Exploring Neural Synchronization with EEG Using Fractal Animations

Anonymous CogSci submission

Abstract

This study explores inter-subject neural synchronization, measured via inter-subject correlation (ISC), using EEG during fractal animation observation. Fractal animations, characterized by iterative self-similarity and visual complexity, provide a controlled stimulus devoid of semantic or emotional content, facilitating analysis of core sensory and predictive mechanisms. Fifteen participants watched fractal animations while their EEG was recorded. Following preprocessing, including artifact removal and spatial filtering, ISC was calculated using correlated component analysis. Results showed robust synchronization in occipital regions, linked to early visual processing, and frontal areas, associated with attentional control. Two control manipulations—phase randomization and temporal shuffling—reduced ISC by 65% and 70% ($p < 0.001$), confirming coherence. Peak synchronization aligned with heightened visual complexity and abrupt transitions. A correlation between self-reported focus and ISC highlighted top-down modulation. These findings endorse fractal animations as a powerful paradigm for studying neural responses, yielding insights into multisensory integration and cognitive processing.

Keywords: Fractal Animations; Neural Synchronization; EEG (Electroencephalography); Inter-Subject Correlation (ISC); Visual Complexity; Cognitive Neuroscience.

Introduction

Shared experiences, such as watching films or listening to music, evoke synchronized neural activity across individuals, a phenomenon termed Inter-Subject Correlation (ISC). ISC, a statistical measure of neural synchronization (INS), captures shared brain responses to common stimuli, reflecting coordinated sensory and cognitive processing (Hasson et al., 2004). Research employing naturalistic stimuli (e.g., films and narratives) has provided valuable insights into how common sensory inputs trigger coordinated brain responses (Lahnakoski et al., 2014). However, these natural stimuli inherently possess semantic, emotional, and social content (Jääskeläinen et al., 2021; Saarimäki, 2021). Due to individual differences, in language proficiency or cultural background, this content may introduce variability in responses, thereby obscuring the fundamental neural mechanisms underlying primary sensory processing and prediction (Kidd et al., 2018).

To overcome these limitations, the present study introduces fractal animations as a stimulus for ISC research. Historically, abstract images have been used to investigate neural behavior, with fractal images receiving special attention for their inherent repetition based on an initial pattern and a pre-designed algorithm (Martins et al., 2014; Poulsen et al., 2017). Generated using mathematical algorithms iterated function systems (IFS), fractal animations produce complex, dynamic, self-similar patterns (Uthayakumar & Prabakar, 2012). Unlike natural stimuli with explicit narratives and affective or linguistic content, fractal animations provide a controlled yet engaging visual experience that isolates perceptual and predictive processing from higher-order cognitive interference (Gonzales-Hess et al., 2022), and their balanced structural regularity with dynamic variation sets them apart from other artificial stimuli (Taylor & Spehar, 2016). Although previous research has examined the impact of fractal images on individual neural behavior (Martins et al., 2014), yet the role of fractal animations in ISC has not been investigated. Such shared neural patterns elucidate the fundamental mechanisms of sensory processing and prediction (Hasson et al., 2004; Madsen & Parra, 2022). Given the unique characteristics of fractal animations, early sensory pathways and higher cognitive functions, such as attention, are activated heterogeneously and with distinct patterns across individuals (Dorosti et al., 2023; Taylor et al., 2024). In this study, we hypothesize that these animations will engage predictive modeling processes and induce significant neural synchronization, particularly in the occipital regions responsible for early visual processing and the prefrontal regions involved in attentional control. Examining this phenomenon at a group level enables the acquisition of more precise and comprehensive results, not only enhancing our understanding of neural processing of these stimuli but also providing deeper insights into neural synchronization and behavioral responses in the context of these visual patterns.

Furthermore, we predict that experimental manipulations that disrupt phase coherence, implemented through phase randomization, will significantly reduce ISC, highlighting the critical role of phase synchronization in coordinating neural responses (Nastase et al., 2019). We also expect ISC to peak during segments of high visual complexity and abrupt transitions, reflecting the brain's predictive response to

In D. Barner, N.R. Bramley, A. Ruggeri and C.M. Walker (Eds.), *Proceedings of the 47th Annual Conference of the Cognitive Science Society*

unexpected visual changes (Dmochowski et al., 2012). Although individual differences such as prior exposure to fractal patterns or variations in attentional focus may influence ISC, the non-narrative design of fractal animations minimizes these confounds (Street et al., 2016).

