Live Complexity Training
Douglas Dailey, mind@growing.com, livecomplexitytraining.com, tagsync.com, (360) 984-6622

Live Complexity Training Resources: Complexity

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Theory: There exists a complexity-based transdiagnostic biomarker of sickness behavior and its remediation.

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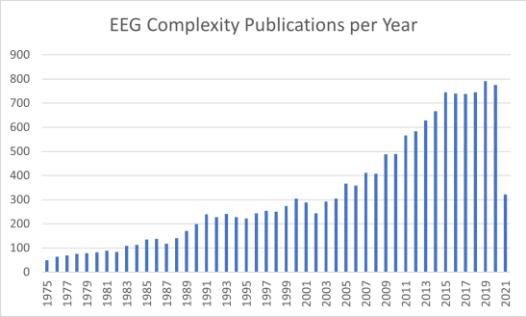
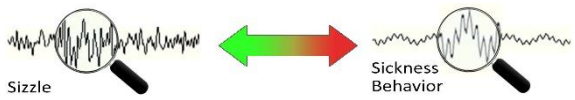
Introduction ▲



In January 2000 physicist Stephen Hawking said that the next century would be the century of complexity. In just the topic of EEG complexity alone there has been a significant increase in publications as shown in the chart to the left.

In the journal NeuroImage early 2021 DaSilva et al [FULL TEXT] observed that electrical activity in the visible (raw) EEG appeared to change states along a continuum with one side showing higher complexity and also higher consciousness. This complexity is labelled "sizzle" on the left in the figure below. This efficient, skillful, adaptive state is often replaced by one that shows increasing levels of unconsciousness, disconnection, and stereotyped EEG patterns easily seen in the raw and qEEG signals as on the right below.



DaSilva et al provide a strong validation to the theory upon which Live Complexity Training has been based since 2014.

In 2016 I presented "Complexity, Canonical Sickness Behavior and EEG Biofeedback" [Bradley Univ Super Brain Summit]. I presented my observations that when adaptogens outweighed anti-adaptogens the EEG would start moving to the left. When anti-adaptogens dominated or when there was excess stress then the EEG started moving to the right and presenting stereotyped patterns. In Live Complexity Training the EEG is used for two purposes 1) as a transdiagnostic biomarker to indicate trends in clinical status, and 2) as feedback for the client to use to train the brain to wake up and emerge from canonical sickness behavior.

It is easy to see in the raw EEG the development of what I call "sizzle" (on the left). It looks like a recording of random noise but it is not. Real random noise is called "white noise". The EEG is "pink noise". In the vigilant EEG pink noise may look like random white noise but it has a non-random self-organizing principle – 1 over F (1/f) power distribution - in which the lower frequencies coordinate with the higher frequencies like the timbre of an instrument or the distribution of branches on the trunk of a tree.

When the lower frequencies and the higher frequencies are in balance it is called self-organized criticality (SOC) and it generates complexity and potentiality. When out of balance the complex landscape is replaced by one with redundant repetitive stereotyped patterns. On the right you easily see fast waves riding on top of slow waves and other redundant, limiting and maladaptive patterns of canonical sickness behavior.

In 2015 I used a Kuramoto Oscillator model [tagsync.com] to confirm and extend my theory about the EEG continuum and sickness behavior. The model shows how physiological signals, such as those used in biofeedback, have three important modes. For beginners I use the

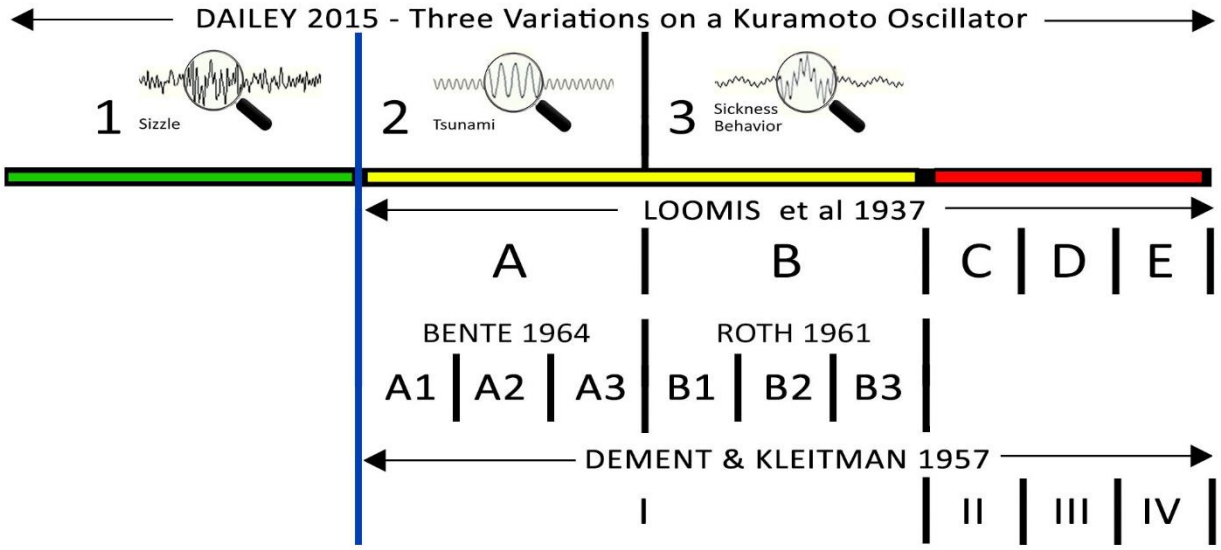
descriptive words “sizzle, tsunami, and sickness behavior” With feedback we can learn to directly regulate our own state of awakeness by plotting our own course on the continuum.

The illustration below shows how these three modes **map to current models** of progressive stages of drowsiness and sleep.

Note that the same left-to-right changes in the EEG below are seen in progression toward sickness behavior as well as in falling asleep. Both are characterized by loss of consciousness and reduction of connectivity. Movements toward the left (below) are characteristic of clinical improvement in a wide variety of conditions. They are also characteristic of normal development. **Such changes in complexity are easy to see during neurofeedback**.

Note that only my stages 2 and 3 (tsunami and sickness behavior) are mapped to the changes in EEG sleep states. These two states also describe conventional vigilance models. The German term vigilanze was originally used by Sir Henry Head to refer to a quality in the behavior of some brain trauma patients that enabled them ultimately to reconnect, adapt and survive. He saw the reduction of vigilance in the behavior of those who experienced withdrawal, disconnection, apoptosis of the self and death.

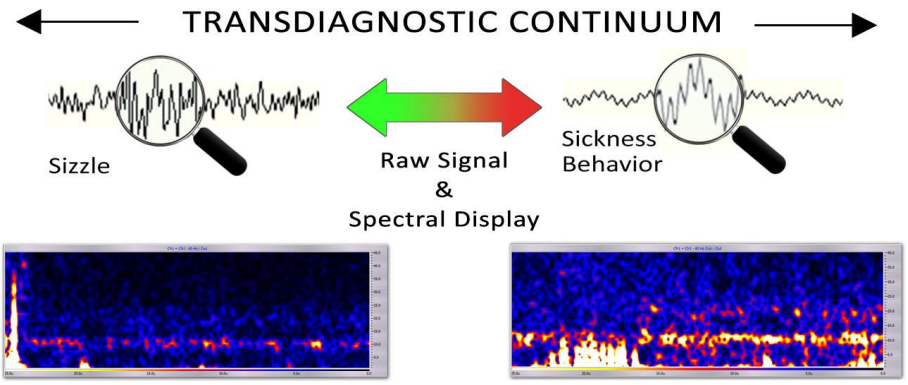
European electroencephalographers such as Lairy, Ey, Bente, Ulrich and others have pointed out that the spontaneous resting EEG can be used to confirm movements along the vigilance continuum. The Kuramoto oscillator model has reframed and extended their observations.



My Kuramoto Oscillator model suggests that there is something to the left of simple vigilance or average awakeness. I call Variation 1 (above) “Sizzle” to describe the waveform. It looks like an audio recording of a random white noise process. However, the adapting EEG moves toward a non-random process called 1/f or pink noise that can look similar. A characteristic of the EEG is that the network will use adjustments of phase of the lower frequency signals in order to

control the amplitude of the higher frequency signals. This is called Phase-Amplitude Cross-Frequency Coupling (PACFC). CFC is the basis for the timbre of an instrument as well as its playability.

In the figure below I suggest a transdiagnostic continuum or dimension that can signal movement toward or away from canonical sickness behavior and/or reduction in consciousness. This document explores the role of adaptive complexification in remediating many types of sickness behavior and in so doing reveals its transdiagnostic significance.



Complexity (sizzle on the left above) has a fractal nature. When you zoom in on a fractal you see more fractal content and information. When you zoom in on sickness behavior you see a simple close-up of fast waves riding on slow waves. Both spectral displays above are from the same client. The display on the left shows the result of several sessions of live complexity training. Note the reduction in fast beta waves riding on top of slower theta waves (as shown on the right.)

Please review the literature below and at livecomplexitytraining.com regarding the role of complexification in clinical and functionally significant conditions. And below, in Appendix 2, you see how this model of adaptive complexification explains fundamental behavior in several different signal types (EEG, HRV, GSR, EMG, nIRS, DTI, MRI, center of balance, metabolic fluctuations, etc).

Adaptogens are factors or interventions that shift the signal to the left towards increased complexity, diversity, creativity, skillful means, etc . Restful sleep, optimal nutrition, social support, natural movement and adaptive maturation are among the best examples of adaptogens. Anti-adaptogens are factors that shift the signal towards the right where they display loss of diversity, habitual limited patterns, fast waves riding on slow waves, and sickness behavior. Anti-adaptogens include trauma, toxins, autosuggestion, non-recuperative sleep, social stress, dysbiosis, epigenetic and metabolic factors, etc. Adaptogens can be neutralized by anti-adaptogens. The balance between adaptogens and anti-adaptogens determines clinical progression.

Because the EEG is a biomarker of movement along the transdiagnostic continuum it can also be used to observe the effects of the balance between adaptogens and anti-adaptogens as a result of functional medicine interventions and lifestyle engineering. Balance in the form of self-organized criticality is nature's only way of generating complexity.

In Live Complexity Training – LCT – the trainee can get real-time EEG feedback about state changes involving body, feelings and mind. For example, habitual maladaptive patterns of posture, breathing and thinking (e.g., rumination) can show very quickly in the instruments and give useful feedback to the trainee.

Learning to identify adaptive complexification in the signals can help guide any sort of intervention. Such changes can also be used in live complexity training (LCT). Adaptive complexification is the direction nature displays in the evolution from reptiles to mammals, in evolution from matters of the cradle to matters of the council, in waking up from sleep, in recovering from sickness behavior, and in developing skillful means in matters of body, feelings and mind.

LCT explains and supports those changes.

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Acupuncture ▲

Xu Y, et al (2018) - **A New Theory for Acupuncture: Promoting Robust Regulation**. Acupunct Meridian Stud 2018 Feb;11(1):39-43. [FULL TEXT]

> Acupuncture does not directly eliminate pathogenic factors or pathological tissue; rather, acupuncture enhances the ability of the human body to self-medicate itself by activating complex regulatory systems and by maintaining physiological homeostasis to prevent or treat diseases. ...Acupuncture is a regulatory way of stimulating the complex systems in the body.

Lin D, et al (2018) - **Analysis on Insomniac Electroencephalogram Data after Treatment with Superficial Needling Based on Approximate Entropy and Correlation Dimensionality**. Zhen Ci Yan Jiu 2018 Mar 25;43(3):180-4. [ABSTRACT]

> …during superficial needling stimulation of Shangen point, the EEG signals were lowered in complexity, and improved in synchronization, stabilization and ordering, favoring sleep at last.

Yuehua G, et al (2017) - **Complexity analysis of EEG under magnetic stimulation on acupoint of Guangming (GB37).** Conf Proc IEEE Eng Med Biol Soc 2017 Jul;2017:2316-2319. [ABS]

> EEG complexity during magnetic stimulation at GB37 was significantly higher than that at the mock point in frontal area, central area and parietal area (electrodes F3, Cz, C4 and P3). Second, EEG signals in central area and parietal area (electrodes C4 and P3) resulting from visual stimulation differed depending on whether magnetic stimulation at GB37 was given. The study has important significance for the application of magnetic stimulation on acupoints.

Ma Y, et al (2016) - **Traditional Chinese medicine: potential approaches from modern dynamical complexity theories**. Front Med. 2016 Mar;10(1):28-32. [ABS]

Yu H-L, et al (2016) - **Magnetic stimulation at Neiguan (PC6) acupoint increases connections between cerebral cortex regions**. Neural Regen Res 2016 Jul;11(7):1141-6. [FULL TEXT]

Pei X, et al (2014) - **WLPVG approach to the analysis of EEG- based functional brain network under manual acupuncture.** Cogn Neurodyn. 2014 Oct; 8(5):417-28. [FULL TEXT]

> In this research, EEG-based functional brain network is built and analyzed through a new wavelet limited penetrable visibility graph (WLPVG) approach. …Manual acupuncture can influence the complexity of EEG sub-bands in different ways and lead the functional brain networks to obtain higher efficiency and stronger small-world property compared with pre- acupuncture control state.

Yi G, et al (2013) - **Multi-scale order recurrence quantification analysis of EEG signals evoked by manual acupuncture in healthy subjects**. Cogn Neurodyn. 2013 Feb; 7(1):79-88. [ABS]

> "By analyzing the complexity of five EEG rhythms, it is found that the complexity of delta rhythm during acupuncture is lower than before acupuncture, and for alpha rhythm is higher, but for beta, theta and gamma rhythms there are no obvious changes.

All of those effects are especially obvious during acupuncture with frequency of 200 times/min."

Addiction ▲

Sevel L, et al (2020) - **Acute Alcohol Intake Produces Widespread Decreases in Cortical Resting Signal Variability in Healthy Social Drinkers**. Alcohol Clin Exp Res. 2020 May 29. [ABS]

> Findings indicate that alcohol intake produces diffuse reductions in fMRI resting signal variability among structures associated with attentional processes. Within these structures, signal complexity was also reduced in a subset of frontal regions. Neurobehavioral effects of acute alcohol consumption may be partially driven by disruption of intraregional neural dynamics among regions involved in higher-order cognitive and attentional processes.

Minnerly C, et al (2019) - **Estimating Mental Health Conditions of Patients with Opioid Use Disorder**. J Addict. 2019; 2019: 8586153. [FULL TEXT]

> Compared to healthy controls, the spectral powers at low frequencies (<8 Hz; δ and ϑ) were increased in most electrodes across the scalp, while powers at the high frequencies (>12 Hz; β and γ) were selectively increased only at electrodes located in the frontal and central scalp. [This is the at the extreme end of the transdiagnostic EEG biomarker for sickness behavior – D Dailey]

Laprevote V, et al (2017) - **Association between increased EEG signal complexity and cannabis dependence.** Eur Neuropsychopharmacol 2017 Dec;27(12):1216-1222. [ABS]

> ...regular cannabis use can impair the capacity to synchronize neural assemblies during specific tasks...Brain complexity was estimated using Lempel-Ziv Complexity (LZC)...cannabis dependence is associated to an increased spontaneous brain complexity in regular users. This result is in line with previous results in acute cannabis users. It may reflect increased randomness of neural activity in cannabis dependence.

Zhao Q, et al (2017) **- Nonlinear Dynamic Complexity and Sources of Resting-state EEG in Abstinent Heroin Addicts**. IEEE Trans Nanobioscience. 2017 Jul;16(5):349-355. [ABS]

> The results of nonlinear characteristics (e.g., the correlation dimension, Kolmogorov entropy, and Lempel-Ziv complexity) showed that the EEG signals in alpha band from AHAs were significantly more irregular.

Kobrin KL, et al (2016) - **Acquisition of morphine conditioned place preference increases the dendritic complexity of nucleus accumbens core neurons**. Addict Biol. 2016 Nov;21(6):1086-1096. [ABS]

Chang JS, et al (2015) - **Altered cardiorespiratory coupling in young male adults with excessive online gaming.** Biol Psychol. 2015 Sep;110:159-66. [ABS]

> During video game play, reduced cardiorespiratory coupling (CRC) was observed in individuals with PIU (problematic internet use) excessive gaming type compared with controls, implicating central autonomic dysregulation. The PIU tendency was associated with the severity of autonomic dysregulation.

Zhang D, et al (2014) - **Nicotine exposure increases the complexity of dopamine neurons in the parainterfascicular nucleus (PIF) sub-region of VTA**. J Neuroeng Rehabil. 2014 Jun 12;11:103. [FULL TEXT]

> Our results have shown that the local field potentials corresponding to the neurons located in the PIF region of the VTA have ApEn values significantly higher ($p = 2x10\text{-}4$) in the maternal nicotine cases when compared to the saline.

Chen TY, et al (2011) - **Complexity of VTA DA neural activities in response to PFC transection in nicotine treated rats.** J Neuroeng Rehabil. 2011 Feb 27;8:13. [FULL TEXT]

> Our findings suggest that PFC plays a vital role in mediating VTA activity. We speculate that increased firing complexity with acute nicotine administration in PFC intact subjects is due to the close functional coupling between PFC and VTA. This hypothesis is supported by the fact that deletion of PFC results in minor alterations of VTA DA neural firing when nicotine is acutely administered.

Aging ▲

Zheng H, et al (2020) - **Reduced Dynamic Complexity of BOLD Signals Differentiates Mild Cognitive Impairment from Normal Aging**. Front Aging Neurosci. 2020; 12: 90. [FULL TEXT]

> Notably, the reduction of BOLD signal complexity in the rostral anterior cingulate cortex was significantly associated with greater risk of progression to AD. The present study thus identified Multi-Scale Entropy as a potential imaging biomarker for the early diagnosis of pre-clinical Alzheimer's disease and provides further insights into the neuropathology of cognitive decline in prodromal AD

Müller V, et al (2019) - **Lifespan Changes in Network Structure and Network Topology Dynamics during Rest and Auditory Oddball Performance**. Front Aging Neurosci. 2019 Jun 11;11:138. [FULL TEXT]

> Both variability and complexity of Hyper-Frequency Networks were strongly related to the perceptual speed scores. …We conclude that network variability and complexity measures reflect temporal and structural topology changes in the functional organization and reorganization of neuronal cell assemblies across the lifespan.

Dong J, et al (2018) - **Hurst Exponent Analysis of Resting-State fMRI Signal Complexity across the Adult Lifespan.** Front Neurosci. 2018; 12: 34. [FULL TEXT]

> …healthy aging is accompanied by a loss of complexity in frontal and parietal lobe and increased complexity in insula, limbic, and temporal lobe. …Hurst Exponent Analysis may serve as a new parameter to assess healthy aging process.

Jia Y, et al (2017) - **Sample entropy reveals an age-related reduction in the complexity of dynamic brain.** Sci Rep. 2017 Aug 11;7(1):7990. [FULL TEXT]

> A brainwide map of SampEn in healthy subjects shows larger values in the caudate, the olfactory gyrus, the amygdala, and the hippocampus, and lower values in primary sensorimotor and visual areas. Association analysis in healthy subjects indicated that SampEn of the amygdala-cortical connectivity decreases with advancing age. Such age-related loss of SampEn, however, disappears in patients with schizophrenia. These findings suggest that SampEn of the dynamic functional connectivity is a promising indicator of normal aging.

Chatterjee A, et al (2017) - **Aging and efficiency in living systems: Complexity, adaptation and self-organization.** Mech Ageing Dev. 2017 Apr;163:2-7. [ABS]

> In order to support our claims, we draw parallels between technological progress and biological growth. Such parallels are used to support the universal applicability of the metrics and the methodology presented in this paper.

Ishii R, et al (2017) - **Healthy and Pathological Brain Aging: From the Perspective of Oscillations, Functional Connectivity, and Signal Complexity**. Neuropsychobiology. 2017;75(4):151-161. [ABS]

Madan CR, et al (2016) - **Cortical complexity as a measure of age-related brain atrophy**. Neuroimage. 2016 Jul 1;134:617-29. [FULL TEXT]

> Initially computing a single measure for the entire cortical ribbon, i.e., unparcellated gray matter, we found fractal dimensionality to be more sensitive to age-related differences than either cortical thickness or gyrification index.

