15.90±6.27	9.98±6.11	11.58±5.50
Occurrence (times/s)	A	2.44±0.64	3.00±0.84	2.43±0.55	2.59±0.77	2.38±0.99	2.73±0.63
	B	1.57±0.57	1.59±0.55	1.51±0.46	1.56±0.65	1.53±0.45	1.61±0.52
	C	2.29±0.95	2.77±0.61	2.28±0.90	2.40±0.59	2.27±1.08	2.89±0.78
	D	1.41±0.76	1.96±0.80	1.46±0.64	1.75±0.63	1.24±0.68	1.55±0.67
Duration (ms)	A	108.10±33.74	117.38±37.08	118.21±27.01	141.03±61.30	119.98±56.62	131.49±65.39
	B	110.20±37.36	107.89±53.55	105.89±39.57	95.74±48.63	122.10±39.12	100.43±40.26
	C	261.37±170.45	132.66±42.98	239.06±116.85	159.56±58.29	272.42±160.53	147.50±59.43
	D	78.82±37.33	74.33±23.48	84.16±45.62	95.31±33.80	78.66±53.72	76.79±27.81

Statistical value (Landscape)	Microstate	Positive HC VS MDD			Neutral HC VS MDD			Negative HC VS MDD		
		t value	P value	Cohen's d	t value	P value	Cohen's d	t value	P value	Cohen's d
Coverage (%)	A	-3.818	<0.001	1.070	-2.451	0.019	0.691	-3.438	0.001	0.968
	B	0.721	0.475	0.203	0.295	0.769	0.082	0.409	0.684	0.113
	C	4.802	<0.001	1.339	4.607	<0.001	1.293	5.029	<0.001	1.391
	D	-0.993	0.325	0.274	-2.404	0.019	0.667	-2.478	0.017	0.693
Occurrence (times/s)	A	-1.534	0.132	0.418	-0.828	0.412	0.232	-2.657	0.011	0.745
	B	-0.603	0.549	0.168	-0.262	0.794	0.073	-0.121	0.904	0.033
	C	-2.394	0.021	0.656	-0.551	0.584	0.150	-2.168	0.035	0.592
	D	-1.594	0.117	0.442	-1.649	0.105	0.457	-2.481	0.016	0.690
Duration (ms)	A	-0.676	0.502	0.188	-1.713	0.096	0.488	-0.940	0.351	0.261
	B	1.965	0.055	0.546	0.821	0.415	0.229	0.178	0.858	0.050
	C	3.773	0.001	1.016	3.138	0.003	0.851	3.795	0.001	1.017
	D	0.159	0.874	0.043	-1.006	0.319	0.276	0.522	0.604	0.142

demonstrated lower connectivity (0.289 ± 0.077) than the HC group (0.367 ± 0.069; $t_{50} = -3.52$, p = 0.0054, Bonferroni-corrected).

No significant group differences were observed in occipital intra-regional FC. For COH, the difference was non-significant (p = 0.42), and likewise for PLV (p = 0.39).

These connectivity alterations reflect disrupted neural integration pathways in MDD, potentially impairing the coordination between perceptual and emotional appraisal systems during aesthetic evaluation.

The locations of these connectivity changes correspond and overlap with the centroid positions of MS-A (posterior/visual pattern) and MS-D (anterior/prefrontal pattern) topographical maps. This spatial overlap suggests a direct link between altered microstate representations and disrupted brain network communication in MDD. Specifically, MS-A has been associated with visual perception, while MS-D reflects prefrontal control and cognitive integration. The impaired anterior–posterior connectivity may thus indicate a breakdown in top-down modulation of sensory information, possibly leading to reduced emotional engagement during aesthetic processing in MDD.