Methodology

Fifteen right-handed volunteers (age 20–35, mean 27.4 ± 3.2) with normal vision were recruited from a university community. Restricting the sample to right-handed individuals minimized hemispheric variability, as handedness can influence the lateralization of brain-related function. They were carefully screened to ensure no history of neurological or psychiatric disorders, which could affect Electroencephalography (EEG) signals and compromise the study's findings. Prior to joining, each person provided written informed consent, and the study was conducted in accordance with ethical guidelines and approved by the institutional ethics committee. To reduce potential neurophysiological variability, all were instructed to abstain from consuming caffeine for at least four hours and avoid alcohol or medications for 24 hours before the experiment. These precautions ensured a consistent baseline for EEG recording across the group.

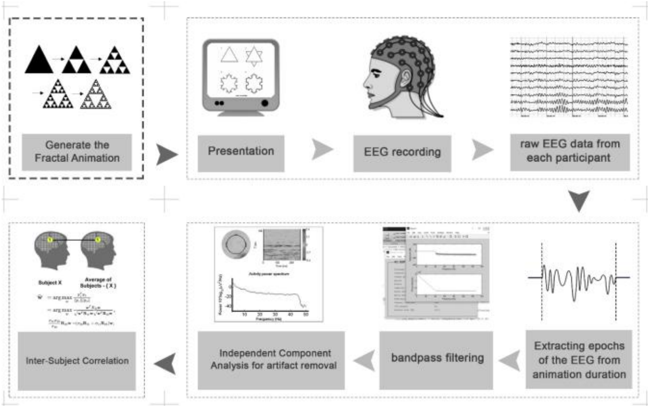

Figure 1: Workflow: Fractal animation, EEG recording, preprocessing, and ISC analysis.

The main visual cues consisted of 24 fractal animations generated via IFS, mathematical algorithms that create intricate, self-repeating designs. Each animation's fractal dimension, used as a gauge of intricacy, was quantified using the box-counting method, where higher values indicated more elaborate visuals. To ensure variety, parameters such as scaling factor, symmetry, motion path, and transition rate between fractal segments were systematically modified. These adjustments allowed us to evaluate the brain-based reaction to different degrees of detail and sudden shifts.

The animations were shown on a 42-inch monitor at a distance of 1.3 m in a dim, sound-insulated room to reduce external interference. Each display lasted 10–60 seconds and was presented at a frame rate of 24 frames per second. To avoid order effects, the sequence of these animations was shuffled for each volunteer, ensuring unbiased brain signals. Figure 2 summarizes the 24 fractal animations with labels and durations, illustrating the spectrum of visual intricacy and structural variety. These displays served as the basis for examining inter-subject coherence, enabling exploration of how common visual inputs prompt coordinated brain responses in a controlled, non-narrative setup.

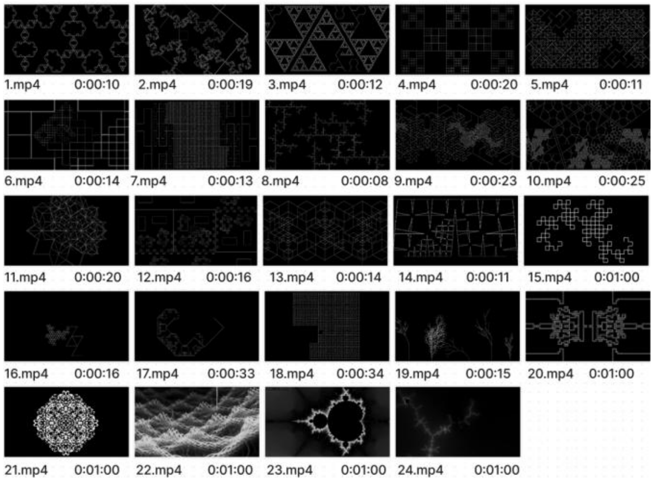

Figure 2: Summary of the 24 fractal animations used as visual stimuli, labeled sequentially (1.mp4 to 24.mp4) with their respective durations shown below each frame.