Ueno K, et al (2015) - **Neurophysiological basis of creativity in healthy elderly people: a multiscale entropy approach.** Clin Neurophysiol. 2015 Mar; 126(3):524-31. [ABS]

> "Considering the general "loss of complexity" theory of aging, our finding of increased EEG complexity in elderly people with heightened creativity supports the idea that creativity is associated with activated neural networks."

Zappasodi F, et al (2015) - **Age-Related Changes in Electroencephalographic Signal Complexity**. PLoS One. 2015 Nov 4;10(11):e0141995. [FULL TEXT]

> Since fractal dimension has been proposed to be related to the complexity of the signal dynamics, our data demonstrate that the complexity of neuronal electric activity changes across the life span of an individual, with a steady increase during young adulthood and a decrease in the elderly population.

Wang CH, et al (2014) - **The association of physical activity to neural adaptability during visuo-spatial processing in healthy elderly adults**: A multiscale entropy analysis. Brain Cogn. 2014 Oct 29; 92C:73-83. [ABS]

> We observed that physically active elderly adults had better accuracy on both visuo-spatial attention and working memory conditions relative to their sedentary counterparts. Additionally, these physically active elderly adults displayed greater MSE

values at larger time scales at the Fz electrode in both attention and memory conditions." MSE = Multiscale Entropy. "

Ihl R, et al (1999) - **Differential diagnosis of aging, dementia of the Alzheimer type and depression with EEG-segmentation**. Dement Geriatr Cogn Disord. 1999 Mar-Apr;10(2):64-9. [ABS]

> EEG segmentation can be used to measure altered brain function in aging and diseases of the brain. The parameter 'number of different segments' makes clear how many different potential fields are involved in brain activity during a given period of time.
>
> Aged patients with endogenous depression had more different segments than patients with mild DAT (dementia, Alzheimer type). The reduction of the number of different segments in DAT compared to controls and patients suffering from depression may be helpful for differential diagnosis. *The higher number of different segments in aged versus young controls could be interpreted as a sign of increased complexity in the aged brain.*

Anokhin AP, et al (1996) - **Age increases brain complexity**. Electroencephalogr Clin Neurophysiol. 1996 Jul; 99(1):63-8. [ABS]

> "Thus, the "wisdom of old age' may find its neurophysiological basis in greater complexity of brain dynamics compared to young ages." "The results confirm the hypothesis: after a jump in the brain dynamics complexity during puberty a linear increase with age is observed. During maturation (7-25 years), the maximum gain in complexity occurs over the frontal associative cortex."

Alzheimer's Disease & Dementia ▲

Zheng H, et al (2020) - **Reduced Dynamic Complexity of BOLD Signals Differentiates Mild Cognitive Impairment from Normal Aging**. Front Aging Neurosci. 2020; 12: 90. [ABS]

> Notably, the reduction of BOLD signal complexity in the rostral anterior cingulate cortex was significantly associated with greater risk of progression to AD. The present study thus identified Multi-Scale Entropy as a potential imaging biomarker for the early diagnosis of pre-clinical Alzheimer's disease and provides further insights into the neuropathology of cognitive decline in prodromal AD

Gutierrez-de Pablo V, et al (2020) - **Relationship between the Presence of the ApoE ε 4 Allele and EEG Complexity along the Alzheimer's Disease Continuum**. Sensors (Basel) 2020 Jul 10;20(14):E3849. [ABS]

> Our results showed that AD continuum is characterized by a progressive complexity loss.

Nobukawa S, et al (2020) - **Classification Methods Based on Complexity and Synchronization of Electroencephalography Signals in Alzheimer's Disease.** Front Psychiatry. 2020 Apr 7;11:255. [FULL TEXT]

> Cortical disconnection, which is induced by the pathological progression of AD, leads to impairment in the interaction between different brain regions; consequently reducing functional connectivity and complexity.

Wang XW, et al (2019) - **Sample entropy and surrogate data analysis for Alzheimer's disease.** Math Biosci Eng. 2019 Jul 29;16(6):6892-6906. [FULL TEXT]

> …the SampEn of AD patients was significantly decreased ($p < 0:01$) at electrodes c3, f3, o2 and p4, which confirmed that AD could cause complexity loss. …Our method is capable of distinguishing AD patients from healthy subjects, which is consistent with the concept of physiologic complexity, and providing insights for understanding of AD.

Perpetuini D, et al (2019) - **Autonomic impairment in Alzheimer's disease is revealed by complexity analysis of functional thermal imaging signals during cognitive tasks**. Physiol Meas. 2019 Mar 22;40(3):034002. [ABS]

> AD patients exhibited lower complexity of fIRI (functional infrared imaging) signals during the tests, which could be indicative of a stronger sympathetic activity with respect to HC. No significant effects were found at rest. No differences were found on employing frequency-based analysis.

Nobukawa S, et al (2019) - **Atypical temporal-scale-specific fractal changes in Alzheimer's disease EEG and their relevance to cognitive decline.** Cogn Neurodyn. 2019 Feb;13(1):1-11. [FULL TEXT]

> …the AD group demonstrated reduced fractality at both slow and fast temporal scales. Moreover, we confirmed that the fractality at fast temporal scales correlates with cognitive decline. These properties might serve as a basis for a useful approach to characterizing temporal neural dynamics in AD or other neurodegenerative disorders.

Grieder M, et al (2018) - **Default Mode Network Complexity and Cognitive Decline in Mild Alzheimer's Disease.** Front Neurosci. 2018; 12: 770. [FULL TEXT]

> Conclusively, a loss of nodal signal complexity potentially impairs synchronization across nodes and thus preempts functional connectivity changes. MSE presents a putative functional marker for cognitive decline that might be more sensitive than functional connectivity alone.

Fan M, et al (2018) - **Topological Pattern Recognition of Severe Alzheimer's Disease via Regularized Supervised Learning of EEG Complexity**. Front Neurosci. 2018 Oct 4;12:685. [FULL TEXT]

> …the long-term complexity of EEG signals decreases with the severity of AD.

Mazzon G, et al (2018) - **Memorization Test and Resting State EEG Components in Mild and Subjective Cognitive Impairment.** Curr Alzheimer Res. 2018;15(9):809-819. [ABS]

> EEG complexity reduction - that has been found already in SCI - could be a possible early hallmark of AD.

Li X, et al (2018) - **Decreased resting-state brain signal complexity in patients with mild cognitive impairment and Alzheimer's disease: a multiscale entropy analysis.** Biomed Opt Express. 2018 Apr 1; 9(4): 1916–1929. [FULL TEXT]

> The quantitative analysis of MSE revealed that reduced brain signal complexity in AD patients in several networks, namely, the default, frontoparietal, ventral and dorsal attention networks. For the default and ventral attention networks, the MSE values also showed significant positive correlations with cognitive performances. These findings demonstrated that the MSE-based analysis method could serve as a novel tool for fNIRS study in characterizing and understanding the complexity of abnormal cortical signals in AD cohorts.

Houmani N, et al (2018) - **Diagnosis of Alzheimer's disease with Electroencephalography in a differential framework**. PLoS One. 2018 Mar 20;13(3):e0193607. [FULL TEXT]

> We show that two EEG features, namely epoch-based entropy (a measure of signal complexity) and bump modeling (a measure of synchrony) are sufficient for efficient discrimination between these groups.

Wang J, et al (2017) - **Enhanced Gamma Activity and Cross-Frequency Interaction of Resting-State Electroencephalographic Oscillations in Patients with Alzheimer's Disease**. Front Aging Neurosci. 2017 Jul 26;9:243. [FULL TEXT]

> We propose that the pathological increase of ongoing gamma-band power might result from the disruption of the GABAergic interneuron network in AD patients. Furthermore, the cross-frequency over-couplings, which reflect the enhanced synchronization, might indicate the attenuated complexity of the neuronal network, and AD patients have to use more neural resources to maintain the resting brain state. Overall, our findings provide new evidence of the disturbance of the brain oscillation network in AD and further deepen our understanding of the central mechanisms of AD.

Deng B, et al (2017) - **Multivariate multi-scale weighted permutation entropy analysis of EEG complexity for Alzheimer's disease**. Cogn Neurodyn. 2017 Jun;11(3):217-231. [ABS]

> ...the EEG analysis results show that in contrast with the normal group, the significantly decreased complexity of AD patients is distributed in the temporal and occipitoparietal regions for the theta and the alpha bands, and also distributed from the right frontal to the left occipitoparietal region for the theta, the alpha and the beta bands at each time scale, which may be attributed to the brain dysfunction. Therefore, it suggests that the MMSWPE method may be a promising method to reveal dynamic changes in AD.

Morabito FC, et al (2016) - **Deep Learning Representation from Electroencephalography of Early-Stage Creutzfeldt-Jakob Disease and Features for Differentiation from Rapidly Progressive Dementia.** Int J Neural Syst. 2016 May 3:1650039. [ABS]

> A novel technique of quantitative EEG for differentiating patients with early-stage Creutzfeldt-Jakob disease (CJD) from other forms of rapidly progressive dementia (RPD) is proposed. The discrimination is based on the extraction of suitable features from the time-frequency representation of the EEG signals through continuous wavelet transform

(CWT). An **average measure of complexity of the EEG signal obtained by permutation entropy (PE)** is also included

Weyerman JJ, et al (2016) - **Personal Journal Keeping and Linguistic Complexity Predict Late-Life Dementia Risk: The Cache County Journal Pilot Study**. J Gerontol B Psychol Sci Soc Sci. 2016 Jul 8. pii: gbw076. [ABS]

> In the larger sample, ever being a journal writer significantly predicted a 53% reduction in all-cause dementia risk. In the subsample with transcribed writings, Percentage of 6+ Letter Words predicted AD and all-cause dementia risk, with all logistic regression models controlling for age, education, gender, and Latter-Day Saints affiliation.

Liu X, et al (2016) - **Multiple characteristics analysis of Alzheimer's electroencephalogram by power spectral density and Lempel-Ziv complexity**. Cogn Neurodyn. 2016 Apr; 10(2): 121–133. [FULL TEXT]

Zueva MV, et al (2015) **- Fractality of sensations and the brain health: the theory linking neurodegenerative disorder with distortion of spatial and temporal scale-invariance and fractal complexity of the visible world**. Front Aging Neurosci. 2015 Jul 15;7:135. [FULL TEXT]

Bertrand JA, et al (2015) - **Brain Connectivity Alterations Are Associated with the Development of Dementia in Parkinson's Disease**. Brain Connect. 2016 Apr;6(3):216-24. [ABS]

> Brain connectivity EEG measures, such as multiscale entropy (MSE) and phase-locking value (PLV) analyses, may be more informative and sensitive to brain alterations leading to dementia than previously used methods. …Patients who developed dementia showed higher signal complexity and lower PLVs in low frequencies (mainly in delta frequency) than patients who remained dementia-free and controls. Conversely, both patient groups showed lower signal variability and higher PLVs in high frequencies (mainly in gamma frequency) compared to controls, with the strongest effect in patients who developed dementia. These findings suggest that specific disruptions of brain communication can be measured before PD patients develop dementia, providing a new potential marker to identify patients at highest risk of developing dementia and who are the best candidates for neuroprotective trials.

Jimenez-Rodríguez A, et al (2015) - **The shape of dementia: new measures of morphological complexity in event-related potentials (ERP) and its application to the detection of Alzheimer's disease.** Med Biol Eng Comput. 2015 Sep;53(9):889-97. [ABS]

> …we propose two new measures of complexity which relate the spectral content of the signal with its temporal waveform: the spectral matching coefficient and the spectral matching entropy. …The results indicate that AD ERP signals are, indeed, more complex in the shape than that of controls, and this result is evidenced mainly by means of our new measures which have a better performance compared to similar ones.

Azami H, et al (2015) - **Evaluation of resting-state magnetoencephalogram complexity in Alzheimer's disease with multivariate multiscale permutation and sample entropies**. Conf Proc IEEE Eng Med Biol Soc. 2015;2015:7422-5. [ABS]

Alzheimer's disease (AD) is one of the fastest growing neurological diseases in the world. We evaluate multivariate multiscale sample entropy (mvMSE) and multivariate multiscale permutation entropy (mvMPE) approaches to distinguish resting-state magnetoencephalogram (MEG) signals of 36 AD patients from those of 26 normal controls.

In most scale factors, the average of the mvMPE and mvMSE values of AD patients are lower than those of controls.

Carlino E, et al (2014) - **Nonlinear analysis of electroencephalogram in frontotemporal lobar degeneration.** Neuroreport. 2014 May 7; 25(7):496-500. [ABS]

"A nonlinear measure of complexity, correlation dimension (D2), was calculated. Our results show an increase in D2 in healthy individuals when the eyes are open, in keeping with an increase in information processing. Conversely, in FTLD patients, no increase in D2 occurred in the open eyes condition, and D2 was significantly lower than that observed in controls."

Zhang M, et al (2014) - **Wavelet entropy analysis of spontaneous EEG signals in Alzheimer's disease**. Sheng Wu Yi Xue Gong Cheng Xue Za Zhi. [ABS]

…wavelet entropy for mild, moderate, severe AD patients was significantly lower than that for normal controls, which was related to the narrow distribution of their wavelet power spectrums. …further studies showed that the wavelet entropy of EEG and the MMSE score were significantly correlated (r= 0. 601-0. 799, P<0.01). Wavelet entropy is a quantitative indicator describing the complexity of EEG signals. Wavelet entropy is likely to be an electrophysiological index for AD diagnosis and severity assessment.

Yang AC, et al (2013) - **Cognitive and neuropsychiatric correlates of EEG dynamic complexity in patients with Alzheimer's disease**. Prog Neuropsychopharmacol Biol Psychiatry. 2013 Dec 2; 47:52-61. [ABS]

"Increased severity of AD was associated with decreased MSE complexity as measured by short-time scales, and with increased MSE complexity as measured by long-time scales. MSE complexity in EEGs of the temporal and occipito-parietal electrodes correlated significantly with cognitive function. MSE complexity of EEGs in various brain areas was also correlated to subdomains of neuropsychiatric symptoms. **MSE analysis revealed abnormal EEG complexity across short- and long-time scales that were correlated to cognitive and neuropsychiatric assessments.** The MSE-based EEG complexity analysis may provide a simple and cost-effective method to quantify the severity of cognitive and neuropsychiatric symptoms in AD patients."

Labate D, et al (2012) - **Complexity Analysis of Alzheimer Disease EEG Data through Multiscale Permutation Entropy**. Proceedings of the 7th International Workshop on Biosignal Interpretation (BSI2012). [FULL TEXT]

AD has 3 main effects on the EEG - 1) slowing, i.e., increased low frequency power plus reduction of mean frequency, 2) reduced complexity and increased regularity of EEG, and 3) loss of synchrony.

Xu J, et al (2012) - **Approximate entropy analysis of event-related potentials in patients with early vascular dementia.** J Clin Neurophysiol. 2012 Jun;29(3):230-6. [ABS]

> The results indicate that patients with VD have fewer attention resources to devote to processing stimuli, lower speed of stimulus classification, and **lower synchrony in their cortical activity during the response period.** We suggest that ApEn, as a measure of ERP complexity, is a promising marker for early diagnosis of VD.

Staudinger T, et al (2011) - **Analysis of complexity based EEG features for the diagnosis of Alzheimer's disease.** Conf Proc IEEE Eng Med Biol Soc. 2011;2011:2033-6. [ABS]

> These measures include: Higuchi fractal dimension (HFD), spectral entropy (SE), spectral centroid (SC), spectral roll-off (SR), and zero-crossing rate (ZCR). HFD is a quantitative measure of time series complexity derived from fractal theory. … Combining these features and training a support vector machine (SVM) resulted in a diagnostic accuracy of 78%, indicating that these feature carry complementary information.

Dauwels J, et al (2011) - **Slowing and Loss of Complexity in Alzheimer's EEG: Two Sides of the Same Coin?** Int J Alzheimers Dis. 2011 Apr 13;2011:539621. [FULL TEXT]

> Medical studies have shown that EEG of Alzheimer's disease (AD) patients is "slower" (i.e., contains more low-frequency power) and is less complex compared to age-matched healthy subjects. …Strong correlation between slowing and loss of complexity is observed in two independent EEG datasets: (1) EEG of predementia patients (a.k.a. Mild Cognitive Impairment; MCI) and control subjects; (2) EEG of mild AD patients and control subjects.

Lou W, et al (2011) - **Multichannel linear descriptors analysis for event-related EEG of vascular dementia patients during visual detection task.** Clin Neurophysiol. 2011 Nov;122(11):2151-6. [ABS]

> The results indicated the VaD patients presented a **reduction of synchronization in the slow frequency band during target detection**, and suggested more neurons might be activated in VaD patients compared with normal controls.

Molnár M, et al (2011) - **Ageing and arithmetic performance, electrophysiological complexity-, and graph theoretical characteristics.** Ideggyogy Sz. 2011 Jan 30;64(1-2):41-9. [ABS]

Snyder SM, et al (2011) - **Addition of EEG improves accuracy of a logistic model that uses neuropsychological and cardiovascular factors to identify dementia and MCI.** Psychiatry Res. 2011 Mar 30;186(1):97-102. [ABS]

> We found that the addition of EEG (non-linear complexity) to a logistic model that included both neuropsychological assessment (ADAS-Cog) and cardiovascular history increased overall accuracy from 80% to 92%. Whereas the analysis is limited by small sample sizes and mixing of diverse pathologies, the findings do provide support that the subgroups may share changes in neuropsychological, cardiovascular, and electroencephalographic factors (specifically ADAS-Cog total score, cardiovascular history, and EEG complexity).

Missonnier P, et al (2010) - **Early disturbances of gamma band dynamics in mild cognitive impairment.** J Neural Transm (Vienna). 2010 Apr;117(4):489-98. [ABS]

> Gamma fractal dimension of progressive mild cognitive impairment (PMCI) cases displayed significantly higher gamma fractal dimension values compared to stable (SMCI) cases.

Cantero JL, et al (2009) - **Increased synchronization and decreased neural complexity underlie thalamocortical oscillatory dynamics in mild cognitive impairment.** Neuroimage. 2009 Jul 15;46(4):938-48. [ABS]

> In this study, we show that the strength of phase coupling and the level of phase predictability between thalamocortical and cortico-cortical EEG sources of low alpha frequency are abnormally facilitated in MCI patients when compared to healthy elderly subjects. Additionally, we found a loss of neural complexity intrinsic to both thalamic and cortical generators of lower alpha in MCI patients, which likely influenced the aberrant phase synchronization behavior between EEG-alpha sources in this high risk group of AD.

Stevens A, et al (1998) - **Cognitive decline unlike normal aging is associated with alterations of EEG temporo-spatial characteristics.** Eur Arch Psychiatry Clin Neurosci. 1998;248(5):259-66. [ABS]

> Normal aging seems not to be accompanied by changes in temporo-spatial EEG patterns. The data suggest that fragmentation of the electrophysiological processes underlies cognitive dysfunction in Alzheimer's disease.

Yagyu T, et al (1997) - **Global dimensional complexity of multichannel EEG in mild Alzheimer's disease and age-matched cohorts**. Dement Geriatr Cogn Disord. 1997 Nov-Dec;8(6):343-7. [ABS]

> Multichannel EEG as sequence of momentary brain field maps constitutes a trajectory through K-dimensional state space (K = number of channels); the complexity of this trajectory is assessed by the nonlinear measure of global correlation dimension (Global Dimensional Complexity, GDC) with the number of electrodes as embedding dimension…. AD patients differed significantly (GDC = 4.56) from mild cognitive impairments (GDC = 4.98) and from subjective memory complaints (GDC = 4.93). GDC also had significant positive correlations with mental condition and performance (MMSE and WAIS-R scores). Thus, the dynamics of brain state development over time in mild AD differs from that in mild cognitive impairment and in subjective memory complaint cases.

Anesthesia ▲

Kakur M, et al (2020) - **Variations in Electrocortical Activity due to Surgical Incision in Anaesthetized Cardiac Patients: Electroencephalogram-Based Quantitative Analysis**. J Healthc Eng. 2020 Feb 27;2020:4643584. [FULL TEXT]

Pappas I, et al (2019) - **δ-Oscillation Correlates of Anesthesia-induced Unconsciousness in Large-scale Brain Networks of Human Infants**. Anesthesiology. 2019 Dec;131(6):1239-1253. [ABS]

> At the sensor level, complexity decreased during anesthesia, showing less whole-brain integration with prominent alterations in the connectivity of frontal and parietal sensors (median difference, 0.0293; 95% CI, -0.0016 to 0.0397). At the source level, similar results were observed (median difference, 0.0201; 95% CI, -0.0025 to 0.0482) with prominent alterations in the connectivity between default-mode and frontoparietal regions. Anesthesia resulted in fragmented modules as modularity increased at the sensor… Sevoflurane is associated with decreased capacity for efficient information transfer in the infant brain. Such findings strengthen the hypothesis that conscious processing relies on an efficient system of integrated information transfer across the whole brain.