Additionally, while there were slight variations among other channels, these changes were scattered and did not exhibit clear patterns. According to recent neuro-aesthetic models, the emotional appraisal system and the default mode network, which supports self-referential processing, are crucial contributors to aesthetic experience.[38] These systems are known to be dysfunctional in depression, characterized by a bias towards negative emotions, insensitivity to rewards, rumination, and aberrant neural circuitry.[39] The increased intra-orbitofrontal connectivity may reflect maladaptive emotional overprocessing, while the reduced anterior–posterior FC could hinder the integration of perceptual inputs with internal evaluations, contributing to the atypical aesthetic preferences often reported in patients with depression. To further elucidate the directionality of information flow between brain regions during the aesthetic evaluation process, we conducted an information transfer analysis using Transfer Entropy (TE), a model-free method widely applied to estimate directed functional connectivity based on information theory principles. TE was calculated from preprocessed EEG time series during the 1000–1500 ms window, focusing on directional interactions between frontal/fronto-central region (Fz–FC1–FC2) and occipital regions (O1–O2–Oz) electrodes.

Statistical comparisons using nonparametric permutation tests revealed a significant reduction in top-down information flow from frontal/fronto-central (Fz–FC1–FC2) to occipital (O1–O2–Oz) regions in the MDD group compared to HC (p = 0.008). In contrast, bottom-up transfer (occipital to frontal/fronto-central) did not significantly differ between groups (p = 0.26). These results indicate a selective attenuation of top-down information transfer in MDD,