Throughout data collection, each person maintained a steady gaze, while triggers at animation start and end enabled accurate EEG alignment. Brain signals were captured via a 32-channel cap (10–20 system) at 1024 Hz (later reduced to 256 Hz). The recordings were cleaned using a finite impulse response (FIR) bandpass filter (1–40 Hz) to eliminate slow drifts and high-frequency interference.

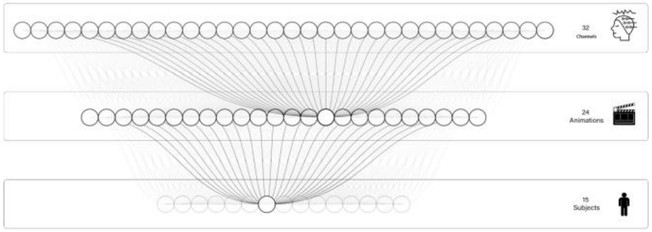

Figure 3: Figure 3 illustrates the experimental design, integrating 32 EEG channels, 24 fractal animations, and 15 participants. This diagram provides a visual overview of the study setup, highlighting the framework for capturing synchronized neural activity during animation viewing.

Artifact rejection was performed using independent component analysis (ICA), with components corresponding to eye blinks, muscle artifacts, and line noise manually inspected and removed. Noisy channels with activity exceeding five standard deviations from the mean were interpolated using spherical spline interpolation. Data were then re-referenced to the average reference method to minimize common-mode noise. Preprocessing was conducted in EEGLAB (MATLAB).

ISC was calculated via Canonical Correlation Analysis (CCA) using a 2-second sliding window with 50% overlap relative to the group average. This technique offered a granular assessment of temporal coherence patterns. CCA was favored over other ISC metrics, such as coherence analysis or inter-subject phase alignment, because it maximizes shared variance across the group while minimizing noise from individual variability. In contrast to standard correlation-based approaches that gauge raw signal similarity, CCA extracts correlated components across all volunteers, making it especially suited for pinpointing content-driven brain-based alignment.

To verify that the observed ISC arose from the presented content rather than chance variations, two control checks were performed. First, a phase-alteration method using Fast Fourier Transform (FFT) produced a 65% decrease in ISC (mean ISC = 0.25). Second, random shuffling of brief EEG segments yielded a 70% drop (mean ISC = 0.22). These outcomes underscored how structured temporal patterns are critical for producing coherent activity.

To account for multiple comparisons, Bonferroni correction was applied to all statistical tests. The normality of ISC distributions was confirmed via the Shapiro–Wilk test ($p > 0.05$) to validate parametric analyses. Paired t-tests ($p < 0.05$, Bonferroni-corrected) and Cohen's d ($d > 0.8$) indicated that ISC in the original data was significantly higher than in the modified conditions.

Additional analyses were done to eliminate potential confounding factors like subject fatigue or general brain entrainment unrelated to the visual cues. A time-shifted ISC evaluation was performed by offsetting each individual's EEG by 5–10 seconds relative to the overall mean. ISC values then approached baseline, suggesting that coherent activity was indeed input-driven rather than reflecting broad shifts in focus or alertness. Moreover, a subset of volunteers underwent a static fractal image condition, which produced markedly lower ISC compared to dynamic fractal animations ($p < 0.001$), further emphasizing the role of temporal structure in eliciting brain-based alignment.

While overall ISC remained robust across individuals, some exhibited lower coherence levels. A noteworthy positive correlation ($r = 0.42$, $p = 0.03$) emerged between ISC amplitude and self-reported focus, suggesting that differences in concentration influenced the degree of coordinated activity.

.