Eagleman SL, et al (2019) - **Nonlinear dynamics captures brain states at different levels of consciousness in patients anesthetized with propofol**. PLoS One. 2019 Oct 30;14(10):e0223921. [FULL TEXT]

> Notably, attractors in conscious and anesthesia-induced unconscious states exhibited significantly different shapes. These shapes have implications for network connectivity, information processing, and the *total number of states available to the brain at these different levels*. They also reflect some of our general understanding of the network effects of consciousness in a way that spectral measures cannot. Thus, *complexity measures could provide a universal means for reliably capturing depth of consciousness* based on EEG changes at the beginning and end of anesthesia administration.

Li D, et al (2019) - **Cortical dynamics during psychedelic and anesthetized states induced by ketamine.** Neuroimage. 2019 Aug 1;196:32-40. [FULL TEXT]

> …the subanesthetic dose of ketamine is associated with an elevated complexity level relative to baseline, while the brain activity following an anesthetic dose of ketamine is characterized by alternating low and high complexity levels until stabilizing at a high level comparable to that during baseline.

Dimitriadis SI (2018) - **Complexity of brain activity and connectivity in functional neuroimaging**. J Neurosci Res. 2018 Nov;96(11):1741-1757. [ABS]

> …we succeeded to totally discriminate healthy controls from schizophrenic using FI and dynamic reconfiguration of DICM. Anaesthesia independently of the drug caused a global decreased of complexity in all frequency bands with the exception in δ…

Eagleman SL, et al (2018) - **Do Complexity Measures of Frontal EEG Distinguish Loss of Consciousness in Geriatric Patients under Anesthesia?** Front Neurosci. 2018 Sep 20;12:645. [FULL TEXT]

> Our results suggest that our new spectral and complexity measures are capable of capturing subtle differences in EEG activity with anesthesia administration…

Padley JR, et al (2018) - **Low pre-operative heart rate variability and complexity are associated with hypotension after anesthesia induction in major abdominal surgery**. J Clin Monit Comput. 2018 Apr;32(2):245-252. [ABS]

> … post-induction hypotension and lower HRV may be associated with severity of illness or poor physiological reserve. Pre-operative HRV was a useful screening tool in identifying patients undergoing major abdominal surgery who were at risk of haemodynamic instability after anesthesia induction.

Rotz RV, et (2017) - **Neuronal oscillations and synchronicity associated with gamma-hydroxybutyrate during resting-state in healthy male volunteers**. Psychopharmacology (Berl). 2017 Jul;234(13):1957-1968. [ABS]

> Compared to placebo, GHB increased CSD of theta oscillations (5-7 Hz) in the posterior cingulate cortex and alpha1 (8-10 Hz) oscillations in the anterior cingulate cortex. Higher blood plasma values were associated with higher lagged phase synchronization values of delta (2-4 Hz) oscillations between the PCC and the right inferior parietal lobules. Additionally, GHB decreased Global Omega Complexity of alpha1 oscillations.

Wang J, et al (2017) - **Suppressed neural complexity during ketamine- and propofol-induced unconsciousness**. Neurosci Lett. 2017 Jul 13;653:320-325. [ABS]

> Both ketamine and propofol reduced the complexity of the EEG signal, but ketamine increased the randomness of the signal and propofol decreased it. The finding supports our claim and suggests EEG complexity as a candidate for a consciousness indicator.

Hudetz AG, et al (2016) - **Propofol anesthesia reduces Lempel-Ziv complexity of spontaneous brain activity in rats.** Neurosci Lett. 2016 Aug 15;628:132-5. [FULL TEXT]

Schartner M, et al (2015) - **Complexity of Multi-Dimensional Spontaneous EEG Decreases during Propofol Induced General Anaesthesia**. PLoS ONE 10(8): e0133532. [FULL TEXT]

> Using the novel “synchrony coalition entropy” and Kuramoto oscillator simulations the authors show “a robustly measurable decrease in the complexity of spontaneous EEG during general anaesthesia.”

Sarasso S, et al (2015) - **Consciousness and Complexity during Unresponsiveness Induced by Propofol, Xenon, and Ketamine**. Curr Biol. 2015 Dec 7;25(23):3099-105. [FULL TEXT]

> Both frontal and parietal TMS elicited a low-amplitude electroencephalographic (EEG) slow wave corresponding to a local pattern of cortical activation with low complexity during propofol anesthesia, a high-amplitude EEG slow wave corresponding to a global, stereotypical pattern of cortical activation with low complexity during xenon anesthesia, and a wakefulness-like, complex spatiotemporal activation pattern during ketamine anesthesia. Crucially, participants reported no conscious experience after emergence from propofol and xenon anesthesia, whereas after ketamine they reported long, vivid dreams unrelated to the external environment. These results are relevant because they suggest that brain complexity may be sensitive to the presence of disconnected consciousness in subjects who are considered unconscious based on behavioral responses.

Bai Y, et al (2015) - **Permutation Lempel-Ziv complexity measure of electroencephalogram in GABAergic anaesthetics**. Physiol Meas. 2015 Dec;36(12):2483-501. [ABS]

> Monitoring the brain state in anaesthesia is crucial for clinical doctors. In this study, we propose a novel nonlinear method, the permutation Lempel-Ziv complexity (PLZC) index, which describes the complexity in the electroencephalographic (EEG) signal to quantify the effect of GABAergic anaesthetics on brain activities. This index outperformed LZC, PE, CPEI, RE, SE, and BIS or SFS in tracking drug concentration changes during GABAergic anaesthetics. PLZC is a potentially superior method for applications in intra-operative monitoring.

Angelman Syndrome ▲

Frohlich J, et al (2020) - **High-voltage, diffuse delta rhythms coincide with wakeful consciousness and complexity in Angelman syndrome**. Neurosci Conscious. 2020 Jun 14;2020(1):niaa005. [FULL TEXT]

> These findings (i) warn against reverse inferring an absence of consciousness solely on the basis of high-amplitude EEG delta oscillations, (ii) corroborate rare observations of preserved consciousness under hypersynchronization in other conditions, (iii) identify biomarkers of consciousness that have been validated under conditions of abnormal cortical dynamics, and (iv) *lend credence to theories linking consciousness with complexity*.

Anxiety ▲

de la Torre-Luque A, et al (2016) - **Complexity and nonlinear biomarkers in emotional disorders: A meta-analytic study**. Neurosci Biobehav Rev. 2016 Sep;68:410-422. [ABS]

> Results revealed that anxious patients exhibited lower complexity than controls ($p<0.05$) despite panic patients showed more irregular respiratory activity. Inconclusive results were found for bipolar patients but pointed to higher randomness when suffering manic episodes. Finally, depressed patients showed a loss of complexity in the cardiac system and a loss of orderliness (despite a higher complexity) in brain and stress-related hormonal systems. As a conclusion, our findings highlight that either a loss of complexity or a loss of ordered complexity characterize the physiological systems of patients with emotional disorders.

Aydin S, et al (2015) - **Classification of obsessive compulsive disorder by EEG complexity and hemispheric dependency measurements.** Int J Neural Syst. 2015 May;25(3):1550010. [ABS]

> Particularly, patients are characterized by lower EEG complexity at both pre-frontal regions and right fronto-temporal locations. Our results are compatible with imaging studies that define OCD as a sub group of anxiety disorders exhibited a decreased

complexity (such as anorexia nervosa [Toth et al., Int. J. Psychophysiol.51(3) (2004) 253-260] and panic disorder [Bob et al., Physiol. Res.55 (2006) S113-S119]).

Kim BS, et al (2014) - **Differential regulation of observational fear and neural oscillations by serotonin and dopamine in the mouse anterior cingulate cortex.** Psychopharmacology (Berl). 2014 Nov;231(22):4371-81. [ABS]

> The administration of 5-HT and 5-HT and DA together, but not DA alone, reduced the freezing response of observing mice. 5-HT enhanced delta-band activity and reduced alpha- and gamma-band activities in the ACC, whereas DA reduced only alpha-band activity. Based on entropy, reduced complexity of ACC neural activity was observed with 5-HT treatment. …The current results demonstrated that DA D2 receptors in the ACC are required for observational fear learning, whereas increased 5-HT levels disrupt observational fear and alter the regularity of ACC neural oscillations.

Bornas X, et al (2013) - **Self-focused cognitive emotion regulation style as associated with widespread diminished EEG fractal dimension.** Int J Psychol. 2013;48(4):695-703. [ABS]

> The cognitive regulation of emotions is important for human adaptation. Self-focused emotion regulation (ER) strategies have been linked to the development and persistence of anxiety and depression. …Results showed that a diminished fractal dimensionality (FD) over the scalp significantly correlated with self-focused ER style scores, even after controlling for negative affect, which has been also considered to influence the use of ER strategies. The lower the EEG FD, the higher were the self-focused ER style scores. …The diminished FD of the EEG may reflect a disposition to engage in self-focused ER strategies as people prone to ruminate and self-blame show a less complex resting EEG activity, which may make it more difficult for them to exit their negative emotional state.

Attention Deficit, etc. ▲

Rezaeezadeh M, et al (2020) - **Attention Deficit Hyperactivity Disorder Diagnosis using non-linear univariate and multivariate EEG measurements: a preliminary study.** Phys Eng Sci Med. 2020 Jun;43(2):577-592. [ABS]

> … ADHD children have higher brain activity and TBR compared to normal children… their neural system is more regular. …ADHD children have reduced dynamical complexity of neural system.

Malinowska U, et al (2019) - **Spectral analysis versus signal complexity methods for assessing attention related activity in human EEG.** Conf Proc IEEE Eng Med Biol Soc. 2019 Jul;2019:4517-4520. [ABS]

> We aimed to find the most effective analytical method for assessment of attention related activity to be used in neurofeedback training. We compared commonly used spectral EEG methods with those measuring signal complexity - based on calculation of entropy and fractal dimension. …The results indicated: (i) the importance of the

individual analysis of signals from each subject and session, (ii) benefits of applying signal complexity methods to support spectral analysis in a further application and (iii) an advantage of the signal complexity method, carrying information of assembles of spectral components, over common spectral methods.

Chen H, et al (2019) - **EEG characteristics of children with attention-deficit/hyperactivity disorder.** Neuroscience. 2019 May 15;406:444-456. [ABS]

> …Resting-State EEG complexity of ADHD children was significantly lower than controls and may be a suitable biomarker candidate.

Gu Y, et al (2017) - **Complexity analysis of fNIRS signals in ADHD children during working memory task**. Sci Rep. 2017 Apr 11;7(1):829. [FULL TEXT]

> We found that PE (permutation entropy) values exhibited significantly negative correlation with the cortical activations ($r = -0.515$, $p = 0.003$), and the PE values of right dorsolateral prefrontal cortex in ADHD children were significantly larger than those in normal controls ($p = 0.027$). In addition, the PE values of right dorsolateral prefrontal cortex were positively correlated to the ADHD index ($r = 0.448$, $p = 0.012$). These results suggest that complexity analysis of fNIRS signals could be a promising tool in diagnosing children with ADHD.

Chenxi L, et al (2016) - **Complexity analysis of brain activity in attention-deficit/hyperactivity disorder: A multiscale entropy analysis**. Brain Res Bull. 2016 Jun;124:12-20. [ABS]

> We estimated the MSE by calculating the sample entropy values of delta, theta, alpha and beta frequency bands over twenty time scales using coarse-grained procedure. The results showed increased complexity of EEG data in delta and theta frequency bands and decreased complexity in alpha frequency bands in ADHD children. The findings of this study revealed aberrant neural connectivity of kids with ADHD during interference task. The results showed that MSE method may be a new index to identify and understand the neural mechanism of ADHD.

Zarafshan H, et al (2016) - **Electroencephalogram complexity analysis in children with attention-deficit/hyperactivity disorder during a visual cognitive task**. J Clin Exp Neuropsychol. 2016;38(3):361-9. [ABS]

> The mean LZC of the ADHD children was significantly larger than healthy children over the right anterior and right posterior regions during the cognitive performance. In the ADHD group, complexity of the right hemisphere was higher than that of the left hemisphere, but the complexity of the left hemisphere was higher than that of the right hemisphere in the normal group.

Chenxi L, et al (2016) - **Complexity analysis of brain activity in attention-deficit/hyperactivity disorder: A multiscale entropy analysis.** Brain Res Bull. 2016 Jun;124:12-20. [ABS]

> The multiscale entropy (MSE) is a novel method for quantifying the intrinsic dynamical complexity of physiological systems over several scales…. The results showed increased complexity of EEG data in delta and theta frequency bands and decreased complexity in alpha frequency bands in ADHD children. The findings of this study revealed aberrant

neural connectivity of kids with ADHD during interference task. The results showed that MSE method may be a new index to identify and understand the neural mechanism of ADHD.

Zarafshan H, et al (2016) - **Electroencephalogram complexity analysis in children with attention-deficit/hyperactivity disorder during a visual cognitive task.** J Clin Exp Neuropsychol. 2016;38(3):361-9. [ABS]

> The mean Lempel-Ziv complexity (LZC) of the ADHD children was significantly larger than healthy children over the right anterior and right posterior regions during the cognitive performance. In the ADHD group, complexity of the right hemisphere was higher than that of the left hemisphere, but the complexity of the left hemisphere was higher than that of the right hemisphere in the normal group. CONCLUSION: Although fronto-striatal dysfunction is considered conclusive evidence for the pathophysiology of ADHD, our arithmetic mental task has provided evidence of structural and functional changes in the posterior regions and probably cerebellum in ADHD.

Fagerholm ED, et al (2015) - **Cascades and Cognitive State - Focused Attention Incurs Subcritical Dynamics**. The Journal of Neuroscience, March 18, 2015 • 35(11):4626–4634. [FULL TEXT]

> ...the resting state is associated with near-critical dynamics, in which a high dynamic range and a large repertoire of brain states may be advantageous. In contrast, a focused cognitive task induces subcritical dynamics, which is associated with a lower dynamic range, which in turn may reduce elements of interference affecting task performance.

Zhao Y, et al (2015) - **Brain Vigilance Analysis Based on the Measure of Complexity**. Sheng Wu Yi Xue Gong Cheng Xue Za Zhi. 2015 Aug;32(4):725-9. [ABS]

> The experimental results showed that: PE could well reflect the dynamic changes of EEG when vigilance decreases, and has advantages of fast arithmetic speed, high noise immunity, and low requirements for EEG length. This can be used as a measure of the brain vigilance indicators.

Alba G, et al (2015) - **Electroencephalography signatures of attention-deficit/hyperactivity disorder: clinical utility.** Neuropsychiatr Dis Treat. 2015 Oct 22;11:2755-69. [FULL TEXT]

Cerquera A, et al (2012) - **Nonlinear dynamics measures applied to EEG recordings of patients with attention deficit/hyperactivity disorder: quantifying the effects of a neurofeedback treatment.** Conf Proc IEEE Eng Med Biol Soc. 2012;2012:1057-60. [ABS]

> Five measures were applied: largest Lyapunov exponent, Lempel-Ziv complexity, Hurst exponent, and multiscale entropy on two different scales. The purpose is to test whether these measures are apt to detect and quantify differences from EEG registers between pre- and post-treatment. The results indicate that these measures could have a potential utility for detection of quantitative changes in specific EEG channels. In addition, the performance of some of these measures improved when the bandwidth was reduced to 3-30 Hz.

In summary, reduction of the bandwidth of the EEG registers to 3-30 Hz allows to detect in a better way quantitative differences in EEG registers of ADHD patients after neurofeedback treatment. In this preprocessing scenario, differences are widely detectable in more than 10 channels by use of the measure LZC. This finding can be explained by the importance of the theta, alpha and beta waves, located in 3-30 Hz, to identify signs of ADHD in EEG registers

Sohn H, et al (2010) - **Linear and non-linear EEG analysis of adolescents with attention-deficit/hyperactivity disorder during a cognitive task.** Clin Neurophysiol. 2010 Nov;121(11):1863-70. [ABS]

We aimed to investigate whether electroencephalograph (EEG) dynamics differ in adolescents with attention-deficit/hyperactivity disorder (ADHD) compared with healthy subjects during the performance of a cognitive task. …The approximate entropy (ApEn), a non-linear information-theoretic measure, was calculated to quantify the complexity of the EEGs. … The mean ApEn of the ADHD patients was significantly lower than the healthy subjects over the right frontal regions (Fp2 and F8) during the performance of the cognitive task, but not at rest. …The differences in EEG complexity between the two groups suggest that cortical information processing is altered in ADHD adolescents, and thus their levels of cortical activation may be insufficient to meet the cognitive requirements of attention-demanding tasks.

Ahmadlou M, et al (2010) - **Wavelet-Synchronization Methodology: A New Approach for EEG-Based Diagnosis of ADHD**. Clin EEG Neurosci. 2010 Jan;41(1):1-10. [ABS]

Autism ▲

Wadhera T, et al (2020) - **Conditional entropy approach to analyze cognitive dynamics in autism spectrum disorder**. Neurol Res.2020 Jul 4;1-10. [ABS]
https://pubmed.ncbi.nlm.nih.gov/32628095/

A higher conditional entropy in and left hemisphere and frontal regions of interested reflected atypical brain complexity in ASD.

Zhang L, et al (2020) - **Diagnosing autism spectrum disorder using brain entropy: A fast entropy method**. Comput Methods Programs Biomed. 2020 Jul;190:105240. [ABS]

…lower entropy was found in the ASD patients. The ApEn (approximate entropy) of the left postcentral gyrus and the SampEn (sample entropy) of the right lingual gyrus were both significantly negatively related to Autism Diagnostic Observation Schedule total scores in the ASD patients. … ApEn and SampEn could be potential biomarkers in ASD investigations.

Hadoush H, et al (2019) - **Brain Complexity in Children with Mild and Severe Autism Spectrum Disorders: Analysis of Multiscale Entropy in EEG.** Brain Topogr. 2019 Sep;32(5):914-92. [ABS]

Multiscale entropy (MSE) model quantifies the complexity of brain functions by measuring the entropy across multiple time-scales. …Averaged MSE values of children

with mild ASD were higher than averaged MSE value in children with severe ASD in right frontal, …right parietal, …left parietal, …and central cortical area. …MSE could serve as a sensitive method for identifying the severity level of ASD.

Easson AK, et al (2019) - **BOLD signal variability and complexity in children and adolescents with and without autism spectrum disorder**. Dev Cogn Neurosci. 2019 Apr;36:100630. [FULL TEXT]

Negative correlations were observed between each brain measure and the severity of ASD behaviors across all participants.

Zhao J, et al (2019) - **Feature exaction and classification of autism spectrum disorder children related electroencephalographic signals based on entropy.** Sheng Wu Yi Xue Gong Cheng Xue Za Zhi. 2019 Apr 25;36(2):183-188. [ABS]

The results showed that the complexity of EEGs in children with autism was lower than that of the normal control group. Among all four entropies, Wavelet Entropy got a better classification performance than others. Classification results vary in different regions, and the frontal lobe showed the best performance.

Kang J, et al (2018) - **Transcranial Direct Current Stimulation (tDCS) Can Modulate EEG Complexity of Children with Autism Spectrum Disorder.** Front Neurosci. 2018 Apr 16;12:201. [FULL TEXT]

A maximum entropy ratio (MER) method was adapted to measure the change of complexity of EEG series. It was found that the MER value significantly increased after tDCS. This study suggests that tDCS may be a helpful tool for the rehabilitation of children with ASD.

Dona O, et al (2017) - **Temporal fractal analysis of the rs-BOLD signal identifies brain abnormalities in autism.** PLoS One. 2017; 12(12). [FULL TEXT]

In this study, we were able to find regions in the brain with reported decreased signal complexity using the FD methodology. These regions have been previously reported as dysfunctional for ASD patients and correlated with behavioral assessments.

Simon DM, et al (2017) - **Neural Correlates of Sensory Hyporesponsiveness in Toddlers at High Risk for Autism Spectrum Disorder.** J Autism Dev Disord. 2017 Sep;47(9):2710-2722. [FULL TEXT]

(In high risk toddlers)…sensory hyporesponsivity is associated with reduced neural complexity and information content, but only at short time scales that correspond to high frequency brain activity.