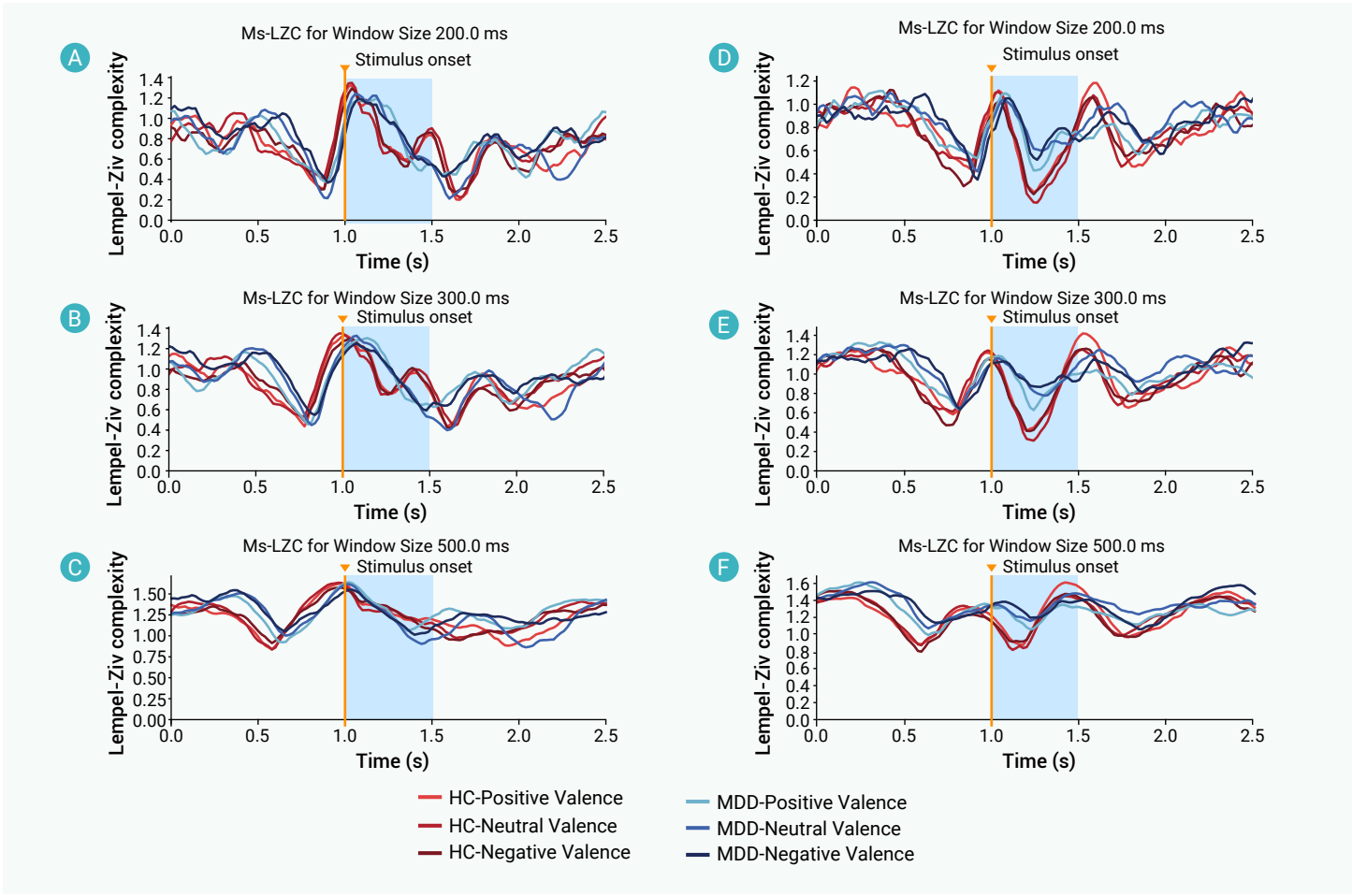

Figure 4. Evolution of average entropy of microstate complexity during aesthetic evaluation (A–C) show the Ms-LZC time courses during face aesthetic evaluation using sliding windows of 200 ms, 300 ms, and 500 ms, respectively. (D–F) show the corresponding Ms-LZC results for landscape aesthetic evaluation using the same window lengths. Solid lines represent the HC group, and dashed lines represent the MDD group. Shaded areas indicate the standard error of the mean (SEM) across participants. Vertical dashed lines mark stimulus onset (1.0 s) and average response time (~1600 ms). The choice of window lengths (200 ms, 300 ms, and 500 ms) reflects different temporal resolutions for capturing dynamic complexity: shorter windows emphasize finer microstate transitions, while longer windows capture broader temporal structure. The comparison across window sizes allows for evaluation of robustness in group differences and time-locked effects. Statistically significant time intervals showing between-group differences (based on nonparametric cluster-based permutation tests) are marked with horizontal bars above the curves. These results highlight reduced temporal complexity in the MDD group during critical periods of aesthetic judgment, particularly in the 300 ms window.

suggesting a reduced influence of frontal regions on occipital activity during aesthetic evaluation.

This pattern of altered directed connectivity is consistent with prior findings of impaired prefrontal feedback in depression and aligns with our microstate-level observations of reduced anterior–posterior coordination. The reduced top-down flow from higher-order evaluative regions to lower-order perceptual areas may limit the integration of sensory inputs with affective and self-referential processing, potentially contributing to the atypical aesthetic responses observed in individuals with MDD. Importantly, these interpretations remain correlational, reflecting statistical dependencies in EEG activity rather than definitive causal relationships.

DISCUSSIONS

Our study reveals significant differences in EEG microstate parameters between the MDD and HC groups during aesthetic perception. Specifically, our results indicate that microstates during the evaluation of facial and landscape images exhibit distinct spatial and temporal dynamics between the two groups.

First, we observed that the MDD group showed higher coverage and occurrence of microstate A (posterior pattern) and lower coverage and duration of microstate D (prefrontal pattern) across all types of aesthetic stimuli. This finding suggests that individuals with MDD have a distinct pattern of brain activity, particularly in regions associated with visual and prefrontal processing. The increased coverage of microstate A in the MDD group may reflect an enhanced engagement of the visual cortex, possibly linked to heightened visual processing or negative attentional biases commonly observed in depression.[40] Visual processing in depression is often biased towards negative stimuli,[41] which may be reflected by an overactive posterior processing network. Conversely, the reduced coverage and duration of microstate D point to a disruption in prefrontal cortex function, which is critical for executive control, emotional regulation and self-reflection.[42] This pattern of altered prefrontal engagement is consistent with theories of cognitive and emotional dysregulation in depression.[43]