Results

EEG evaluations showed that watching fractal animations led to notable ISC, fluctuating over time. These variations illustrate the brain's adaptive capacity to achieve real-time coordinated responses, in tandem with the evolving intricacy of visual cues. Peak coherence was especially evident during intervals of increased detail and sudden shifts, suggesting that anticipation-based mechanisms become active to handle abrupt changes. Consistently elevated neural synchronization (measured via ISC) appeared in the occipital areas (linked to early-stage vision) and in the frontal zones (related to focus modulation and executive oversight). Short clips (<15 seconds) produced quick coherence peaks (mean ISC ≈ 0.72), while longer segments (15–60 seconds) yielded more sustained, multi-phase waves, with ISC ranging from 0.58 to 0.84. An ANOVA indicated a robust effect of clip duration ($p < 0.001$), confirming a direct association between temporal detail and enhanced brain-based coherence ($p < 0.005$).

Topographic and Temporal Patterns

Topographic analysis indicated the highest ISC at occipital channels (Oz, O1, O2), revealing involvement of primary and secondary visual areas (V1, V2) in processing contrast, orientation, and motion. Robust coherence in these locations underscores the importance of low-level visual features in overall brain consistency. Frontal sites (F3, F4, F7) showed significant ISC, illustrating top-down regulation and forecasting-based modeling in the dorsolateral prefrontal cortex (DLPFC). Activity here points to higher-level modulation of intricate visual inputs. Moderate ISC also emerged in parietal areas (P3, P4), reflecting their role in sensory integration and focus allocation via the posterior parietal cortex (PPC).

Time-series evaluation displayed ISC peaks concurrent with transitions between fractal segments, pointing to prediction-error processes as the brain adapts to unforeseen detail changes. These observations fit hierarchical anticipation theories, in which coordinated activity represents continuous updates of sensory assumptions.

Frequency-domain examination showed involvement of theta (4–7 Hz) and alpha (8–12 Hz) bands in occipital areas, underpinning vision, feature binding, and sensory gating. Prominent alpha coherence implies regulated perceptual processing and filtration of extraneous input. In frontal zones, enhanced beta (13–30 Hz) indicates top-down oversight and anticipation-based handling. The presence of beta alignment suggests reliance on recognized patterns to predict upcoming visual transformations.

These insights underscore the significance of forecasting-based frameworks, hierarchical processing, and focus-driven mechanisms in ISC. The dynamic interaction between bottom-up sensory routes and top-down oversight highlights the value of fractal animations as a robust visual cue for examining collective brain coupling and perceptual coordination processes.

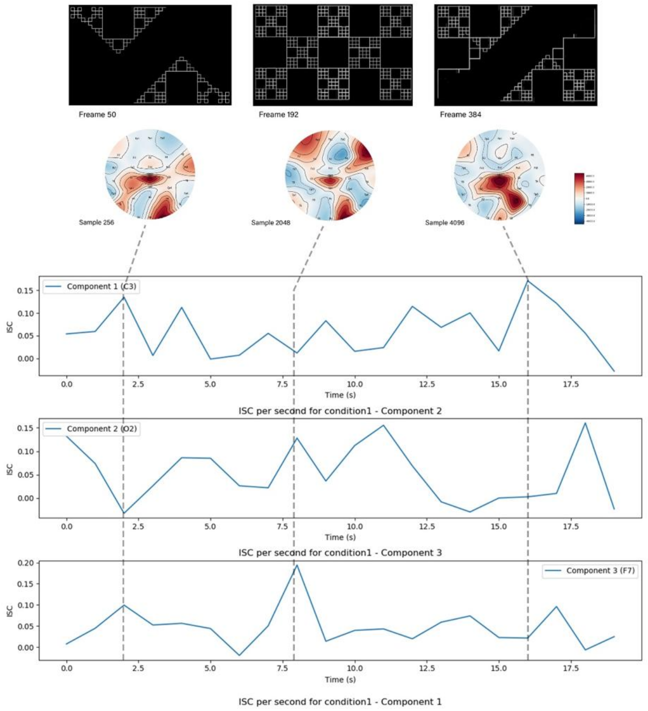

Figure 4: presents the ISC analysis output for the fourth animation (20 seconds), showing specific frames (50, 192, 384) and corresponding EEG topographical maps (samples 256, 2048, 4096). The plot illustrates temporal dynamics of neural synchronization across channels C3, O2, and F7, highlighting peak coherence during visual transitions..