Liu T, et al (2017) - **Altered electroencephalogram complexity in autistic children shown by the multiscale entropy approac**h. Neuroreport. 2017 Feb 8;28(3):169-173. [FULL TEXT]

A decreased electroencephalogram complexity was observed in the ASD children both during the observation and during the imitation tasks. On comparing the two tasks, significant differences were observed between groups in the right hemisphere, and also

the central cortex for the observation task. Multiscale entropy could provide further evidence of the relationship between ASD and cerebral dysfunction.

Takahashi T, et al (2016) - **Enhanced brain signal variability in children with autism spectrum disorder during early childhood**. Hum Brain Mapp. 2016 Mar;37(3):1038-50. [FULL TEXT]

> Results revealed an age-related increase of brain signal variability in a specific timescale in typically developing children, whereas atypical age-related alteration was observed in the ASD group. … In the ASD group, symptom severity was associated region-specifically and timescale-specifically with reduced brain signal variability.

Ghanbari Y, et al (2015) - **Joint analysis of band-specific functional connectivity and signal complexity in autism.** J Autism Dev Disord. 2015 Feb;45(2):444-60. [FULL TEXT]

> . …higher complexity in TD than ASD, in frontal regions in the delta band and occipital-parietal regions in the alpha band, and lower complexity in TD than in ASD in delta (parietal regions), theta (central and temporal regions) and gamma (frontal-central boundary regions); increased short-range connectivity in ASD in the frontal lobe in the delta band and long-range connectivity in the temporal, parietal and occipital lobes in the alpha band. Finally, and perhaps most strikingly, group differences between ASD and TD in complexity and FC appear spatially complementary, such that where FC was elevated in ASD, complexity was reduced (and vice versa). The correlation of regional average complexity and connectivity node strength with symptom severity scores of ASD subjects supported the overall complementarity (with opposing sign) of connectivity and complexity measures, pointing to either diminished connectivity leading to elevated entropy due to poor inhibitory regulation or chaotic signals prohibiting effective measure of connectivity.

Okazaki R, et al (2015) - **Changes in EEG complexity with electroconvulsive therapy in a patient with autism spectrum disorders: a multiscale entropy approach.** Front Hum Neurosci. 2015 Feb 26;9:106. [FULL TEXT]

> Along with ECT, the frontocentral region showed decreased EEG complexity at higher temporal scales, whereas the occipital region expressed an increase at lower temporal scales. Furthermore, these changes were associated with clinical improvement associated with the elevation of brain-derived neurotrophic factor, which is a molecular hypothesis of ECT, playing key roles in ASD pathogenesis. Changes in EEG complexity in a region-specific and temporal scale-specific manner that we found might reflect atypical EEG dynamics in ASD.

Mišić B, et al (2015) - **Coordinated Information Generation and Mental Flexibility: Large-Scale Network Disruption in Children with Autism.** Cereb Cortex. 2015 Sep;25(9):2815-27. [FULL TEXT]

> We **used multiscale entropy (MSE)** to estimate the rate at which information was generated in a set of sources distributed across the brain. Multivariate partial least-squares analysis revealed **2 distributed networks, operating at fast and slow time scales, that respond completely differently to set shifting in ASD compared with**

control children, indicating disrupted temporal organization within these networks. Moreover, when typically developing children engaged these networks, they achieved faster reaction times. When children with ASD engaged these networks, there was no improvement in performance, suggesting that the networks were ineffective in children with ASD. Our data demonstrate that the coordination and temporal organization of large-scale neural assemblies during the performance of cognitive control tasks is disrupted in children with ASD, contributing to executive function deficits in this group

Catarino A, et al (2011) - **Atypical EEG complexity in autism spectrum conditions: a multiscale** [ABS] **entropy analysis.** Clin Neurophysiol. 2011 Dec;122(12):2375-83.

> Intrinsic complexity subserves adaptability in biological systems. One recently developed measure of intrinsic complexity of biological systems is multiscale entropy (MSE). …Results demonstrate a reduction of EEG signal complexity in the ASC group, compared to typical controls, over temporo-parietal and occipital regions. No significant differences in EEG power spectra were observed between groups, indicating that changes in complexity values are not a reflection of changes in EEG power spectra. …Results suggest that EEG complexity, as indexed by MSE measures, may also be a marker for disturbances in task-specific processing of information in people with autism.

Bosl W, et al (2011) - **EEG complexity as a biomarker for autism spectrum disorder risk**. BMC Med. 2011 Feb 22;9:18. [FULL TEXT]

> BACKGROUND: Complex neurodevelopmental disorders may be characterized by subtle brain function signatures early in life before behavioral symptoms are apparent. Such endophenotypes may be measurable biomarkers for later cognitive impairments. The nonlinear complexity of electroencephalography (EEG) signals is believed to contain information about the architecture of the neural networks in the brain on many scales. Early detection of abnormalities in EEG signals may be an early biomarker for developmental cognitive disorders. The goal of this paper is to demonstrate that the modified multiscale entropy (mMSE) computed on the basis of resting state EEG data can be used as a biomarker of normal brain development and distinguish typically developing children from a group of infants at high risk for autism spectrum disorder (ASD), defined on the basis of an older sibling with ASD.
>
> Multiscale entropy appears to go through a different developmental trajectory in infants at high risk for autism (HRA) than it does in typically developing controls.
>
> Classification accuracy for boys was close to 100% at age 9 months and remains high (70% to 90%) at ages 12 and 18 months. …mMSE computed from resting state EEG signals may be a useful biomarker for early detection of risk for ASD and abnormalities in cognitive development in infants.

Lai MC, et al (2010) - **A shift to randomness of brain oscillations in people with autism.** Biol Psychiatry. 2010 Dec 15;68(12):1092-9. [ABS]

> Fractal parameters such as the Hurst exponent, H, describe the complexity of endogenous low-frequency fMRI time series on a continuum from random (H = .5) to

ordered (H = 1). Shifts in fractal scaling of physiological time series have been associated with neurological and cardiac conditions.

Complex fractal scaling of fMRI time series was found in both groups but globally there was a significant shift to randomness in the ASC (mean H = .758, SD = .045) compared with neurotypical volunteers (mean H = .788, SD = .047). Between-group differences in H, which was always reduced in the ASC group, were seen in most regions previously reported to be involved in autism, including cortical midline structures, medial temporal structures, lateral temporal and parietal structures, insula, amygdala, basal ganglia, thalamus, and inferior frontal gyrus. …Autism is associated with a small but significant shift to randomness of endogenous brain oscillations. Complexity measures may provide physiological indicators for autism as they have done for other medical conditions.

Birth and Perinatal Trauma ▲

Costa CS, et al (2017) - **Complexity of brain signals is associated with outcome in preterm infants**. J Cereb Blood Flow Metab. 2017 Oct; 37(10). [FULL TEXT]

Here, we apply Multiscale Entropy (MSE) analysis to assess the complexity of systemic and cerebral near-infrared spectroscopy (NIRS) signals… Decreased complexity of brain signals was associated with mortality and brain injury. Measurement of brain signal complexity in preterm infants is feasible and could represent a significant advance in the brain-oriented care.

Schnettler WT, et al (2016) - **Complexity analysis of fetal heart rate preceding intrauterine demise**. Eur J Obstet Gynecol Reprod Biol. 2016 Aug;203:286-90. [FULL TEXT]

Kim HR, et al (2003) - **Delivery modes and neonatal EEG: spatial pattern analysis.** Early Hum Dev. 2003 Dec;75(1-2):35-53. [ABS]

"Animal studies indicate that postnatal adaptation and development of neonates could be different due to the birth method and that these effects may last throughout adulthood."

Compared to the C-section, the vaginal delivered neonate's EEG recordings showed a significant increase of amplitude at Fp1 in the pattern 24 h after the delivery, but not 2 h after delivery. Dynamics in this spectral analyses were not significantly different between both groups 2 h after delivery, but the regional differences increased during the next day between both groups. CONCLUSIONS: This could come from the early insufficient complexity in C-section neonates. Global EEG complexity in C-section neonates fell short of that of vaginal delivered neonates 2 h after delivery.

Skelin I, et al (2015) - **Multigenerational prenatal stress increases the coherence of brain signaling among cortico-striatal-limbic circuits in adult rats.** Neuroscience. 2015 Mar 19;289:270-8. [ABS]

The FP (field potential) power was significantly lower in most structures across most frequency bands in MGPNS animals, and the relative increase in power from baseline

during the task was lower for the beta band (12-30Hz) in MGPNS animals as compared to controls. The coherence of FPs between brain regions, however, was much higher in MGPNS animals among all structures and for most frequency bands. We propose that this pattern of changes in brain signaling reflects a simplification of network processing, which is consistent with reports of reduced spine density and dendritic complexity in the brains of animals receiving PNS (prenatal stress). Our data support the proposal that recurrent ancestral stress leads to adaptations in the brain, and that these may confer adaptive behavior in some circumstances as compared to single-generation PNS.

Fan W, et al (2003) - **Characteristic of children's EEG complexity at different ages and in different states**. Beijing Da Xue Xue Bao. 2003 Oct;35(5):462-5. [ABS]

EEG complexity was analyzed by non-linear measure in 7 states: awake with eyes opened, awake with eyes closed, NREM (nonrapid eye movements) sleep including stages I and II (light sleep), III and IV (deep sleep) and REM (rapid eye movements) sleep. Meanwhile, the correlation was analyzed between complexity and ages. RESULTS: (1) The global EEG complexity in state of being awake with eyes opened was greater than that with eyes closed; that in wakefulness state was greater than in sleep state. The EEG complexity gradually decreased with the increase of deep sleep in NREM sleep state.

The complexity in REM sleep state was greater than that in deep sleep state, but lower than in wakefulness state. (2) The global EEG complexity was positively related to ages in state of being awake with eyes opened, state of being awake with eyes closed, light sleep, and not related to ages in deep-sleep state and REM sleep state. (3) In every brain area EEG complexity was positively related to ages in state of being awake with eyes closed. In paracentral region EEG complexity was positively related to ages in states of being awake with eyes opened and light sleep. CONCLUSION:

The EEG complexity was used to study the brain dynamical characteristics in different physiology states and the relationship between encephalic electric activity and brain development. It can be used as an objective index to evaluate the function and development of brain.

Sheehan JC, et al (2017) - **The effect of task complexity on planning in preterm-born children**. Clin Neuropsychol. 2017 Feb;31(2):438-458. [ABS]

Brain Injury ▲

Popa LL, et al (2020) - **The Role of Quantitative EEG in the Diagnosis of Neuropsychiatric Disorders.** Med Life. Jan-Mar 2020;13(1):8-15. [FULL TEXT]

QEEG has brought new techniques of EEG signals feature extraction: analysis of specific frequency band and signal *complexity*, analysis of connectivity, and network analysis. The clinical application of QEEG is extensive, including neuropsychiatric disorders, epilepsy, stroke, dementia, traumatic brain injury, mental health disorders, and many

> others. …to date, the role of QEEG is not necessarily to pinpoint an immediate diagnosis but to provide additional insight …and specific treatment response evaluation.

Rosanova M, et al (2018) - **Sleep-like cortical OFF-periods disrupt causality and complexity in the brain of unresponsive wakefulness syndrome patients**. Nat Commun. 2018 Oct 24;9(1):4427. [FULL TEXT]

> … loss of brain complexity after severe injuries is due to a pathological tendency of cortical circuits to fall into silence (OFF-period) upon receiving an input, a behavior typically observed during sleep.

Dona O, et al (2017) - **Fractal Analysis of Brain Blood Oxygenation Level Dependent (BOLD) Signals from Children with Mild Traumatic Brain Injury (mTBI).** PLoS One. 2017; 12(1): e0169647. [FULL TEXT]

> …we were able to find regions in the brain that despite not showing any abnormality in an anatomical scan, reported decreased signal complexity using FD methodology. These regions have been previously reported as dysfunctional for mTBI patients. The method we have proposed is able to provide additional information of mTBI in a non-invasive and fast manner and could hopefully help in the design of future treatment plans.

Saykally JN, et al (2017) - **Repetitive Mild Closed Head Injury Alters Protein Expression and Dendritic Complexity in a Mouse Model.** J Neurotrauma. 2017 Jul 12. [ABS]

Howard JT, et al (2017) - **The neurovascular complexity index as a potential indicator of traumatic brain injury severity: A case-series study**. J Trauma Acute Care Surg. 2017 Jul;83(1 Suppl 1):S77-S82. [ABS]

Gao L, et al (2016) - **Cerebrovascular Signal Complexity Six Hours after Intensive Care Unit Admission Correlates with Outcome after Severe Traumatic Brain Injury**. J Neurotrauma. 2016 Nov 15;33(22):2011-2018. [ABS]

> Disease states are associated with a breakdown in healthy interactions and are often characterized by reduced signal complexity. We applied approximate entropy (ApEn) analysis to investigate the correlation between the complexity of heart rate (ApEn-HR), mean arterial pressure (ApEn-MAP), intracranial pressure (ApEn-ICP), and a combined ApEn-product (product of the three individual ApEns) and outcome after traumatic brain injury.
>
> Patients in the lowest quartile for ApEn-product were over four times more likely to die (39.5% vs. 9.3%, $p < 0.001$) than those in the highest quartile.
>
> Our results demonstrate that as early as 6 h into monitoring, complexity measures from easily attainable vital signs, such as HR and MAP, in addition to ICP, can help triage those who require more intensive neurological management at an early stage.

Fino PC, et al (2016) - **Decreased high-frequency center-of-pressure complexity in recently concussed asymptomatic athletes**. Gait Posture. 2016 Oct;50:69-74. [ABS]

This decrease in entropy may associate with reported increases in intra-cortical inhibition. Furthermore, a single-case study suggested high frequency MV-CompMSE may be a useful clinical tool for concussion management.

Cerebral Palsy ▲

Sajedi F, et al (2013) - **Linear and nonlinear analysis of brain dynamics in children with cerebral palsy**. Res Dev Disabil. 2013 May; 34(5):1388-96. [ABS]

> "...a definitely higher delta and lower theta and alpha powers, and higher EEG complexity in CP patients."

Chronic Fatigue Syndrome ▲

Wu T, et al (2016) - **Electroencephalogram characteristics in patients with chronic fatigue syndrome**. Neuropsychiatr Dis Treat. 2016; 12: 241–249. [FULL TEXT]

> "... energy values of δ, θ, and α1 waves significantly increased in the observation group... in the right frontal and left occipital regions... was more significant ... the correlation dimension in the observation group was significantly lower than the control group, suggesting decreased EEG complexity in CFS patients.

Cognition and its Disorders ▲

Palix J, et al (2020) - **Temporal regularity of cerebral activity at rest correlates with slowness of reaction times in intellectual disability**. Clin Neurophysiol. 2020 Aug;131(8):1859-1865. [ABS]

> Brain signal approximate entropy is shown to correspond with processing speed for the first time: in intellectual disability (ID) participants, the higher the regularity in brain signals at rest, the slower RTs will be in the active state. ID should be understood as a lack of lability in the cortical transition to the active state, weakening the efficiency of adaptive behavior.

Friedman N, et al (2019) - **EEG-Based Prediction of Cognitive Load in Intelligence Tests**. Front Hum Neurosci. 2019; 13: 191. [FULL TEXT]

Jin L, et al (2019) - **Differences in brain signal complexity between experts and novices when solving conceptual science problem: a functional near-infrared spectroscopy study**. Neurosci Lett. 2019 Apr 23;699:172-176. [ABS]

> (During testing) the permutation entropy values in the inferior frontal gyrus were smaller for experts, especially in the right IFG.

Anderson ND (2019) - **State of the science on mild cognitive impairment (MCI).** CNS Spectr. 2019 Feb;24(1):78-87. [ABS]

…analysis of signal complexity using electroencephalography or magnetoencephalography holds promise as a biomarker

Timothy LT, et al (2017) - **Classification of mild cognitive impairment EEG using combined recurrence and cross recurrence quantification analysis**. Int J Psychophysiol. 2017 Oct;120:86-95. [ABS]

A new approach of combining complexity and synchronization features for EEG classification of MCI subjects is proposed…

Baglio G, et al (2016) - **Social Competence in Children with Borderline Intellectual Functioning: Delayed Development of Theory of Mind across All Complexity Levels**. Front Psychol. 2016 Oct 21;7:1604. [FULL TEXT]

Ahmadlou M, et al (2014) - **Complexity of functional connectivity networks in mild cognitive impairment subjects during a working memory task**. Clin Neurophysiol. 2014 Apr; 125(4):694-702. [ABS] "

"...complexity of functional networks involved in the working memory function in MCI subjects is reduced at alpha and theta bands compared with control subjects, and at the theta band this reduction is more pronounced in the whole brain and intra left hemisphere."

McBride JC, et al (2014) - **Spectral and complexity analysis of scalp EEG characteristics for mild cognitive impairment and early Alzheimer's disease**. Comput Methods Programs Biomed. 2014 Apr; 114(2):153-63. [ABS]

These results demonstrate the great promise for scalp EEG spectral and complexity features as noninvasive biomarkers for detection of MCI and early AD."

Coma ▲

Nenadovic V, et al (2014) - **Phase synchronization in electroencephalographic recordings prognosticates outcome in paediatric coma**. PLoS One. 2014 Apr 21; 9(4): e94942. [ABS]

Children who had a poor outcome following brain injury secondary to cardiac arrest, TBI or stroke, had ... a lower spatial complexity of the synchrony patterns and a lower temporal variability of the synchrony index values at 15 Hz when compared to those patients with a good outcome.

Consciousness ▲

Wang Y, et al (2020) - **Spinal cord stimulation modulates complexity of neural activities in patients with disorders of consciousness.** Int J Neurosci. 2020 Jul;130(7):662-670. [ABS]

Spinal cord stimulation (SCS) is a valuable treatment for patients with disorders of consciousness (DOC). This study used permutation entropy (PeEn) of neural activities to

quantify brain responses to SCS. …When SCS was on, PeEn increased as compared to the baseline. When SCS was shut off, PeEn decreased…. PeEn from EEG data could be used to evaluate SCS modulation effects, and EEG complexity might be a critical index to describe brain responses to SCS in DOC. … MCS were more significant than those for VS, especially in the frontal region.

Varley T, et al (2020) - **Fractal dimension of cortical functional connectivity networks & severity of disorders of consciousness**. PLoS One. 2020 Feb 13;15(2):e0223812. [FULL TEXT]

These results suggest that cortical functional connectivity networks display fractal character and that this is associated with level of consciousness in a clinically relevant population, with higher fractal dimensions (i.e. more complex) networks being associated with higher levels of consciousness. This supports the hypothesis that level of consciousness and system complexity are positively associated, and is consistent with previous EEG, MEG, and fMRI studies.

Liang Z, et al (2020) - **Constructing a Consciousness Meter Based on the Combination of Non-Linear Measurements and Genetic Algorithm-Based Support Vector Machine.** IEEE Trans Neural Syst Rehabil Eng. 2020 Feb;28(2):399-408. [ABS]

Multi-dimensional measurements, especially the PE, SampEn, PLZC, and DFA, when combined with GA-SVM, are promising methods for constructing a framework to quantify consciousness.

Corchs S, et al (2019) - **Computational Methods for Resting-State EEG of Patients with Disorders of Consciousness**. Front Neurosci. 2019; 13: 807. [FULL TEXT]

The main reason of the application of entropy-related techniques is based on the decreased complexity of EEG data in less aware patients. …Mainly based on the definition of entropy, “complexity measures” characterize all those approaches used to evaluate the amount of information recorded by the system and represented, in this case, through the recorded EEG traces.

Miras JRD, et al (2019) **- Fractal dimension analysis of states of consciousness and unconsciousness using transcranial magnetic stimulation**. Comput Methods Programs Biomed. 2019 Jul;175:129-137. [ABS]

We found that FDI is significantly lower in sleep and sedation when compared to wakefulness and provides an almost perfect intra-subject discrimination between conscious and unconscious states. …These results support the combination of FD measures of cortical integration and cortical differentiation as a novel paradigm of tracking complex spatiotemporal dynamics in the brain that could provide further insights into the link between complexity and the brain's capacity to sustain consciousness.