Furthermore, the differences in microstate parameters between MDD and HC groups were most pronounced during the evaluation of facial aesthetics. The HC group exhibited a more dynamic switching between microstates, characterized by brief peaks with frequent transitions among microstates A-F, B-F, and C-F, and a dominant presence of microstate D-F. In contrast, the MDD group showed a prolonged dominance of microstate C-F (anterior pattern). This suggests a potential over-reliance on anterior brain regions during aesthetic perception, particularly regions implicated in cognitive control and emotional regulation. This aligns with existing literature that highlights altered anterior cingulate cortex (ACC) activity in depression, associated with rumination and impaired cognitive control.[44,45] The ACC, a key node in the default mode network, is involved in self-referential thought processes, which are often maladaptive in depression, leading to perseverative thinking and emotional dysregulation.[46]

Interestingly, during landscape aesthetic evaluations, both groups exhibited

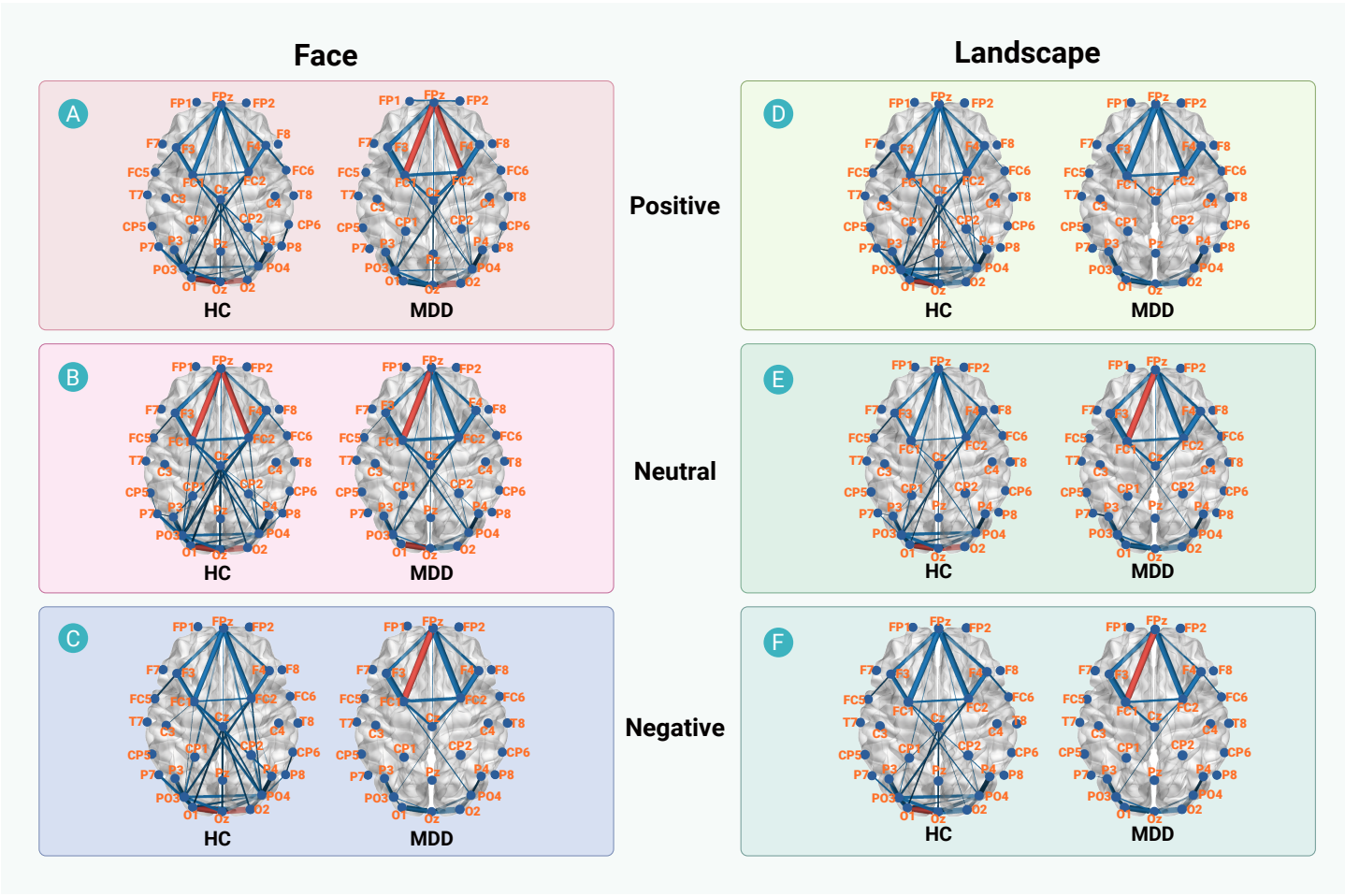

Figure 5. Functional connectivity (FC) changes during the critical 500 ms aesthetic perception in each group (A-C) FC visualization for aesthetic perception of facial images with positive, neutral, and negative valence, respectively. (D-F) FC visualization for aesthetic perception of landscape images with positive, neutral, and negative valence, respectively. In the FC visualization, red indicates FC values greater than 0.9, and blue indicates FC values greater than 0.7. The names and positions of the electrodes are marked in the figure. The thickness of the lines represents the absolute value of the FC metric.

less pronounced microstate transitions, with the MDD group showing a consistent dominance of microstates C-L and A-L. This finding suggests that landscape images elicit a different pattern of brain activity compared to facial images, possibly due to their more neutral or less emotionally charged nature. In the MDD group, the consistency of microstates C-L and A-L could indicate a diminished ability to shift attention or engage with visual stimuli flexibly, potentially reflecting a broader cognitive inflexibility characteristic of depression.