Spectral EEG Analysis

Spectral analysis indicated distinct frequency-band contributions. Enhanced coupling in the theta (4–7 Hz) and alpha (8–12 Hz) bands in occipital regions reflects strong engagement of visual processing networks, while increased beta activity (13–30 Hz) in frontal regions suggests a role in higher-order cognitive control. A mixed-model ANOVA confirmed a significant interaction between frequency band and coupling magnitude ($p < 0.001$): ISC in theta and alpha bands was significantly greater in occipital regions than in frontal regions ($p < 0.005$), whereas beta synchrony was more pronounced in frontal regions compared to occipital regions ($p < 0.01$).

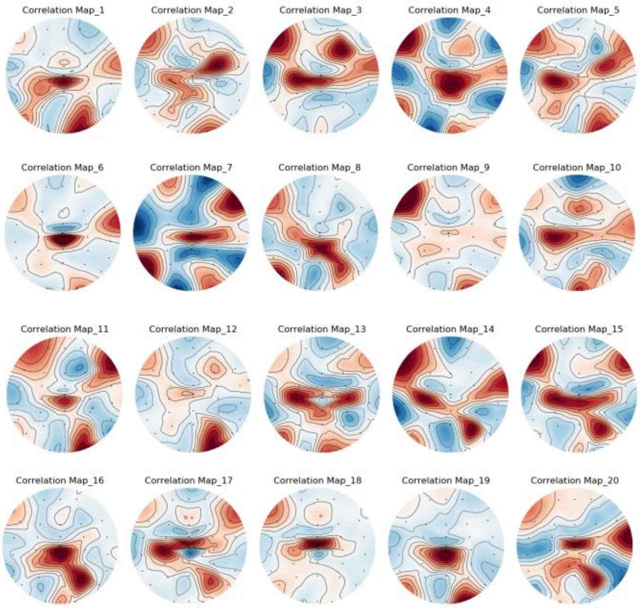

Figure 5: The topographical series illustrates the prominence and neural activities of the subject group while viewing animation number 4 over a duration of 20 seconds. Each map represents EEG correlation data for each second, with 256 EEG data samples per second visualized in each activity plot.

Control Manipulations

Control tests confirmed that ISC was triggered by the presented input rather than chance correlations. Phase-based alteration via FFT diminished ISC by 65% (mean ISC = 0.25), and random segment shuffling caused a 70% reduction (mean ISC = 0.22). Paired t-tests ($p < 0.001$) verified significantly higher ISC in the unmodified data, emphasizing how the structured qualities of fractal animations are crucial for producing coordinated brain activity.

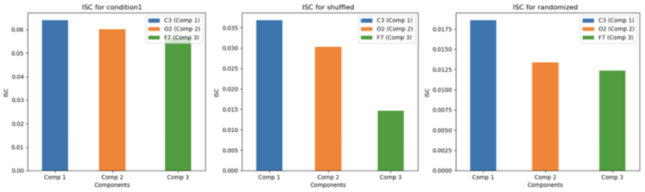

Figure 6: 1 Differences in correlation levels of channels with high correlation in the comparison bar chart of ISC for randomized and shuffled. The plot example is related to animation 4.

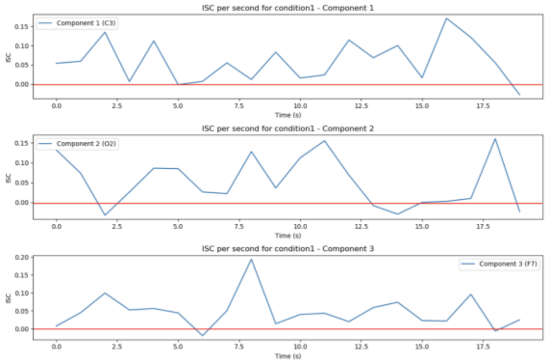

Figure 7: Zero line in time series before Evaluation The plot example pertains to animation 4.