Liang Z, et al (2018) - **Long-Range Temporal Correlations of Patients in Minimally Conscious State Modulated by Spinal Cord Stimulation**. Front Physiol. 2018 Oct 29;9:1511. [FULL TEXT]

This phenomenon may indicate that more cortical areas were engaged in the information integration after SCS. In addition, the GDFAE values increased significantly

in the frontal area at delta, theta, and alpha bands after SCS. At the theta band, a significant increase in GDFAE was observed in the occipital area. No significant change was found at beta or gamma bands in any brain region. These findings show that the enhanced LRTCs after SCS occurred primarily at low-frequency bands in the frontal and occipital regions. As the LRTCs reflect the long-range temporal integration of EEG signals, our results indicate that *information integration became more "complex" after SCS.*

Riganello F, et al (2018) - **A Heartbeat Away From Consciousness: Heart Rate Variability Entropy Can Discriminate Disorders of Consciousness and Is Correlated with Resting-State fMRI Brain Connectivity of the Central Autonomic Network.** Front Neurol. 2018; 9: 769. [FULL TEXT]

Complexity Index of Minimally Conscious State compared to Unresponsive Wakefulness Syndrome patients "has high discriminative power and low false negative rate at one third of the estimated human assessors' misdiagnosis, providing an easy, inexpensive and non-invasive diagnostic tool. CI reflects functional connectivity changes in the CAN, suggesting that CI can provide an indirect way to screen and monitor connectivity changes in this neural system."

Bodart O, et al (2018) - **Global structural integrity and effective connectivity in patients with disorders of consciousness.** Brain Stimul. Mar-Apr 2018;11(2):358-365. [FULL TEXT]

The perturbational complexity index (PCI) is a transcranial magnetic stimulation (TMS) derived marker of effective connectivity. …Global fractional anisotropy could predict 74% of PCI variance in the whole sample and 56% in the patients' group.

Mashour GA, et al (2018) - **Neural Correlates of Unconsciousness in Large-Scale Brain Networks**. Trends Neurosci. 2018 Mar;41(3):150-160. [FULL TEXT]

Studies of sleep, anesthesia, and pathologic states of unconsciousness with high-density EEG and transcranial magnetic stimulation demonstrate a reduction of complexity and effective connectivity compared to consciousness. …consistent with the hypothesis that a disruption in the dynamic repertoire is associated with the suppression of consciousness, and perhaps contributes to it.

Mateos DM, et al (2018) - **Measures of entropy and complexity in altered states of consciousness**. Cogn Neurodyn. 2018 Feb;12(1):73-84. [FULL TEXT]

…values of entropy and complexity of the signals tend to be greatest when the subjects are in fully alert states, falling in states with loss of awareness or consciousness. …the investigation of the structure of cognition using the frameworks of complexity will reveal mechanistic aspects of brain dynamics associated not only with altered states of consciousness but also with normal and pathological conditions.

Mateos DM, et al (2017) - **Consciousness as a global property of brain dynamic activity**. Phys Rev E. 2017 Dec;96(6-1):062410. [ABS]

> …found higher complexity in states characterized not only by conscious awareness but also by subconscious cognitive processing, such as sleep stages

Ruffini G (2017) - **An algorithmic information theory of consciousness**. Neurosci Conscious. 2017 Oct 12;2017(1):nix019. [FULL TEXT]

> … methods to study the complexity of the brain's output streams or of brain state as correlates of conscious state…

Wang J, et al (2017) - **Suppressed neural complexity during ketamine- and propofol-induced unconsciousness**. Neurosci Lett. 2017 Jul 13;653:320-325. [ABS]

> We analyzed the randomness (type-I complexity) and complexity (type-II complexity) of electroencephalogram (EEG) signals before and after bolus injection of ketamine or propofol. For the analysis, we use Mean Information Gain (MIG) and Fluctuation Complexity (FC), which are information-theory-based measures that quantify disorder and complexity of dynamics respectively. Both ketamine and propofol reduced the complexity of the EEG signal, but ketamine increased the randomness of the signal and propofol decreased it. The finding supports our claim and suggests EEG complexity as a candidate for a consciousness indicator.

Wislowska M, et al (2017) **- Night and day variations of sleep in patients with disorders of consciousness**. Sci Rep. 2017; 7: 266. [FULL TEXT]

> Surprisingly, the prevalence of sleep spindles and slow waves did not systematically vary between day and night in patients, whereas day-night changes in EEG power spectra and signal complexity were revealed in minimally conscious but not unaware patients.

Bodart O, et al (2017) - **Measures of metabolism and complexity in the brain of patients with disorders of consciousness.** Neuroimage Clin. 2017 Feb 6;14:354-362. [FULL TEXT]

> …the perturbational complexity index (PCI), a new measure based on the analysis of the electroencephalographic response to transcranial magnetic stimulation, has also been suggested as a tool to distinguish between unconscious and conscious states. The aim of the study was to cross-validate FDG–PET and PCI, and to identify signs of consciousness in otherwise unresponsive patients.

Erra RG, et al (2016) - **Statistical mechanics of consciousness: Maximization of information content of network is associated with conscious awareness**. Phys Rev E. 2016 Nov;94(5-1):052402. [ABS]

> It is said that complexity lies between order and disorder. In the case of brain activity and physiology in general, complexity issues are being considered with increased emphasis. …Normal wakeful states are characterized by the greatest number of possible configurations of interactions between brain networks, representing highest entropy values. Therefore, the information content is larger in the network associated to conscious states, suggesting that consciousness could be the result of an optimization of information processing.

Thul A, et al (2016) - **EEG entropy measures indicate decrease of cortical information processing in Disorders of Consciousness.** Clin Neurophysiol. 2016 Feb;127(2):1419-1427. [ABS]

> The utilized EEG entropy analyses were able to relate to patient groups with different Disorders of Consciousness.

Zhao Y, et al (2015) - **Brain Vigilance Analysis Based on the Measure of Complexity**. Sheng Wu Yi Xue Gong Cheng Xue Za Zhi. 2015 Aug;32(4):725-9. [ABS]

> The experimental results showed that: PE could well reflect the dynamic changes of EEG when vigilance decreases, and has advantages of fast arithmetic speed, high noise immunity, and low requirements for EEG length. This can be used as a measure of the brain vigilance indicators.

Sitt JD, et al (2014) - **Large scale screening of neural signatures of consciousness in patients in a vegetative or minimally conscious state**. Brain. 2014 Aug; 137(Pt 8):2258-70. [ABS]

> "We show that low-frequency power, electroencephalography complexity, and information exchange constitute the most reliable signatures of the conscious state. When combined, these measures synergize to allow an automatic classification of patients' state of consciousness."

Sarasso S, et al (2014) - **Quantifying cortical EEG responses to TMS in (un)consciousness**. Clin EEG Neurosci. 2014 Jan; 45(1):40-9. [ABS]

> "These studies invariably show that the complexity of the cortical response to TMS collapses when consciousness is lost during deep sleep, anesthesia and vegetative state following severe brain injury, while it recovers when consciousness resurges in wakefulness, during dreaming, in the minimally conscious state or locked-in syndrome."

Casali AG, et al (2013) - **A theoretically based index of consciousness independent of sensory processing and behavior**. Sci Transl Med. 2013 Aug 14;5(198):198ra105. [ABS]

> We introduce and test a theory-driven index of the level of consciousness called the perturbational complexity index (PCI). PCI is calculated by (i) perturbing the cortex with transcranial magnetic stimulation (TMS) to engage distributed interactions in the brain (integration) and (ii) compressing the spatiotemporal pattern of these electrocortical responses to measure their algorithmic complexity (information). …PCI reliably discriminated the level of consciousness in single individuals during wakefulness, sleep, and anesthesia, as well as in patients who had emerged from coma and recovered a minimal level of consciousness. PCI can potentially be used for objective determination of the level of consciousness at the bedside.

Bob P (2007) - **Chaos, brain and divided consciousness.** Acta Univ Carol Med Monogr. 2007;153:9-80. [ABS]

> Because epileptiform activity has specific chaotic behavior and calculated information entropy from EDA records reflects the complexity of the deterministic structure in the system there is a relevant assumption that unilaterally increased complexity may

produce interhemispheric disbalance and increased chaoticity which hypothetically may serve as a dynamic source of epileptiform discharges related to trauma induced kindling mechanism.

Massimini M, et al (2009) - **A perturbational approach for evaluating the brain's capacity for consciousness**. Prog Brain Res. 2009;177:201-14. [ABS] [FULL TEXT]

Tononi G, et al (1998) - **Consciousness and Complexity**. Science Vol 282, 4 Dec 1998, 1846-1851. [ABS]

> "1) A group of neurons can contribute directly to conscious experience only if it is part of a distributed functional cluster that achieves high integration in hundreds of milliseconds. 2) To sustain conscious experience, it is essential that this functional cluster be highly differentiated, as indicated by high values of complexity." ..."*A strong prediction based on our hypothesis is that the complexity of the dynamic core should correlate with the conscious state of the subject*."

Creativity ▲

Ueno K, et al (2015) - Neurophysiological basis of creativity in healthy elderly people: a multiscale entropy approach. Clin Neurophysiol. 2015 Mar; 126(3):524-31. [ABS]

> "Considering the general "loss of complexity" theory of aging, our finding of increased EEG complexity in elderly people with heightened creativity supports the idea that creativity is associated with activated neural networks."

Peng Z, et al (2015) - **Entropic Movement Complexity Reflects Subjective Creativity Rankings of Visualized Hand Motion Trajectories**. Front Psychol. 2015 Dec 17;6:1879. [FULL TEXT]

> Our results suggest that entropic complexity measures of hand motion may reveal domain-specific individual differences in kinesthetic creativity.

Mölle M, et al (1999) **- EEG complexity and performance measures of creative thinking**. Psychophysiology. 1999 Jan; 36(1):95-104. [ABS]

> "Higher frontal EEG complexity during divergent than convergent thinking could be the result of the concurrent activation of a greater number of independently oscillating processing units."

Depression ▲

Čukić M, et al (2020) - **Nonlinear analysis of EEG complexity in episode and remission phase of recurrent depression.** Int J Methods Psychiatr Res. 2020 Jun;29(2):e1816. [FULL TEXT]

> Depressed patients had higher HFD and SampEn complexity compared to healthy subjects. The complexity was higher in patients who were in remission than in those in the acute episode. Altered complexity was present in the frontal and centro-parietal

regions when compared to control group. The complexity in frontal and parietal regions differed between the two phases of depressive disorder. …Complexity measures of EEG distinguish between the healthy controls, patients in remission and episode.

Wu L, et al (2020) - **Spatio-temporal dynamics of EEG features during sleep in major depressive disorder after treatment with escitalopram: a pilot study**. BMC Psychiatry. 2020; 20: 124. [FULL TEXT]

...after treatment, there was a significant increase in the relative energy (RE) of δ1 band (0.5 - 2 Hz), accompanied by a significant decrease in the RE of β2 band (20 - 30 Hz). Lempel-Ziv complexity and Co-complexity values were significantly lower.

Wolff A, et al (2019) - **Atypical Temporal Dynamics of Resting State Shapes Stimulus-Evoked Activity in Depression-An EEG Study on Rest-Stimulus Interaction**. Front Psychiatry. 2019 Oct 15;10:719. [FULL TEXT]

Lebiecka K, et al (2018) - **Complexity Analysis of EEG Data in Persons with Depression Subjected to Transcranial Magnetic Stimulation.** Front Physiol. 2018 Sep 28;9:1385. [FULL TEXT]

Comparison between groups showed a higher FD in MDD responders than in MDD non-responders in every band before as well as after stimulation.

Torre-Luque ADL, et al (2017) - **Complexity and Irregularity in the Brain Oscillations of Depressive Patients: A Systematic** Review. Neuropsychiatry (London) (2017) 7(5), 466–477. [FULL TEXT]

Diagnostic studies essentially examined the brain oscillations in the broad frequency band and reported larger complexity or irregularity in depressives, as shown by the fractal dimension measures and informational measures. Regarding the intervention studies, the larger the decrease in brain complexity (e.g. in fractal dimension) the higher the amelioration of depressive symptomatology. The increased complexity found in brain oscillations of depressives may probably be related to deficits in cortical inhibition control mechanisms.

Ho P-S, et al (2017) - **Complexity analysis of resting state fMRI signals in depressive patients**. Conf Proc IEEE Eng Med Biol Soc. [ABS]

…depressive patients exhibited higher complexity in the left frontoparietal network than that seen in healthy controls, which is known to be critical for executive control functions.

Akar SA, et al (2015) - **Nonlinear analysis of EEG in major depression with fractal dimensions**. Conf Proc IEEE Eng Med Biol Soc. 2015;2015:7410-3. [ABS]

As a result, a significantly increased complexity was found in both parietal and frontal regions of MDD patients. This significantly increased complexity was observed not only in full-band activity but also in beta and gamma sub-bands of EEG.

Akar SA, et al (2015) - **Nonlinear analysis of EEGs of patients with major depression during different emotional states.** Comput Biol Med. 2015 Dec 1;67:49-60. [ABS]

> … nonlinear parameters, such as Katz fractal dimension (KFD), Higuchi fractal dimension (HFD), Shannon entropy (ShEn), Lempel-Ziv complexity (LZC) and Kolmogorov complexity (KC), were computed from the EEG signals of two groups under different experimental states: noise (negative emotional content) and music (positive emotional content) periods.
>
> First, higher complexity values were generated by MDD patients relative to controls. Significant differences were obtained in the frontal and parietal scalp locations using KFD ($p<0.001$), HFD ($p<0.05$), and LZC ($p=0.05$). Second, lower complexities were observed only in the controls when they were subjected to music compared to the resting baseline state in the frontal ($p<0.05$) and parietal ($p=0.005$) regions. In contrast, the LZC and KFD values of patients increased in the music period compared to the resting state in the frontal region ($p<0.05$). Third, the patients′ brains had higher complexities when they were exposed to noise stimulus than did the controls′ brains. Moreover, MDD patients′ negative emotional bias was demonstrated by their higher brain complexities during the noise period than the music stimulus.

Bob P (2015) - **Sharp-wave EEG abnormalities and neural complexity in depressive patients: preliminary report.** Neuropsychiatric Electrophysiology (2015) 1:11. [FULL TEXT]

> The results show that the depressive patients with episodic sharp-wave EEG abnormalities had significantly lower EEG complexity than the control groups of patients. The data also indicate that benzodiazepines significantly influence neural complexity and increase it in the subgroup of patients with sharp wave abnormalities, and on the other hand decrease the level of complexity in the control subgroup of depressive patients.

Zhang Y, et al (2015) - **Neural complexity in patients with post-stroke depression: A resting EEG study.** J Affect Disord. 2015 Dec 1;188:310-8. [ABS]

> PSD patients showed lower neural complexity compared with PSND and CONT subjects in the whole brain regions. …LZC in the whole brain regions, especially in frontal and temporal. LZC parameters used for PSD recognition possessed more than 85% in specificity, sensitivity and accuracy, suggesting the feasibility of LZC (Lempel-Ziv complexity) to serve as screening indicators for PSD. Increased slow wave rhythms were found in PSD patients and clearly correlation was confirmed between neuronal complexity and spectral power of the four EEG rhythms.

Akdemir AS, et al (2015) - **Nonlinear analysis of EEGs of patients with major depression during different emotional states**. Comput Biol Med. 2015 Dec 1;67:49-60. [ABS]

Leuchter AF, et al (2015) - **Rhythms and blues: modulation of oscillatory synchrony and the mechanism of action of antidepressant treatments.** Ann N Y Acad Sci. 2015 May;1344:78-91. [FULL TEXT]

> Oscillatory synchrony in complex systems may help mediate neuroplastic changes related to neurodevelopment, learning, and memory, as well as medication and neuromodulatory treatment for MDD.

Meerwijk EL, et al (2015) - **Resting-state EEG delta power is associated with psychological pain in adults with a history of depression.** Biol Psychol. 2015 Feb;105:106-14. [FULL TEXT]

> "Frontal delta power predicted psychological pain while controlling for depressive symptoms, with participants who exhibited less power experiencing greater psychological pain. Frontal fractal dimension symmetry, a nonlinear measure of complexity, also predicted psychological pain, such that greater left than right complexity was associated with greater psychological pain. Frontal alpha asymmetry did not contribute unique variance to any regression model of psychological pain."

Valenza G, et al (2015) - **Nonlinear digital signal processing in mental health: characterization of major depression using instantaneous entropy measures of heartbeat dynamics**. Front Physiol. 2015 Mar 13;6:74. [FULL TEXT]

Kalev K, e al (2015) - **Lempel-Ziv and multiscale Lempel-Ziv complexity in depression.** Conf Proc IEEE Eng Med Biol Soc. 2015;2015:4158-61. [ABS]

> The results revealed the incapability of traditional LZC to differentiate depressive subjects from healthy controls in eyes open condition, while MLZC differentiated two groups in numerous channels at different frequencies, giving the highest classification accuracy in channel F3 (86 %) at frequencies 9 and 15.5 Hz. The results indicate that the high frequency information, which is lost in calculation of traditional LZC, has a great value in differentiating between depressive and control groups.

Okazaki R, et al (2013) - **Effects of electroconvulsive therapy on neural complexity in patients with depression: report of three cases.** J Affect Disord. 2013 Sep 5;150(2):389-92. [ABS]

> "... aberrant functional connectivity underlies the pathophysiology of depression, which engenders abnormal electroencephalogram (EEG) complexity. ...The decrease in EEG complexity with ECT might be a result of amelioration of functional connectivity in the brain of a depressed patient." "... aberrant functional connectivity underlies the pathophysiology of depression, which engenders abnormal electroencephalogram (EEG) complexity.

Bornas X, et al (2013) - **Self-focused cognitive emotion regulation style as associated with widespread diminished EEG fractal dimension.** Int J Psychol. 2013;48(4):695-703. [ABS]

> The cognitive regulation of emotions is important for human adaptation. Self-focused emotion regulation (ER) strategies have been linked to the development and persistence of anxiety and depression. …Results showed that a diminished FD over the scalp significantly correlated with self-focused ER style scores, even after controlling for negative affect, which has been also considered to influence the use of ER strategies. The lower the EEG FD, the higher were the self-focused ER style scores. Correlational analyses of specific self-focused ER strategies showed that self-blaming and rumination were negatively associated with diminished FD of the EEG, but catastrophizing and blaming others were not. No significant correlations were found for ER strategies more focused on situation or others. Results are discussed within the self-organized criticality theory of brain dynamics: **The diminished FD of the EEG may reflect a disposition to**

engage in self-focused ER strategies as people prone to ruminate and self-blame show a less complex resting EEG activity, which may make it more difficult for them to exit their negative emotional state.

Fernández A, et al (2010) - **Analysis of brain complexity and mental disorders.** Actas Esp Psiquiatr. 2010 Jul-Aug;38(4):229-38. [ABS]

> Parameters of EEG-MEG complexity usually estimate the predictability of brain oscillations and/or the number of independent oscillators underlying the observed signals. More importantly, complexity parameters seem to be sensitive to the temporal components of brain activity, and therefore might reflect the dynamical nature of psychiatric disorders.

Tang Y, et al (2009) - **Entropy analysis of the EEG alpha activity in depression patients.** Sheng Wu Yi Xue Gong Cheng Xue Za Zhi. 2009 Aug;26(4):739-42. [ABS]

> Results showed that the alpha activity of depression patients is more complex during resting and is more regular during the mental arithmetic than that of the controls. Renyi Entropy analysis can well characterize the alpha activity in depression patients and could be a valuable tool to study cognitive process and also a potential effective approach for the diagnosis of depression.

Li Y, et al (2008) - **Abnormal EEG complexity in patients with schizophrenia and depression.** Clin Neurophysiol. 2008 Jun;119(6):1232-41. [ABS]

> In all the groups, the LZC (Lempel-Ziv complexity) of EEG decreased during the mental arithmetic compared with those under the resting conditions. Both the schizophrenia and the depression groups had a higher LZC ($p<0.05$) than the controls…. Compared with conventional spectral analysis, LZC was more sensitive to both the power spectrum and the temporal amplitude distribution. LZC was associated with the ability to attend to the task and adapt the information processing system to the cognitive challenge. …LZC of EEG is associated with mental activity. Thus, LZC analysis can be an important tool in understanding the pathophysiology of schizophrenia and depression in future studies.