[47] The HC group, on the other hand, exhibited an increased occurrence of microstate B-L (central-posterior pattern), which may reflect a more balanced engagement of the brain regions involved in visual and cognitive processing. The difference between these two groups underscores how depression may alter not just emotional responses to aesthetics, but also the cognitive flexibility with which individuals engage with different types of aesthetic stimuli.[48]

The functional connectivity analysis further supports our microstate findings. Both groups showed the strongest brain functional connectivity in occipital and anterior/fronto-central regions, which are crucial for early visual processing and higher-order evaluative functions.[49] However, the MDD group exhibited notable differences in connectivity strength between anterior and posterior networks. These alterations could reflect disruptions in the integration of perceptual inputs with evaluative and self-referential processes necessary for aesthetic appreciation.[50]

Chatterjee's framework for the neural underpinnings of visual aesthetics highlights the importance of early vision, which involves processing simple components such as color, shape, and motion in the occipital cortex and frontal-parietal attentional circuits. Intermediate vision integrates these components into larger visual targets, while late vision, including prefrontal, insular, temporal pole, and ventromedial regions, is responsible for cognitive and emotional processing. Cela-Conde et al.[51] identified the main regions involved in Chatterjee's model, underscoring the complex interplay between visual processing and emotional evaluation in aesthetic experiences.

Further supporting these findings, Orgo et al.[52] discovered that MDD patients exhibit significantly reduced small-world properties, indicating a more random brain network and increased functional connectivity. Shim et al.[53] also found that MDD patients show significantly decreased path length and clustering coefficient in brain network connectivity within alpha and theta bands, suggesting weaker interregional connections.