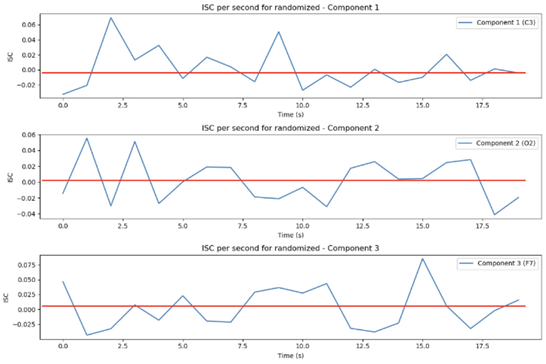

Figure 8: Zero line in time series before after randomized. The plot example pertains to animation 4.

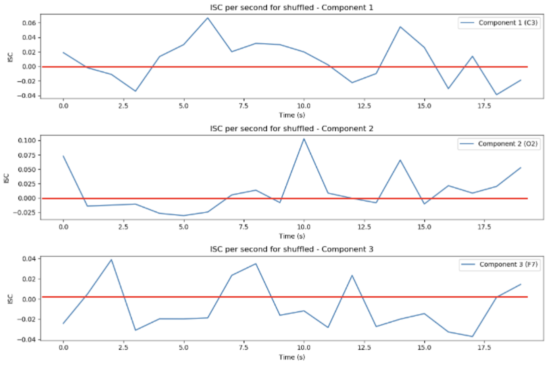

Figure 9: Zero line in time series before after shuffled. The plot example pertains to animation 4.

Individual Variability and Summary

Although ISC was generally robust, some subjects exhibited lower coordination levels. A significant positive correlation (r = 0.42, p = 0.03) was observed between ISC magnitude and self-reported focus level, suggesting that concentration modulates brain-based coherence.

Overall, fractal animations reliably induced inter-subject coupling, particularly in occipital and frontal areas. These findings align with anticipatory coding frameworks, demonstrating that ISC peaks coincide with moments of increased visual intricacy and abrupt transitions. The observed reduction in ISC following phase random manipulation and temporal shuffling indicates that coherence is directly linked to the structured properties of the content rather than random fluctuations.

Discussion

This study demonstrates that fractal animations reliably induce shared cerebral responses, supporting the idea that structured, dynamic visual prompts can evoke common patterns of brain activity without relying on semantic, emotional, or social content. The strong ISC observed in our study, particularly in the occipital zones associated with primary visual processing and the frontal zones involved in attentional control and predictive modeling, underscores the effectiveness of fractal structures in driving coordinated brain activity. These findings extend previous research by demonstrating that brain-level coherence can emerge purely from the intrinsic complexity of visual input, independent of higher-order cognitive influences.

Our results align closely with predictive coding theories, which propose that the brain continuously constructs and updates models of sensory input by minimizing prediction errors. The dynamic nature of fractal animations, characterized by abrupt transitions and rapid shifts in complexity, appears to induce these prediction errors, triggering coordinated brain-based reactions. ISC peaks consistently coincided with moments of heightened visual intricacy and sudden changes in fractal patterns, reinforcing the role of anticipatory mechanisms in harmonizing neural responses across individuals. This suggests that fractal animations engage both low-level sensory processing and higher-order predictive modeling.

Spectral analysis further supports these interpretations. Strong theta (4–7 Hz) and alpha (8–12 Hz) coupling in occipital areas indicates heightened engagement of visual processing networks, while increased beta (13–30 Hz) activity in frontal regions suggests involvement in cognitive control and attention regulation. This pattern aligns with prior findings, where theta and alpha synchronization has been associated with visual focus and sensory integration, while beta activity is linked to top-down processing and decision-making. These findings suggest that fractal animations activate a broad network of brain circuits, reinforcing their value as a controlled yet cognitively engaging stimulus for ISC research.

To validate that the observed ISC was stimulus-driven rather than arising from random fluctuations, two control manipulations were performed. Phase-based alteration via Fast Fourier Transform (FFT) led to a 65% reduction in ISC, while random reordering of short EEG segments resulted in a 70% decrease. These findings confirm that structured temporal patterns, rather than intrinsic signal correlations, play a crucial role in generating inter-subject brain alignment. This reinforces the notion that predictable yet dynamically evolving visual structures engage shared neural computations.