Ihl R, et al (1999) - **Differential diagnosis of aging, dementia of the Alzheimer type and depression with EEG-segmentation**. Dement Geriatr Cogn Disord. 1999 Mar-Apr;10(2):64-9. [ABS]

> EEG segmentation can be used to measure altered brain function in aging and diseases of the brain. The parameter 'number of different segments' makes clear how many different potential fields are involved in brain activity during a given period of time.
>
> Aged patients with endogenous depression had more different segments than patients with mild DAT (dementia, Alzheimer type). The reduction of the number of different segments in DAT compared to controls and patients suffering from depression may be helpful for differential diagnosis. The higher number of different segments in aged versus young controls could be interpreted as a sign of increased complexity in the aged brain.

Pezard L, et al (1996) - **Depression as a dynamical disease.** Biol Psychiatry. 1996 Jun 15;39(12):991-9. [ABS]

> A previous study has shown that brain activity can be characterized by a decrease of dynamical complexity in depressive subjects. The present paper confirms and extends these conclusions through the use of recent methodological advances: first episode and recurrent patients strongly differ in their dynamical response to therapeutic interventions.

Nandrino JL, et al (1994) - **Decrease of complexity in EEG as a symptom of depression.** Neuroreport. 1994 Jan 12;5(4):528-30. [ABS]

> We demonstrate here that the EEG dynamics of major depressive subjects is more predictable, that is less complex, than that of control subjects. …Although the specificity of this dynamic signature for different stages of depression is to be confirmed, the assumption of a strong link between a healthy system and a high level of complexity in dynamics is further supported.

Development ▲

Jannesari M, et al (2020) - **Stability of neuronal avalanches and long-range temporal correlations during the first year of life in human infants**. Brain Struct Funct. 2020; 225(3): 1169–1183. [FULL TEXT]

Miskovic V, et al (2016) - **Charting moment-to-moment brain signal variability from early to late childhood**. Cortex. 2016 Oct;83:51-61. [ABS]

> Large-scale brain signals exhibit rich intermittent patterning, reflecting the fact that the cortex actively eschews fixed points in favor of itinerant wandering with frequent state transitions. Fluctuations in endogenous cortical activity occur at multiple time scales and index a dynamic repertoire of network states that are continuously explored, even in the absence of external sensory inputs. Here, we quantified such moment-to-moment brain signal variability at rest in a large, cross-sectional sample of children ranging in age from seven to eleven years. *Our findings revealed a monotonic rise in the complexity of electroencephalogram (EEG) signals as measured by sample entropy, from the youngest to the oldest age cohort, across a range of time scales and spatial regions. From year to year, the greatest changes in intra-individual brain signal variability were recorded at electrodes covering the anterior cortical zones.*

Zare M, et al (2016) - **Automatic classification of 6-month-old infants at familial risk for language-based learning disorder using a support vector machine**. Clin Neurophysiol. 2016 Jul;127(7):2695-703. [ABS]

> In comparing EEG of infants with positive family history of language-learning disorders (FH+) with those of infants with negative family history of language-learning disorders, “FH+ infants' EEG complexity patterns were significantly different from FH- infants.” The ability to identify infants at highest risk for LLD using "automatic classification"

strategies is a novel convergent approach that may facilitate earlier diagnosis and remediation.

Kaffashi F, et al (2013) - **An analysis of the kangaroo care intervention using neonatal EEG complexity: a preliminary study**. Clin Neurophysiol. 2013 Feb;124(2):238-46. [ABS]

> The SSC (skin-to-skin contact) premature neonate group had increased complexity when compared to the non-SSC premature neonate group at the same PMA…. Based on the hypothesis that EEG-derived complexity increases with neurophysiological maturation as supported by previously published research, SSC accelerates brain maturation in healthy preterm infants as quantified by time series measures of predictability when compared to a similar non-SSC group.

Vakorin VA, et al (2011) - **Variability of brain signals processed locally transforms into higher connectivity with brain development**. J Neurosci. 2011 Apr 27;31(17):6405-13. [ABS]

> We found that developmental changes were characterized by a decrease in the amount of information processed locally, with a peak in alpha frequency range. This effect was accompanied by an increase in the variability of brain signals processed as a distributed network. Complementary analysis of phase locking revealed an age-related pattern of increased synchronization in the lower part of the spectrum, up to the alpha rhythms. At the same time, we observed the desynchronization effects associated with brain development in the higher beta to lower gamma range.

Lippé S, et al (2009) - **Differential maturation of brain signal complexity in the human auditory and visual system.** Front Hum Neurosci. 2009 Nov 16;3:48. [FULL TEXT]

> Here, we show that during development, EEG signal complexity increases from one month to 5 years of age in response to auditory and visual stimulation. However, the rates of change in complexity were not equivalent for the two responses. Infants' signal complexity for the visual condition was greater than auditory signal complexity, whereas adults showed the same level of complexity to both types of stimuli.

Shahin AJ, et al (2010) - **Development of auditory phase-locked activity for music sounds**. J Neurophysiol. 2010 Jan;103(1):218-29. [FULL TEXT]

> Phase-locking for theta (4-8 Hz), alpha (8-14 Hz), lower-to-mid beta (14-25 Hz), and upper-beta and gamma (25-70 Hz) bands strengthened with age. Phase-locking in the upper-beta and gamma range matured later than in lower frequencies and was stronger for music sounds than for pure tones, likely reflecting the maturation of neural networks that code spectral complexity.

McIntosh AR, et al (2008) - **Increased brain signal variability accompanies lower behavioral variability in development.** PLoS Comput Biol. 2008 Jul 4;4(7):e1000106. [FULL TEXT]

> … brain signal variability increased with age, and showed strong negative correlations with intrasubject RT variability and positive correlations with accuracy. *Thus, maturation appears to lead to a brain with greater functional variability, which is indicative of enhanced neural complexity. This variability may reflect a broader repertoire of metastable brain states and more fluid transitions among them that enable optimum*

responses. Our results suggest that the moment-to-moment variability in brain activity may be a critical index of the cognitive capacity of the brain.

Janjarasjitt S, et al (2008) - **Nonlinear dynamical analysis of the neonatal EEG time series: the relationship between neurodevelopment and complexity**. Clin Neurophysiol. 2008 Apr;119(4):822-36. [ABS]

> In particular, the dimensional complexity tends to increase with neurodevelopment and maturation as indicated by their PMA and birth status (premature or full-term). In particular, the brain dynamics of neonates born prematurely is less complex than the brain dynamics of neonates born full-term even at the same PMA. We attribute this to differences in the neurodevelopment between these two cohorts. We propose that *the dimensional complexity can be used as an index for quantifying neurodevelopment*. SIGNIFICANCE: The dimensional complexity as measured by the correlation dimension of the sleep EEG time series may potentially be a useful measure for quantifying neurodevelopment in neonates

Anokhin AP, et al (2000) - **Complexity of electrocortical dynamics in children: developmental aspects**. Dev Psychobiol. 2000 Jan;36(1):9-22. [ABS]

> Dimensional complexity (DCx) is an EEG measure derived from nonlinear systems theory that can be indicative of the global dynamical complexity of electrocortical activity.
>
> *DCx measured both at rest and during tasks increased with age.* Specific effects of brain topography, condition, and gender became stronger with age, suggesting an increase in structural and functional differentiation of the cortex. Hemispheric asymmetry of DCx recorded during tasks also increased with age, with the task-induced DCx reduction being stronger in the left hemisphere. Gender differences in DCx suggested faster cerebral maturation in girls over late adolescence. Relationships between DCx and spectral power varied as a function of tasks and scalp locations, suggesting that these EEG measures can reflect different aspects of cortical functioning.

Hadders-Algra M (1997) - **Assessment of spontaneous motor activity in young infants: an effective method for the detection of brain function disorders**]. Ned Tijdschr Geneeskd. 1997 Apr 26;141(17):816-20. [ABS]

> A method for the assessment of the brain function of young infants was recently introduced. It consists of evaluation of the quality of spontaneously generated generalized movements (general movements, GMs). GMs appear at an early stage of pregnancy and persist until approximately the 4th month after term. Normal GMs are characterized by the triad of complexity, variation and fluency. Mildly abnormal GMs. indicating mild dysfunction of the nervous system, are not fluent but jerky or stiff. Markedly abnormal GMs, indicating major nervous system dysfunction, are characterized mostly by absence of complexity and variation of the movements: the movements are monotonous and stereotyped. The quality of the GMs can be evaluated by means of so-called global Gestalt perception. The technique can be learned in a few days. The quality of the GMs has a clear predictive significance for the child's development. Children with normal GMs will be free of handicaps in later life, whereas

three-quarters of the children showing clearly abnormal GMs throughout the postnatal GM period do develop handicaps. Assessment of the quality of the GMs is a relatively cheap, non-invasive method of evaluating the current and future brain function of young infants.

Down Syndrome ▲

Hemmati S, et al (2013) - **Down syndrome's brain dynamics: analysis of fractality in resting state.** Cogn Neurodyn. 2013 Aug; 7(4):333-40. [ABS]

> "The results showed higher fractality of the DS brain in almost all regions compared to the normal brain, which indicates less centrality and higher irregular or random functioning of the DS brain regions. Also, laterality analysis of the frontal lobe showed that the normal brain had a right frontal laterality of complexity whereas the DS brain had an inverse pattern (left frontal laterality). ...the higher EEG fractality in DS is associated with the higher fractality in the low frequencies (delta and theta), in broad regions of the brain, and the high frequencies (beta and gamma), majorly in the frontal regions."

Dyslexia ▲

Eroglu G, et al (2020) - **Changes in EEG complexity with neurofeedback and multi-sensory learning in children with dyslexia - A multiscale entropy analysis**. Appl Neuropsychol Child. 2020 Jun 9;1-12. [ABS]

> The experimental group showed significantly lower complexity at the lowest temporal scale and the medium temporal scales than the typically developing group… *Post-treatment, the experimental group's lower complexity increased to the typically developing group's levels at lower and medium temporal scales in all channels.*

Eating Disorders (Anorexia, Bullimia) ▲

Tóth E, et al (2004) - **Nonlinear and linear EEG complexity changes caused by gustatory stimuli in anorexia nervosa**. Int J Psychophysiol. 2004 Feb;51(3):253-60. [ABS]

> In anorexia nervosa patients lower-dimensional complexity was observed in the majority of recording sites than that seen in controls, independent of taste conditions. Higher Omega complexity was seen in control subjects in the left side irrespective of taste effects. No such hemispheric difference was observed in AN. The lower-dimensional complexity seen in AN patients may be caused by long-lasting effects of malnutrition. The lack of a significant Omega complexity change in response to exposure of sweet taste in the left side seen in AN patients may correspond to a decreased sensitivity to such stimuli in these subjects.

EEG Recording ▲

Trujillo LT, et al (2017) - **The Effect of Electroencephalogram (EEG) Reference Choice on Information-Theoretic Measures of the Complexity and Integration of EEG Signals**. Front Neurosci. 2017 Jul 25;11:425. [FULL TEXT]

> Our observations suggest that the Laplacian-transformation should be preferred for the computation of scalp-level CI(X) and I(X) due to its positive impact on EEG signal quality and statistics, reduction of volume-conduction, and the higher accuracy this provides when estimating scalp-level EEG complexity and integration.
>
> The second measure, called interaction complexity CI(X), is a statistical measure of a system's information content that results from the interactions among the system's elements. The relationship between complexity and integration follows an "inverted-U" non-monotonic function (Tononi et al., 1994; see Figure Figure1).1). Complexity is low at low integration values when system components are fully statistically independent; complexity is high at intermediate integration values when there is heterogenous statistical dependence among system components (i.e., when a system is highly integrated and specialized; Tononi et al., 1998a), and complexity is low at high integration values when system components are fully statistically dependent.

Zhang Y, et al (2016) - **Using Lempel-Ziv Complexity to Assess ECG Signal Quality**. J Med Biol Eng. 2016;36(5):625-634. [FULL TEXT]

> This study demonstrates that LZ complexity is sensitive to noise level (especially for HF noise) and can thus be a valuable reference index for the assessment of ECG signal quality.

Ibáñez-Molina AJ, et al (2015) - **Multiscale Lempel-Ziv complexity for EEG measures**. Clin Neurophysiol. 2015 Mar; 126(3):541-8. [ABS]

> "complexity was lower for eyes closed than for eyes open conditions."

Simons S, et al (2015) - **Volume conduction effects on bivariate Lempel-Ziv Complexity of Alzheimer's disease electroencephalograms**. Conf Proc IEEE Eng Med Biol Soc. 2015;2015:7414-7. [ABS]

> These results show that, while previously published findings are still valid, volume conduction mitigation is required to ensure non-linear signal processing methods identify changes in signals only due to the purely local signal alone.

Ahmadi K, et al (2013) - **Brain activity of women is more fractal than men**. Neurosci Lett. 2013 Feb 22; 535:7-11. [ABS]

> "The results showed significantly greater FDs in females compared to males in all brain regions except in lateral and occipital lobes. This indicates a higher complexity of the brain dynamics in females relative to males. ...The results showed that delta, alpha, and beta bands are the frequency bands that contribute most to the gender differences in

brain complexity. Furthermore, the lateralization analysis showed the leftward lateralization of complexity in females is greater than in males."

Khairuddin HR, et al (2013) - **Analysis of EEG signals regularity in adults during video game play in 2D and 3D**. Conf Proc IEEE Eng Med Biol Soc. 2013; 2013:2064-7. [ABS]

"...the complexity level increased from eyes closed to eyes open condition; and further increased in the case of 3D as compared to 2D game play."

Emotional Regulation ▲

de la Torre-Luque A, et al (2016) - **Complexity and nonlinear biomarkers in emotional disorders: A meta-analytic study**. Neurosci Biobehav Rev. 2016 Sep;68:410-422. [ABS]

Results revealed that anxious patients exhibited lower complexity than controls ($p<0.05$) despite panic patients showed more irregular respiratory activity. Inconclusive results were found for bipolar patients but pointed to higher randomness when suffering manic episodes. Finally, depressed patients showed a loss of complexity in the cardiac system and a loss of orderliness (despite a higher complexity) in brain and stress-related hormonal systems. As a conclusion, our findings highlight that either a loss of complexity or a loss of ordered complexity characterize the physiological systems of patients with emotional disorders.

Jie X, et al (2014) - **Emotion recognition based on the sample entropy of EEG**. Biomed Mater Eng. 2014;24(1):1185-92. [ABS]

Bornas X, et al (2013) - **Self-focused cognitive emotion regulation style as associated with widespread diminished EEG fractal dimension.** Int J Psychol. 2013;48(4):695-703. [ABS]

The diminished FD of the EEG may reflect a disposition to engage in self-focused ER strategies as *people prone to ruminate and self-blame show a less complex resting EEG activity, which may make it more difficult for them to exit their negative emotional state.*

Encephalopathy ▲

Popa LL, et al (2020) - **The Role of Quantitative EEG in the Diagnosis of Neuropsychiatric Disorders.** Med Life. Jan-Mar 2020;13(1):8-15. [FULL TEXT]

QEEG has brought new techniques of EEG signals feature extraction: analysis of specific frequency band and signal *complexity*, analysis of connectivity, and network analysis. The clinical application of QEEG is extensive, including neuropsychiatric disorders, epilepsy, stroke, dementia, traumatic brain injury, mental health disorders, and many others. …to date*, the role of QEEG is not necessarily to pinpoint an immediate diagnosis but to provide additional insight …and specific treatment response evaluation.*

Chen Y-M, et al (2020) - **Extreme delta brush patterns guide the complex motor phenomenon of anti-NMDA receptor encephalitis: A case report**. Medicine (Baltimore). 2020 Feb;99(9):e19384. [FULL TEXT

> A previous study has reported the "*extreme delta brush*" (EDB), a unique electroencephalography (EEG) pattern, in NMDAR encephalitis patients. EDB is present in only one third of anti-NMDAR encephalitis patients and is characterized by beta bursts overriding on delta waves in EEG analysis. [Ed. – *delta brush appears as fast waves riding on slow waves*.]

Jacob JE, et al (2018) - **Can Chaotic Analysis of Electroencephalogram Aid the Diagnosis of Encephalopathy?** Neurol Res Int. 2018 May 29;2018:8192820. [FULL TEXT]

> …significant lower values for chaotic parameters, correlation dimension, and largest Lyapunov exponent for EEG in patients with metabolic encephalopathy compared to normal EEG. The chaotic features of EEG have been shown in previous studies to be an indicator of the complexity of brain dynamics. The smaller values of chaotic features for encephalopathy suggest that *normal complexity of brain function is reduced in encephalopathy.*

Schmitt SE, et L (2012) - **Extreme delta brush: a unique EEG pattern in adults with anti-NMDA receptor encephalitis.** Neurology 2012;79:1094–100. [FULL TEXT]

Epilepsy ▲

Sathyhanarayana A, et al (2020) - **Nonlinear Analysis of Visually Normal EEGs to Differentiate Benign Childhood Epilepsy with Centrotemporal Spikes (BECTS)**. Sci Rep. 2020 May 21;10(1):8419. [FULL TEXT]

> The epileptic zone in the BECTS patients appears to exhibit lower complexity, and these nonlinear measures may potentially serve as a clinical screening tool for BECTS…

Yakovleva TV, et al (2020) **- EEG Analysis in Structural Focal Epilepsy Using the Methods of Nonlinear Dynamics (Lyapunov Exponents, Lempel-Ziv Complexity, and Multiscale Entropy).** Scientific World Journal. 2020 Feb 11;2020:8407872. [FULL TEXT]

Namazi H, et al (2020) - **Complexity-based classification of EEG signal in normal subjects and patients with epilepsy**. Technol Health Care. 2020;28(1):57-66. [ABS]

> …EEG signal during seizure has greatest complexity and the EEG signal during the seizure-free interval has lowest complexity.

Spring AM, et al (2020) - **Graph index complexity as a novel surrogate marker of high frequency oscillations in delineating the seizure onset zone.** Clin Neurophysiol. 2020 Jan;131(1):78-87. [ABS]

Wandschneider B, et al (2019) - **Developmental MRI markers cosegregate juvenile patients with myoclonic epilepsy and their healthy siblings**. Neurology. 2019 Sep 24;93(13):e1272-e1280. [FULL TEXT]

> Compared to controls, patients and siblings showed increased folding complexity and surface area in prefrontal and cingulate cortices. In these regions, they also displayed abnormally increased geodesic distance, suggesting network isolation and decreased efficiency, with strongest effects for limbic, fronto-parietal, and dorsal-attention networks.

Gao X, et al (2019) - **Automatic detection of epileptic seizure based on approximate entropy, recurrence quantification analysis and convolutional neural networks**. Artif Intell Med. 2020 Jan;102:101711. [ABS]

Zhyang M, et al (2018) - **Wavelet entropy analysis for ictal electroencephalogram signals of child absence epilepsy**. Sheng Wu Yi Xue Gong Cheng Xue Za Zhi. 2018 Aug 25;35(4):530-538. [ABS]

> The complexity of ictal EEG for CAE is obviously declined in CAE. The wavelet entropies declined could become quantitative electrophysiological parameters for epileptic seizures, and it also could provide a theoretical basis for the study of neuromodulation techniques in epileptic seizures.

Mei Z, et al (2018) - **Bio-Signal Complexity Analysis in Epileptic Seizure Monitoring: A Topic Review**. Sensors (Basel). 2018 May 26;18(6):1720. [FULL TEXT]

> These discoveries have revealed that complexity is a fundamental aspect of physiological processes. The inherent nonlinearity and non-stationarity of physiological processes limits the methods based on simpler underlying assumptions to point out the pathway to a more comprehensive understanding of their behavior and relation with certain diseases. The perspective of complexity may benefit both the research and clinical practice through providing novel data analytics tools devoted for the understanding of and the intervention about epilepsies.

Liu H, et al (2017) **- Impairment of heart rhythm complexity in patients with drug-resistant epilepsy: An assessment with multiscale entropy analysis**. Epilepsy Res. 2017 Dec;138:11-17. [ABS]

> The heart rate complexity is impaired for DRE patients. Complexity indices (CI) are useful to discriminate DRE patients from subjects with normal cardiac complexity. These findings indicate that MSE method may serve as a complementary approach for characterizing and understanding abnormal heart rate dynamics in epilepsy. Furthermore, the CI may potentially be used as a biomarker in monitoring epilepsy.

Zavala-Yoe R, et al (2017) - **Dynamic complexity measures and entropy paths for modelling and comparison of evolution of patients with drug resistant epileptic encephalopathy syndromes (DREES).** Metab Brain Dis. 2017 Jun 9. [ABS]

Noel JP, et al (2017) - **Multisensory temporal function and EEG complexity in patients with epilepsy and psychogenic nonepileptic events**. Epilepsy Behav. 2017 May;70(Pt A):166-172. [ABS]

> …patients with PNEE bind information from audition and vision over larger temporal intervals when compared with control subjects as well as patients with epilepsy. This difference in multisensory function appears to be specific to the temporal domain, and may be a contributing factor to the behavioral and perceptual alterations seen in this population.