Recent neuroaesthetic models propose that the default mode network, which supports self-referential processing, and the emotional appraisal system are key contributors to aesthetic experiences. These systems are known to be dysfunctional in depression, characterized by a bias toward negative emotions, reward insensitivity, ruminative thinking, and abnormal neural circuits. Our findings corroborate this, as the altered connectivity and microstate dynamics in the MDD group may reflect these underlying dysfunctions. Such dysfunctions likely contribute to the altered aesthetic preferences observed in MDD patients, including a diminished capacity for emotional and cognitive engagement with aesthetically pleasing stimuli.

The consistency between our findings and these previous studies further substantiates the alterations in brain connectivity and aesthetic perception in MDD patients. The identified changes in microstates parameters and functional connectivity observed in our study aligning with the broader literature suggests that depression may alter the way aesthetic stimuli are processed and evaluated in the brain, potentially contributing to the altered aesthetic preferences seen in depressed individuals.

CONCLUSIONS

Our study has several implications for understanding the neural mecha-

nisms underlying aesthetic experiences in depression. The distinct microstate dynamics and functional connectivity patterns observed in the MDD group suggest that depression may alter the way aesthetic stimuli are processed, possibly contributing to the abnormal aesthetic preferences observed in MDD patients. These findings highlight the potential of EEG microstate analysis as a tool for investigating the neural basis of aesthetic experiences and their alterations in psychiatric conditions.

Our findings of altered EEG microstate dynamics and disrupted functional connectivity in prefrontal and posterior brain regions in MDD patients have important clinical relevance. The observed reductions in microstate flexibility and abnormal network interactions may serve as neurophysiological biomarkers to aid early diagnosis of depression and to stratify patients based on neural dysfunction severity. Furthermore, these EEG markers could inform personalized treatment approaches, such as targeting prefrontal or anterior–posterior networks with neuromodulation techniques (TMS/tDCS) to improve cognitive and emotional regulation in MDD. However, there are several limitations to this study that warrant further investigation. First, we analyzed the EEG microstates in sensor space. Whether these conclusions are held in source space still requires further study. Second, the sample size in our study was relatively small. Larger sample size and multicenter cooperation should be considered in future studies to increase generalizability. Finally, while we observed interesting differences in microstate sequences when viewing positive versus negative images, we could not fully explain these variations. Further research is needed to elucidate the neural mechanisms underlying aesthetic processing in depression, including the causal relationships between microstate dynamics, functional connectivity, and aesthetic experiences. Longitudinal studies could examine how these neural patterns evolve with treatment and recovery, offering insights into the potential therapeutic effects of interventions targeting aesthetic and emotional processing. With continued refinement of analytical methods, EEG microstate characteristics—spatial, temporal, and connectivity patterns—hold significant promise for advancing our understanding of depression and informing clinical applications.

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FUNDING AND ACKNOWLEDGMENTS

This study is supported by Shanghai Education Commission Research and Innovation Program (2019-01-07-00-02-E00037), National Key Research and Development Program of China (2018YFE0126700), Program of Shanghai Subject Chief Scientist (17XD1401700), "111" Program of Higher Education Discipline Innovation, Shanghai Jiao Tong University Scientific and Technological Innovation Funds, a Ministry Key Project (GW0980006); Shanghai Municipal Commission of Science and Technology Program (21dz2210100) and the STCSM International Science and Technology Cooperation Project (23490712600) (to W.L.), This research was also funded by China Scholarship Council (202506230146) (to X.M.) and the 73rd Batch of Surface Projects for Chinese Postdoctoral Researchers (2023M732261) granted to YD. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

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DECLARATION OF INTERESTS

The authors declare no competing interests.

ETHICAL STATEMENT AND PATIENT CONSENT

The study received approval from the Institutional Review Board for Human Research Protections of Shanghai Jiao Tong University (B2020011I).

DATA AND CODE AVAILABILITY

DOI: 10.6084/m9.figshare.30661733

SUPPLEMENTAL INFORMATION

It can be found online at https://doi.org/10.59717/j.xinn-life.2026.100192