Despite the strong alignment effects observed across participants, some individuals exhibited lower ISC levels. A significant positive correlation (r = 0.42, p = 0.03) between self-reported visual concentration and ISC magnitude suggests that attentional engagement influences the strength of shared neural responses. Participants who reported higher levels of focus exhibited stronger ISC, implying that active attention enhances brain alignment during fractal animation viewing.

One limitation of this study is the absence of direct behavioral measures, such as reaction time tasks or cognitive assessments, which could further elucidate attentional influences on ISC. Additionally, the participant pool was primarily drawn from a single university community, potentially limiting generalizability. Future research could include participants with diverse cultural, educational, and mathematical backgrounds to enhance the robustness of fractal-induced neural synchronization. Incorporating eye-tracking data could also clarify whether gaze fixation patterns contribute to ISC variability. Furthermore, while fractal animations provide a controlled visual input, future research should explore comparative analyses with natural stimuli, such as dynamic landscapes or biological motion, to better understand the distinctions between artificial and naturalistic visual complexity in driving ISC.

Conclusion

This study introduces fractal animations as a controlled visual paradigm for investigating inter-subject neural synchronization. Unlike naturalistic stimuli, which introduce semantic, emotional, and cultural confounds, fractal animations evoke robust ISC solely through their structured visual complexity. Our findings indicate that alignment is most pronounced in occipital and frontal regions, consistent with anticipatory coding frameworks. Control manipulations confirmed that ISC was driven by structured temporal properties rather than random signal correlations, reinforcing the role of dynamic complexity in neural coupling.

These results significantly advance our understanding of brain alignment and offer a valuable framework for future research. Potential applications include cognitive training, neurofeedback, and clinical assessments, particularly in evaluating attentional control in conditions such as ASD or ADHD. Future studies should explore how fractal-based stimuli can be optimized for these applications and further investigate the neural mechanisms underlying ISC across different stimulus modalities.

In summary, fractal animations provide a powerful tool for studying shared neural dynamics, emphasizing the importance of structured visual intricacy in inter-subject brain alignment. These findings pave the way for future research into predictive processing, attention modulation, and neural synchronization in controlled, non-narrative environments.

Acknowledgments

We express our sincere gratitude to Dr. Reza Khosrowabadi for his invaluable guidance, insightful feedback, and unwavering support throughout the development of this study. His expertise in cognitive neuroscience and EEG analysis significantly contributed to the design and interpretation of our research, enhancing the quality and rigor of this work.

References

Chalnick, A., & Billman, D. (1988). Unsupervised learning of correlational structure. *Proceedings of the Tenth Annual Conference of the Cognitive Science Society* (pp. 510–516). Hillsdale, NJ: Lawrence Erlbaum Associates.

Dmochowski, J. P., Sajda, P., Dias, J., & Parra, L. C. (2012). Correlated components of ongoing EEG point to emotionally laden attention – A possible marker of engagement? *Frontiers in Human Neuroscience, 6.* https://doi.org/10.3389/fnhum.2012.00112

Dorosti, S., Namazi, H., & Khosrowabadi, R. (2023). Analysis of the complexity of EEG signals in relation to the complexity of fractal animations. *Fractals*, *31*(01), 2350001. https://doi.org/10.1142/S0218348X23500019

Feigenbaum, E. A. (1963). The simulation of verbal learning behavior. In E. A. Feigenbaum & J. Feldman (Eds.), *Computers and thought*. New York: McGraw-Hill.

Gonzales-Hess, N., Taylor, R., & Sereno, M. (2022). Contributed session III: Phenomenological assessment of dynamic fractals. *Journal of Vision*, *22*(3), 39. https://doi.org/10.1167/jov.22.3.39

Hasson, U., Nir, Y., Levy, I., Fuhrmann, G., & Malach, R. (2004). Intersubject synchronization of cortical activity during natural vision. *Science*, *303*(5664), 1634–1640. https://doi.org/10.1126/science.1089506

Hill, J. A. C. (1983). A computational model of language acquisition in the two-year-old. *Cognition and Brain Theory*, *6*, 287–317.