Li P, et al (2016) - **Classification of 5-S Epileptic EEG Recordings Using Distribution Entropy and Sample Entropy.** Front Physiol. 2016 Apr 14;7:136. [FULL TEXT]

> … Distribution Entropy performed robustly for short-length EEG data indicating relative independence from input parameters and small intra-class fluctuations. In addition, it showed acceptable performance for all three classification problems (interictal EEG from normal, ictal EEG from normal, and ictal EEG from interictal) compared to SampEn, which showed better results only for distinguishing normal EEG from interictal and ictal. Both SampEn and DistEn showed good reproducibility and consistency, as evidenced by the independence of results on analyzing protocol.

Li WY, et al (2015) - **Multiscale Entropy of Electroencephalogram as a Potential Predictor for the Prognosis of Neonatal Seizures.** PLoS One. 2015 Dec 11;10(12):e0144732. [Full Text]

> Decreased multiscale entropy (MSE) and complexity index (CI) values in patients with neonatal seizures and later epilepsy may reflect the mixed effects of acute insults, underlying brain immaturity, and prolonged seizures-related injuries. The analysis of MSE and CI can therefore provide a quantifiable and accurate way to decrypt the mystery of neonatal seizures, and could be a promising predictor.

Weng WC, et al (2015) - **Complexity of Multi-Channel Electroencephalogram Signal Analysis in Childhood Absence Epilepsy.** PLoS One. 2015 Aug 5; 10(8):e0134083. [FULL TEXT]

> "...the complexity of EEG signals in the ictal state are decreased, apparently mainly over the frontal and central regions…

Bob P, et al (2014) **- Preictal dynamics of EEG complexity in intracranially recorded epileptic seizure: a case report.** Medicine (Baltimore). 2014 Nov; 93(23):e151. [ABS]

> "Recent findings suggest that neural complexity reflecting a number of independent processes in the brain may characterize typical changes during epileptic seizures and may enable to describe preictal dynamics. …there was a statistically significant decrease in PD2 complexity in the preictal period at about 2 minutes before seizure onset in all 64 intracranial channels localized in various brain sites that were included into the analysis and in 3 scalp EEG channels as well."

Artan NS (2016) - **EEG analysis via multiscale Lempel-Ziv complexity for seizure detection**. Conf Proc IEEE Eng Med Biol Soc. 2016 Aug;2016:4535-4538. [ABS]

Protzner AB, et al (2010) - **Hippocampal signal complexity in mesial temporal lobe epilepsy: a noisy brain is a healthy brain.** Arch Ital Biol. 2010 Sep;148(3):289-97. [ABS]

> Using multiscale entropy (MSE) as a measure of complexity, we found that iEEG from the epileptogenic hippocampus showed less complexity than iEEG from the healthy hippocampus.

Jouny CC, et al (2010) - **Partial seizures are associated with early increases in signal complexity**. Clin Neurophysiol. 2010 Jan;121(1):7-13. [FULL TEXT]

> Partial onset seizures are associated with early increases in signal complexity as measured by GAD. This increase is independent of the location of the seizure focus. (Gabor atom density (GAD) measure of signal complexity.)

Executive Functioning ▲

Grundy JG, et al (2019) - **The relation between brain signal complexity and task difficulty on an executive function task.** Neuroimage 2019 Sep;198:104-113. [ABS]

> Brains become more efficient and are able to switch states more readily by increasing the complexity of their neural networks. ...*brain signal complexity in young adults increases as task demands increase,* that increases in brain signal complexity are associated with both speed gains and losses depending on scalp location, and that more difficult tasks are associated with more circumscribed complexity across the scalp. Overall, these findings highlight a critical role for brain signal complexity in predicting behavior on an executive function task among young adults.

Gao J, et al (2019) - **Deception Decreases Brain Complexity**. IEEE J Biomed Health Inform. 2019 Jan;23(1):164-174. [ABS]

> Our findings indicate that the lying task elicits a more ordered brain activity in some specific brain regions than the task of telling the truth. This study not only demonstrates that improved WE measurements could be a powerful quantitative index for detecting lying but also sheds light on the brain mechanisms underlying deceptive behaviors.

Liang WK, et al (2014) - **Revealing the brain's adaptability and the transcranial direct current stimulation facilitating effect in inhibitory control by multiscale entropy**. Neuroimage. 2014 Apr 15; 90:218-34. [ABS]

> "... participants who suffer from poor inhibitory control can efficiently improve their performance with 10 min of electrical stimulation, and such cognitive improvement can be effectively traced back to the complexity within the EEG signals via MSE analysis, thereby offering a theoretical basis for clinical intervention via tDCS for deficits in inhibitory control."

Exercise ▲

Amjad I, et al (2019) - **Therapeutic effects of aerobic exercise on EEG parameters and higher cognitive functions in mild cognitive impairment patients**. Int J Neurosci. 2019 Jun;129(6):551-562. [ABS]

> After one session of aerobic exercise there were significant improvements in slowness (delta waves) and complexity. … Aerobic exercise showed improvement in cognition after short and long-term treatment in MCI subjects and can be used as potential therapeutic candidate.

Wang C-H, et al (2019) - **Aerobic exercise modulates transfer and brain signal complexity following cognitive training.** Biol Psychol. 2019 May;144:85-98. [ABS]

> …we used multiscale entropy (MSE) of electroencephalography (EEG)-a measure of brain signal complexity…the addition of antecedent physical exercise to brain training regimen could enable wider, more robust improvements.

Hogan MJ, et al (2015) - **The effects of cardiorespiratory fitness and acute aerobic exercise on executive functioning and EEG entropy in adolescents.** Front Hum Neurosci. 2015 Oct 19;9:538. [FULL TEXT]

> The results suggest that EEG entropy is sensitive to stimulus processing demands and varies as a function of physical fitness levels, but not acute exercise. Physical fitness, in turn, may enhance cognition in adolescence by facilitating higher functionality of the attentional system in the context of lower levels of frontal EEG entropy.

Wang C-H, et al (2014) - **The association of physical activity to neural adaptability during visuo-spatial processing in healthy elderly adults: A multiscale entropy analysis.** Brain Cogn. 2014 Dec;92C:73-83. [ABS]

> The results suggest that physical activity may be beneficial for adaptability of brain systems in tasks involving visuo-spatial information. MSE thus might be a promising approach to test the effects of the benefits of exercise on cognition

Heart / Heart Rate Variability ▲

Gibson LE, et al (2020) - **Comparison of Invasive and Noninvasive Blood Pressure Measurements for Assessing Signal Complexity and Surgical Risk in Cardiac Surgical Patients.** Anesth Analg. 2020 Jun;130(6):1653-1660. [ABS]

> Beat-to-beat fluctuations in noninvasive ABP measurements were not random but complex; however, their degree of complexity was lower than that of fluctuations in invasively obtained ABP signals…The complexity of noninvasive ABP time series, like that of invasive time series, was inversely associated with estimated surgical risk in patients undergoing cardiovascular operations.

Matić, et al (2020) - **Slow 0.1 Hz Breathing and Body Posture Induced Perturbations of RRI and Respiratory Signal Complexity and Cardiorespiratory Coupling.** Front Physiol. 2020 Feb 14;11:24. [FULL TEXT]

These results support the hypothesis of hierarchical organization of cardiorespiratory complexity mechanisms and their recruitment in ascendant manner with respect to the increase of behavioral challenge complexity. Specific and comprehensive *cardiorespiratory regulation in standing with 0.1 Hz breathing suggests this state as the potentially most beneficial maneuver for cardiorespiratory conditioning*.

Valderas MT, et al (2019) - **Mutual information between heart rate variability and respiration for emotion characterization**. Physiol Meas. 2019 Sep 3;40(8):084001. [ABS]

…human emotion manifested in the HRV and respiratory signal responses could be characterized by means of the information-content complexity.

Riganello F, et al (2018) - **A Heartbeat Away From Consciousness: Heart Rate Variability Entropy Can Discriminate Disorders of Consciousness and Is Correlated with Resting-State fMRI Brain Connectivity of the Central Autonomic Network.** Front Neurol. 2018; 9: 769. [FULL TEXT]

Complexity Index of Minimally Conscious State compared to Unresponsive Wakefulness Syndrome patients "has high discriminative power and low false negative rate at one third of the estimated human assessors' misdiagnosis, providing an easy, inexpensive and non-invasive diagnostic tool. CI reflects functional connectivity changes in the CAN, suggesting that CI can provide an indirect way to screen and monitor connectivity changes in this neural system."

Ruiz-Padial E, et al (2018) - **Fractal dimension of EEG signals and heart dynamics in discrete emotional states**. Biol Psychol. 2018 Sep;137:42-48. [ABS]

Humor elicited the highest FD scores in most EEG channels and the highest HRV, while fear, among all emotions, produced the lowest scores in both measures. These results may contribute to the understanding of the relationship between cortical and heart dynamics and their role on emotion perception.

Wang G, et al (2018) - **Exploring the Relationship between Blood Flux Signals and HRV following Different Thermal Stimulations using Complexity Analysis**. Sci Rep. 2018; 8: 8982. [FULL TEXT]

A 42° C or 44° C thermal stimulation, other than stimulations below 42° C, resulted in a moderate correlation between local blood flux and heart rate variability complexity. The results provide a new perspective in terms of complexity to explore the relationship between skin blood flux signals and cardiac function.

Padley JR, et al (2018) - **Low pre-operative heart rate variability and complexity are associated with hypotension after anesthesia induction in major abdominal surgery**. J Clin Monit Comput. 2018 Apr;32(2):245-252. [ABS]

… post-induction hypotension and lower HRV may be associated with severity of illness or poor physiological reserve. Pre-operative HRV was a useful screening tool in identifying patients undergoing major abdominal surgery who were at risk of haemodynamic instability after anesthesia induction.

Horie T, et al (2018) - **Sample Entropy in Electrocardiogram during Atrial Fibrillation**. Yonago Acta Med. 2018 Mar 28;61(1):49-57. [FULL TEXT]

> The values of SampEn from ECG for chronic AF patients were higher than for subjects without arrhythmia, suggesting greater complexity for the time-series from chronic AF patients. SampEn is considered a new index for evaluating complex systems in ECG.

Liu H, et al (2017) **- Impairment of heart rhythm complexity in patients with drug-resistant epilepsy: An assessment with multiscale entropy analysis**. Epilepsy Res. 2017 Dec;138:11-17. [ABS]

> The heart rate complexity is impaired for DRE patients. Complexity indices (CI) are useful to discriminate DRE patients from subjects with normal cardiac complexity. These findings indicate that MSE method may serve as a complementary approach for characterizing and understanding abnormal heart rate dynamics in epilepsy. Furthermore, the CI may potentially be used as a biomarker in monitoring epilepsy.

Fiskum C, et al (2017) - **Cardiac complexity and emotional dysregulation in children.** Int J Psychophysiol. 2017 Nov;121:38-45. [ABS]

> Sample entropy (SampEn) gives an estimate of signal complexity in cardiac time series and can give information beyond linear heart rate variability. Lower cardiac SampEn is associated with psychopathology in adults. Emotional dysregulation is widely present in adult psychopathology and a forerunner to later mental problems in children.

Schlemmer A, et al (2017) - **Detection and characterization of intermittent complexity variations in cardiac arrhythmia**. Physiol Meas. 2017 Jul 26;38(8):1561-1575. [ABS]

Bugalho P, et al (2017) - **Heart rate changes according to the complexity of motor events in REM sleep behavior disorder.** Clin Neurophysiol. 2017 Jul;128(7):1317-1318. [ABS]

> Reduced Heart Rate Variability (HRV) is considered a marker of autonomic system dysfunction in REM sleep behavior disorder (RBD) (Fantini et al., 2002; Sorensen et al., 2012). Blunted Heart Rate (HR) response was described in RBD and Parkinson's Disease (PD) patients following limb movements during sleep (Fantini et al., 2002; Sorensen et al., 2012) and in PD after arousals (Sorensen et al., 2012). We found no study on the effect of RBD motor events (ME) on HR. RBD related ME can be classified in two types: short lasting, small amplitude, non-purposeful movements and complex, scenic ones, in which patients enact the content of their dreams, usually negative or violent (Frauscher et al., 2007).

Chiu HC, et al (2017) - **Serial heart rhythm complexity changes in patients with anterior wall ST segment elevation myocardial infarction**. Sci Rep. 2017 Mar 2;7:43507. [FULL TEXT]

Calvo M, et al (2017) **- Heart rate complexity analysis in Brugada syndrome during physical stress testing**. Physiol Meas. 2017 Feb;38(2):387-396. [ABS]

Silva LE, et al (2017) - **The role of sympathetic and vagal cardiac control on complexity of heart rate dynamics**. Am J Physiol Heart Circ Physiol. 2017 Mar 1;312(3):H469-H477. [ABS]

Marwaha P, et al (2017) **- Exploring total cardiac variability in healthy and pathophysiological subjects using improved refined multiscale entropy.** Med Biol Eng Comput. 2017 Feb;55(2):191-205. [ABS]

> The results strongly support the reduction in complexity of HRV time series in female group, old-aged, patients suffering from severe cardiovascular and non-cardiovascular diseases, and in their corresponding surrogate time series.

Balasubramanian K, et al (2016) - **Aging and cardiovascular complexity: effect of the length of RR tachograms**. PeerJ. 2016 Dec 6;4:e2755. [FULL TEXT]

> As we age, our hearts undergo changes that result in a reduction in complexity of physiological interactions between different control mechanisms. This results in a potential risk of cardiovascular diseases which are the number one cause of death globally. Since cardiac signals are nonstationary and nonlinear in nature, complexity measures are better suited to handle such data. In this study, three complexity measures are used, namely Lempel–Ziv complexity (LZ), Sample Entropy (SampEn) and Effort-To-Compress (ETC). We determined the minimum length of RR tachogram required for characterizing complexity of healthy young and healthy old hearts. All the three measures indicated significantly lower complexity values for older subjects than younger ones.

Schnettler WT, et al (2016) - **Complexity analysis of fetal heart rate preceding intrauterine demise**. Eur J Obstet Gynecol Reprod Biol. 2016 Aug;203:286-90. [FULL TEXT]

Brindle RC, et al (2016) - **Heart rate complexity: A novel approach to assessing cardiac stress reactivity**. Psychophysiology. 2016 Apr;53(4):465-72. [ABS]

> Correlation dimension (D2), a measure of heart rate (HR) complexity, has been shown to decrease in response to acute mental stress and relate to adverse cardiovascular health. …correlation dimension remained an independent predictor of HR reactivity in a hierarchical linear model containing measures of cardiac parasympathetic and sympathetic activity and their interaction. These results suggest that correlation dimension may provide additional information regarding cardiac stress reactivity above that provided by traditional measures of cardiac autonomic function.

Vanderlei FM, et al (2016) - **Symbolic analysis of heart rate variability during exposure to musical auditory stimulation**. Altern Ther Health Med. 2016 Mar-Apr;22(2):24-31. [ABS]

> Auditory stimulation with the heavy-metal music reduced the parasympathetic modulation of HRV, whereas no significant changes occurred in cardiac autonomic modulation during exposure to the classical music.

Karmakar C, et al (2015) - Distribution Entropy (DistEn): **A complexity measure to detect arrhythmia from short length RR interval time series.** Conf Proc IEEE Eng Med Biol Soc. 2015;2015:5207-10. [ABS]

Chen CH, et al (2015) - **Complexity of Heart Rate Variability Can Predict Stroke-In-Evolution in Acute Ischemic Stroke Patients.** Sci Rep. 2015 Dec 1;5:17552. [FULL TEXT]

> After adjustment for clinical variables, patients with higher complexity index values were significantly less likely to have stroke-in-evolution (SIE) ... In summary, early assessment of HRV by MSE can be a potential predictor of SIE in ICU-admitted non-AF ischemic stroke patients.

Karmakar C, et al (2015) - **Distribution Entropy (DistEn): A complexity measure to detect arrhythmia from short length RR interval time series.** Conf Proc IEEE Eng Med Biol Soc. 2015;2015:5207-10. [ABS]

> Heart rate complexity analysis is a powerful non-invasive means to diagnose several cardiac ailments. Non-linear tools of complexity measurement are indispensable in order to bring out the complete non-linear behavior of Physiological signals. … DistEn shows a promising behavior as bio marker for detecting Arrhythmia from short length RR interval data.

Chang MC, et al (2014) - **Emergence of dynamical complexity related to human heart rate variability**. Phys Rev E Stat Nonlin Soft Matter Phys. 2014 Dec;90(6):062806. [ABS]

> By tuning the adaptability of the environment and the long-range shortcuts we can increase or decrease the dynamical complexity, thereby modeling trends found in the MSE of a healthy human heart rate in different physiological states. When the shortcut and adaptability values increase, the complexity in the system dynamics becomes uncorrelated.

Lin P-F, et al (2014) - **Correlations between the Signal Complexity of Cerebral and Cardiac Electrical Activity: A Multiscale Entropy Analysis**. PLoS ONE 9(2): e87798. [FULL TEXT]

> With the deterioration of health conditions, the change in dynamic patterns of biological signals is characterized by *loss of complexity and development of stereotypy*...
>
> Previous evidence showing decreased EEG complexity in dementia only used statistics for group comparison... but we found a proportional relationship between the brain signal variability and cognitive test score at electrode F8

Hypoglycemia ▲

Fabris C, et al (2014) - **Hypoglycemia-related electroencephalogram changes assessed by multiscale entropy.** Diabetes Technol Ther. 2014 Oct; 16(10):688-94. [ABS]

> "*A decrease in the complexity of EEG occurs when a state of hypoglycemia is entered, because of a degradation of the EEG long-range temporal correlations*."

Hypoxia ▲

Jernajczyk W, et al (2006) - **The influence of acute progressive hypoxia on bioelectrical activity of the brain.** J Physiol Pharmacol. 2006 Sep;57 Suppl 4:165-74. [ABS]

Cortical activity changes appeared, however, in the subjects who experienced emotional distress during the test. These changes were apparent on an expanded analysis of the EEG signal by the use of the Lempel-Ziv complexity that takes into account the ordering of variations in the signal, rather than only the relative frequency of events analyzed by the Shannon entropy. The Lempel-Ziv complexity offers promise as a novel method for unraveling fine and otherwise unexpressed alterations in cortical bioelectrical activity.

Papadelis C, et al (2007) **- The effect of hypobaric hypoxia on multichannel EEG signal complexity**. Clin Neurophysiol. 2007 Jan;118(1):31-52. [ABS]

A significant increase in total power and power of theta and alpha bands was observed during hypoxia. Visual interpretation of ApEn time-courses revealed a characteristic pattern (decreasing during hypoxia and recovering after oxygen re-administration).

Mental Illness ▲

Hager B, et al (2017) - **Neural complexity as a potential translational biomarker for psychosis**. J Affect Disord. 2017 Jul;216:89-99. [ABS]

These observations support the loss of brain complexity hypothesis in psychotic probands. Furthermore, we found significant differences as well as overlaps of pathologic brain signal complexity between psychotic probands by DSM diagnoses, thus suggesting a biological approach to categorizing psychosis based on functional neuroimaging data.

Nenadic I, et al (2017) - **Cortical complexity in bipolar disorder applying a spherical harmonics approach**. Psychiatry Res. 2017 May 30;263:44-47. [ABS]

Recent studies using surface-based morphometry of structural magnetic resonance imaging data have suggested that some changes in bipolar disorder (BP) might be proteneurodevelopmental in origin. We applied a novel analysis of cortical complexity based on fractal dimensions in high-resolution structural MRI scans of 18 bipolar disorder patients and 26 healthy controls. Our region-of-interest based analysis revealed increases in fractal dimensions (in patients relative to controls) in left lateral orbitofrontal cortex and right precuneus, and decreases in right caudal middle frontal, entorhinal cortex, and right pars orbitalis, and left fusiform and posterior cingulate cortices. While our analysis is preliminary, it suggests that early neurodevelopmental pathologies might contribute to bipolar disorder, possibly through genetic mechanisms.