Jääskeläinen, I. P., Sams, M., Glerean, E., & Ahveninen, J. (2021). Movies and narratives as naturalistic stimuli in neuroimaging. *NeuroImage, 224,* 117445. https://doi.org/10.1016/j.neuroimage.2020.117445

Kidd, E., Donnelly, S., & Christiansen, M. H. (2018). Individual differences in language acquisition and processing. *Trends in Cognitive Sciences*, *22*(2), 154–169. https://doi.org/10.1016/j.tics.2017.11.006

Lahnakoski, J. M., Glerean, E., Jääskeläinen, I. P., Hyönä, J., Hari, R., Sams, M., & Nummenmaa, L. (2014). Synchronous brain activity across individuals underlies shared psychological perspectives. *NeuroImage*, *100*, 316–324. https://doi.org/10.1016/j.neuroimage.2014.06.022

Madsen, J., & Parra, L. C. (2022). Cognitive processing of a common stimulus synchronizes brains, hearts, and eyes.

PNAS Nexus, 1(1), pgac020. https://doi.org/10.1093/pnasnexus/pgac020

Martins, M. J., Fischmeister, F. P., Puig-Waldmüller, E., Oh, J., Geißler, A., Robinson, S., Fitch, W. T., & Beisteiner, R. (2014). Fractal image perception provides novel insights into hierarchical cognition. *NeuroImage*, *96*, 300–308. https://doi.org/10.1016/j.neuroimage.2014.03.064

Matlock, T. (2001). How real is fictive motion? Doctoral dissertation, Psychology Department, University of California, Santa Cruz.

Nastase, S. A., Gazzola, V., Hasson, U., & Keysers, C. (2019). Measuring shared responses across subjects using intersubject correlation. *Social Cognitive and Affective Neuroscience.* https://doi.org/10.1093/scan/nsz037

Newell, A., & Simon, H. A. (1972). *Human problem solving.* Englewood Cliffs, NJ: Prentice-Hall.

Ohlsson, S., & Langley, P. (1985). Identifying solution paths in cognitive diagnosis (Tech. Rep. CMU-RI-TR-85-2). Pittsburgh, PA: Carnegie Mellon University, The Robotics Institute.

Poulsen, A. T., Kamronn, S., Dmochowski, J., Parra, L. C., & Hansen, L. K. (2017). EEG in the classroom: Synchronised neural recordings during video presentation. *Scientific Reports, 7*(1), 43916. https://doi.org/10.1038/srep43916

Saarimäki, H. (2021). Naturalistic stimuli in affective neuroimaging: A review. *Frontiers in Human Neuroscience, 15,* 675068. https://doi.org/10.3389/fnhum.2021.675068

Shrager, J., & Langley, P. (Eds.) (1990). *Computational models of scientific discovery and theory formation.* San Mateo, CA: Morgan Kaufmann.

Street, N., Forsythe, A. M., Reilly, R., Taylor, R., & Helmy, M. S. (2016). A complex story: Universal preference vs. individual differences shaping aesthetic response to fractals patterns. *Frontiers in Human Neuroscience*, *10*. https://doi.org/10.3389/fnhum.2016.00213

Taylor, R. P., & Spehar, B. (2016). Fractal fluency: An intimate relationship between the brain and processing of fractal stimuli. In A. Di Ieva (Ed.), *The Fractal Geometry of the Brain* (pp. 485–496). Springer New York. https://doi.org/10.1007/978-1-4939-3995-4_30

Taylor, R. P., Viengkham, C., Smith, J. H., Rowland, C., Moslehi, S., Stadlober, S., Lesjak, A., Lesjak, M., & Spehar, B. (2024). Fractal fluency: Processing of fractal stimuli across sight, sound, and touch. In A. Di Ieva (Ed.), *The Fractal Geometry of the Brain* (Vol. 36, pp. 907–934). Springer International Publishing. https://doi.org/10.1007/978-3-031-47606-8_45

Uthayakumar, R., & Prabakar, G. A. (2012). Creation of fractal objects by using iterated function system. *2012 Third International Conference on Computing, Communication and Networking Technologies (ICCCNT'12),* 1–7. https://doi.org/10.1109/ICCCNT.2012.6395995.