Weng WC, et al (2017) - **Altered resting-state EEG complexity in children with Tourette syndrome: A preliminary study.** Neuropsychology. 2017 May;31(4):395-402. [ABS]

Except for the Fp2 channel, the complexity index values in all channels were reduced in children with Tourette syndrome compared with those in normal controls. A statistically significant reduction in EEG complexity was found in the bilateral central, parietal, occipital, and left temporal regions, indicating disturbed brain connectivity in Tourette syndrome. Although there was no difference of complexity in the higher frequency

spectra, there was a statistically significant difference of complexity in lower frequency in F3 channel, pointing to the importance of examining a range of time scales in exploring EEG signals.

Hopkins J (2016) - **Free Energy and Virtual Reality in Neuroscience and Psychoanalysis: A Complexity Theory of Dreaming and Mental Disorder**. Front Psychol. 2016; 7: 922. [FULL TEXT]

> In Friston's account (variational) FE equals complexity minus accuracy, and is minimized by increasing accuracy and decreasing complexity. Roughly the brain (or model) increases accuracy together with complexity in waking. This is mediated by consciousness-creating active inference—by which it explains sensory impingements in terms of perceptual experiences of their causes. In sleep it reduces complexity by processes that include both synaptic pruning and consciousness/virtual reality/dreaming in REM. The consciousness-creating active inference that effects complexity-reduction in REM dreaming must operate on FE-arousing data distinct from sensory impingement.

Yang AC, et al (2013) - **Is mental illness complex? From behavior to brain**. Prog Neuropsychopharmacol Biol Psychiatry. 2013 Aug 1; 45:253-7. [ABS]

> "…that *mental illness is loss of brain complexity* and the complexity of mental illness can be studied under a general framework by quantifying the order and randomness of dynamic macroscopic human behavior and microscopic neuronal activity."

Fernández A, et al (2010) - **Analysis of brain complexity and mental disorders.** Actas Esp Psiquiatr. 2010 Jul-Aug;38(4):229-38. [ABS]

> … the analysis of brain signals' complexity has been broadly utilized in the investigation of psychiatric disorders. Parameters of EEG-MEG complexity usually estimate the predictability of brain oscillations and/or the number of independent oscillators underlying the observed signals. More importantly, complexity parameters seem to be sensitive to the temporal components of brain activity, and therefore might reflect the dynamical nature of psychiatric disorders. This paper reviews some of the most relevant studies within this field, especially those focusing on the diagnosis, follow-up and prediction of response to treatment.

Memory ▲

Sheehan TC, et al (2018) - **Signal Complexity of Human Intracranial EEG Tracks Successful Associative-Memory Formation across Individuals.** J Neurosci. 2018 Feb 14;38(7):1744-1755. [FULL TEXT]

> High-performing individuals consistently exhibited *less broadband power*, flatter power spectral density slopes, and *greater complexity* in their iEEG signals. Furthermore, within individuals across three separate time scales ranging from seconds to days, successful recall was positively associated with these same metrics. Our data therefore suggest *that memory ability across individuals can be indexed by increased neural signal complexity*.

Migraine ▲

Cao Z, et al (2018) - **Exploring resting-state EEG complexity before migraine attacks**. Cephalalgia. 2018 Jun;38(7):1296-1306. [ABS]

> The electroencephalogram complexity of patients in the preictal phase, which resembled that of normal control subjects, was significantly higher than that of patients in the interictal phase in the prefrontal area … but not in the occipital area.

Strenge H, et al (2001) - **Non-linear electroencephalogram dynamics in patients with spontaneous nocturnal migraine attacks.** Neurosci Lett. 2001 Aug 24;309(2):105-8. [ABS]

> There was, however, a loss of dimensional complexity in the first two non-rapid eye movement sleep states in the migraine night, with statistical significance during the second sleep cycle. For the first time, these results provide evidence of a global dimension decrease that is related to cortical network changes during a migraine attack.

Mindfulness ▲

Kakumanu RJ, et al (2018) - **Dissociating meditation proficiency and experience dependent EEG changes during traditional Vipassana meditation practice**. Biol Psychol. 2018 May;135:65-75. [ABS]

> …only Teachers showed consistent increase in network complexity from baseline rest and state transitions between the different meditation states.

Sik HH, et al (2017) - **Using Wavelet Entropy to Demonstrate how Mindfulness Practice Increases Coordination between Irregular Cerebral and Cardiac Activities**. J Vis Exp. 2017 May 10;(123). [ABS]

> Using the proposed method, the results consistently showed that the wavelet entropy of the brain EEG decreased during the MBSR mindful breathing state as compared to that during the closed-eye resting state.
>
> …a significant correlation was observed during MBSR mindful breathing between the entropy of brain waves and the entropy of heartrate during normal rest in all participants. … Additionally, the most well-correlated brain regions were located in the central areas of the brain. This study provides a methodology for the establishment of evidence that mindfulness practice (i.e., mindful breathing) may increase the coordination between mind and heart activities.

Ibanez-Molina AJ, et al (2016) - **Neurocomputational Model of EEG Complexity during Mind Wandering**. Front Comput Neurosci. 2016; 10: 20. [FULL TEXT]

Gao J, et al (2016) - **Entrainment of chaotic activities in brain and heart during MBSR mindfulness training**. Neurosci Lett. 2016 Mar 11;616:218-23. [FULL TEXT]

We found enhancement of EEG power of alpha and beta waves and lowering of delta waves power during MBSR training state as compared to normal resting state. Wavelet entropy analysis indicated that MBSR mindfulness meditation could reduce the chaotic activities of both EEG and heart rate as a change of state. However, longitudinal change of trait may need more long-term training. For the first time, our data demonstrated that the chaotic activities of the brain and the heart became more coordinated during MBSR training, suggesting that mindfulness training may increase the entrainment between mind and body. The 3D brain regions involved in the change in mental states were identified.

Movement / Posture ▲

Chettouf S, et al (2020) **- Are unimanual movements bilateral?** Neurosci Biobehav Rev. 2020 Jun;113:39-50. [ABS]

> ...lateralized activity in left (pre)motor cortex modulates with task complexity, independently of the type of task and the end-effector involved. Despite this lateralization, however, our review supports the idea of bi-hemispheric cortical activation being a fundamental mode of upper extremity motor control.

Wilkins KB, et al (2020) - **Coordination of multiple joints increases bilateral connectivity with ipsilateral sensorimotor cortices**. Neuroimage. 2020 Feb 15; 207: 116344. [FULL TEXT]

> …increasing the task complexity by combining hand opening while lifting at the shoulder also led to an increase in cross-frequency coupling within the ipsilateral hemisphere including theta, beta, and gamma frequencies, as well as a change in the coupling frequency of the interhemispheric coupling between the primary motor and premotor cortices. These findings demonstrate that increasing the demand of joint coordination between proximal and distal joints leads to increases in communication with the ipsilateral hemisphere as previously observed in distal sequential finger tasks.

Shafer RL, et al (2019) - **Visual feedback during motor performance is associated with increased complexity and adaptability of motor and neural output**. Behav Brain Res. 2019 Dec 30;376:112214. [ABS]

> Consistent with previous literature, motor performance and its complexity were higher when visual feedback was provided relative to when it was withheld. The complexity of the neural signal was also higher when visual feedback was provided. This was most robust at frequency bands (alpha and beta) and scalp regions (parietal and occipital) associated with sensorimotor processing. The findings show that visual feedback increases the information available to the brain when generating complex, adaptive motor output.

Kamal SM, et al (2019) - **Decoding of the relationship between human brain activity and walking paths**. Technol Health Care. 2019 Nov 14. [ABS]

The results of the analysis show that *the complexity of brain activity increases with the increment of complexity of path of movement.* The method of analysis employed in this research can also be employed to analyze the reaction of the human heart and respiration when subjects move on paths with different complexities.

Clark DJ, et al (2019) - **Multimodal Imaging of Brain Activity to Investigate Walking and Mobility Decline in Older Adults (Mind in Motion Study): Hypothesis, Theory, and Methods.** Front Aging Neurosci v.11; 2019 [FULL TEXT]

Our hypothesis is that age-related walking deficits are explained in part by the Compensation Related Utilization of Neural Circuits Hypothesis (CRUNCH). CRUNCH is a well-supported model that describes the over-recruitment of brain regions exhibited by older adults in comparison to young adults, even at low levels of task complexity.

Zhou J, et al (2017) - **The Complexity of Standing Postural Sway Associates with Future Falls in Community-Dwelling Older Adults:** The MOBILIZE Boston Study. Sci Rep. 2017 Jun 7;7(1):2924. [FULL TEXT]

Notably, participants in the lowest quintile of complexity during dual-task standing suffered 48% more falls during the four-year follow-up as compared to those in the highest quintile (IRR = 1.48, p = 0.01, 95% CL = 1.09-1.99). Conversely, traditional postural sway metrics or SPPB performance did not associate with future falls. As compared to traditional metrics*, the degree of multi-scale complexity contained within standing postural sway-particularly during dual task conditions- appears to be a better predictor of future falls in older adults.*

Zago M, et al (2017) - **Multi-segmental movement patterns reflect juggling complexity and skill level**. Hum Mov Sci. 2017 Aug;54:144-153. [ABS]

. We observed that: experience-related modifications in multi-segmental actions exist, such as the progressive reduction of error-correction movements, especially in complex task condition. The systematic identification of motor patterns sensitive to the acquisition of specific experience could accelerate the learning process.

Vieira MF, et al (2017) - **Gait stability, variability and complexity on inclined surfaces**. J Biomech. 2017 Mar 21;54:73-79. [ABS]

Almurad ZMH, et al (2017) - **Complexity matching in side-by-side walking**. Hum Mov Sci. 2017 Aug;54:125-136. [ABS]

We contrasted three conditions: independent walking, side-by-side walking, and arm-in-arm walking. The results are consistent with the complexity matching hypothesis.

Park SW, et al (2017) - **Moving slowly is hard for humans: limitations of dynamic primitives**. J Neurophysiol. 2017 Jul 1;118(1):69-83. [ABS]

Magnani RM, et al (2017) - **Local dynamic stability and gait variability during attentional tasks in young adults**. Gait Posture. 2017 Jun;55:105-108. [ABS]

Local dynamic stability measured in terms of the largest Lyapunov exponent decreased while handling a cell phone (talking and texting). Gait variability and regularity increased

when talking on a cell phone. We conclude that young adults who use a cell phone when walking adapt their gait pattern conservatively, which can be because of increased attentional demand during cell phone use.

Ma S, et al (2017) - **Investigation on Inter-Limb Coordination and Motion Stability, Intensity and Complexity of Trunk and Limbs during Hands-Knees Crawling in Human Adults**. Sensors (Basel). 2017 Mar 28;17(4). pii: E692. [FULL TEXT]

Yamagata M, et al (2017) - **Correlation between movement complexity during static standing and balance function in institutionalized older adults**. Clin Interv Aging. 2017 Mar 8;12:499-503. [FULL TEXT]

> Sample entropy (SampEn) is an analysis to evaluate movement complexity of the center of pressure (COP). A lower value of SampEn indicates lower complexity of COP variability, that is, rigidity, and lower degrees of freedom. Previous studies reported the association of increased SampEn with improved standing balance ability in young subjects. Lower SampEn implies rigidity for postural control. In the present study, it was found that lower SampEn in the sagittal plane was related to a higher balance function, which suggests that older adults utilized body rigidity to maintain postural stability as a compensative strategy.

Bauer CM, et al (2017) - **The effect of muscle fatigue and low back pain on lumbar movement variability and complexity**. J Electromyogr Kinesiol. 2017 Apr;33:94-102. [ABS]

> The effects indicate that pain free participants showed more complex and less predictable lumbar movement with a lower degree of structure in its variability following fatigue while participants suffering from LBP did not. This may be physiological responses to avoid overload of fatigued tissue, increase endurance, or a consequence of reduced movement control caused by fatigue

Niermeyer MA, et al (2017) - **Motor sequencing in older adulthood: relationships with executive functioning and effects of complexity**. Clin Neuropsychol. 2017 Apr;31(3):598-618. [ABS]

> These results clarify prior findings by showing (a) more aspects of motor sequencing relate to executive functioning for older compared to younger adults and (b) for these unique relationships, executive functioning is only related to action during the generation of sequences that are complex.

Gao F, et al (2017) - **Altered Resting-State EEG Microstate Parameters and Enhanced Spatial Complexity in Male Adolescent Patients with Mild Spastic Diplegia**. Brain Topogr. 2017 Mar;30(2):233-244. [ABS]

> Microstate analysis revealed that the occurrence rate of microstate class A and D were significantly higher and the duration of microstate class B was significantly lower in the patients compared to healthy controls, which indicated that the temporal complexity may be higher and certain cognitive functions may be impaired in these patients. Omega complexity analysis showed that the global omega complexity of alpha-2 band was significantly higher in the patients than the controls. Besides, compared to the anterior

> regional omega complexities, the posterior regional omega complexities were significantly lower in the delta, theta, alpha-1 and alpha-2 bands, but significantly higher in the beta-2 and gamma-1 bands. And the regional omega complexities in the delta, theta and alpha-1 bands were significantly higher in the patients than controls. The present study reveals that in male adolescent patients with MSD, the temporal and spatial complexities of EEG signal are enhanced, which may be closely associated with the altered brain functions in these patients.

Zapata-Fonseca L, et al (2016) - **Time-series analysis of embodied interaction: movement variability and complexity matching as dyadic properties**. Front Psychol. 2016 Dec 12;7:1940. [FULL TEXT]

Fino PC, et al (2016) - **Decreased high-frequency center-of-pressure complexity in recently concussed asymptomatic athletes**. Gait Posture. 2016 Oct;50:69-74. [ABS]

> This decrease in entropy may associate with reported increases in intra-cortical inhibition. Furthermore, a single-case study suggested high frequency MV-CompMSE may be a useful clinical tool for concussion management.

Bisi MC, et al (2016) - **Complexity of human gait pattern at different ages assessed using multiscale entropy: From development to decline**. Gait Posture. 2016 Jun;47:37-42. [ABS]

> From young adults to elderlies a slight increase in sample entropy (SEN) values was shown although not statistically significant. While performance gait parameters showed adolescent gait similar to the one of adults, SEN highlighted that their gait maturation is not complete yet. In conclusion, present results suggest that the *complexity of gait, evaluated on the sagittal plane, can be used as a characterizing parameter of the maturation of gait control.*

Barbosa TM, et al (2016) - **Comparison of classical kinematics, entropy, and fractal properties as measures of complexity of the motor system in swimming**. Front Psychol. 2016 Oct 7;7:1566. [FULL TEXT]

> The hip's speed-data as a function of time was collected with a speedo-meter. The speed fluctuation (dv), approximate entropy (ApEn) and the fractal dimension by Higuchi's method (D) were computed. … It can be concluded that swimming data exhibits non-linear properties, which are different among the four competitive swimming strokes.

Hollman JH, et al (2016) - **Complexity, fractal dynamics and determinism in treadmill ambulation: Implications for clinical biomechanists**. Clin Biomech (Bristol, Avon). 2016 Aug;37:91-97. [ABS]

> Reduced inter-stride complexity during ambulation may represent a pathologic state. Evidence is emerging that *treadmill training for rehabilitative purposes may constrain the locomotor system and alter gait dynamics in a way that mimics pathological states*. The purpose of this study was to examine the dynamical system components of gait complexity, fractal dynamics and determinism during treadmill ambulation.

Zhou J, et al (2016) - **Sub-sensory vibratory noise augments the physiologic complexity of postural control in older adults**. J Neuroeng Rehabil. 2016 May 3;13(1):44. [FULL TEXT]

Heldstab SA, et al (2016) - **Manipulation complexity in primates coevolved with brain size and terrestriality**. Sci Rep. 2016 Apr 14;6:24528. [FULL TEXT]

Busa MA, et al (2016) - **Multiscale entropy identifies differences in complexity in postural control in women with multiple sclerosis**. Gait Posture. 2016 Mar;45:7-11. [ABS]

> Loss of postural center-of-pressure complexity (COP complexity) has been associated with reduced adaptability that accompanies disease and aging.
>
> The key dependent variable was the complexity index (CI) of the center of pressure. We observed a lower CI in the MS group compared to controls in both anterior-posterior (AP) and medio-lateral (ML) directions (p's<0.002), during the performance of maximal self-regulated leans (AP: p<0.001; ML: p=0.018), and under limited vision
>
> Decreased cutaneous sensitivity was associated with lower CI values in the AP direction among those with MS. MS is associated with diminished COP complexity under both normal and challenging postures, and (2) complexity is strongly correlated with cutaneous sensitivity, suggesting the unique contribution of impaired somatosensation on postural control deficits in persons with MS.

Park K, et al (2016) **- Effects of aging and Parkinson's disease on joint coupling, symmetry, complexity and variability of lower limb movements during gait**. Clin Biomech (Bristol, Avon). 2016 Mar;33:92-97. [ABS]

> People with Parkinson's disease had the highest asymmetry among the three groups. Aging and Parkinson's disease significantly decreased complexity of hip and ankle joint movements, respectively, while there were no significant differences in variability measures among the three groups.

Oskrochi G, et al (2016) - **An Application of the Multivariate Linear Mixed Model to the Analysis of Shoulder Complexity in Breast Cancer Patients**. Int J Environ Res Public Health. 2016 Mar 2;13(3). [FULL TEXT]

Afsar O, et al (2016) - **Entropy-based complexity measures for gait data of patients with Parkinson's disease**. Chaos. 2016 Feb;26(2):023115. [ABS]

> …renormalized entropy method for stride time variability of gait is found to correctly identify patients with a sensitivity of 80%, while the Shannon entropy and the Kullback-Leibler relative entropy can do this with a sensitivity of only 26.7% and 13.3%, respectively.

Coey CA, et al (2016) - **Complexity matching effects in bimanual and interpersonal syncopated finger tapping.** Neurosci Lett. 2016 Mar 11;616:204-10. [FULL TEXT]

Negahban H, et al (2016) - **Complexity and variability of the center of pressure time series during quiet standing in patients with knee osteoarthritis**. Clin Biomech (Bristol, Avon). 2016 Feb;32:280-5. [ABS]

The complexity loss was observed in patients compared with healthy controls. The observed increase in the variability coupled with a decrease in the complexity could be explained by the exploratory behavior of postural control system to gather information during difficult postural conditions relative to the easy ones. Moreover, the observed increase in the complexity coupled with the decrease in the amount of variability may enhance the flow of information to facilitate the perceptual control of standing balance during dual-task conditions.

Ko JH, et al (2016) - **Aging and the complexity of center of pressure in static and dynamic postural tasks**. Neurosci Lett. 2016 Jan 1;610:104-9. [ABS]

Multi-scale entropy (MSE) and detrended fluctuation analysis showed that the complexity of COP in the old adults was lower compared to the young in the constant target, whereas it was higher in the sine-wave target. The task dependent age-related bi-directional change of COP complexity is counter to the hypothesis of a universal loss of complexity with aging but shows that there is loss of adaptive change in complexity driven by the COP dynamics.

Peng Z, et al (2015) - **Entropic Movement Complexity Reflects Subjective Creativity Rankings of Visualized Hand Motion Trajectories**. Front Psychol. 2015 Dec 17;6:1879. [FULL TEXT]

Our results suggest that entropic complexity measures of hand motion may reveal domain-specific individual differences in kinesthetic creativity.

Hunt N, et all (2014) - **The influence of auditory-motor coupling on fractal dynamics in human gait**. Sci Rep. 2014 Aug 1;4:5879. [FULL TEXT]

Wayne PM, et al (2014) - **Complexity-Based Measures Inform Effects of Tai Chi Training on Standing Postural Control: Cross-Sectional and Randomized Trial Studies**. PLoS One. 2014 Dec 10;9(12):e114731 [FULL TEXT]

Rankin SK, et al (2014) - **Auditory-motor synchronization with temporally fluctuating sequences is dependent on fractal structure but not musical expertise**. Front Psychol. 2014 Sep 3;5:970. [FULL TEXT]

Wang P, et al (2014) - **Complexity analysis of gait signal based on Jensen-Shannon divergence**. Sheng Wu Yi Xue Gong Cheng Xue Za Zhi. 2014 Jun;31(3):583-5. [ABS]

The research of the gait signal complexity is really of great significance for medicine. *By calculating people's gait signal complexity, we can assess a person's health status and thus timely detect and diagnose diseases..*

Nguyen TT, et al (2013) - **Children with heavy prenatal alcohol exposure experience reduced control of isotonic force.** Alcohol Clin Exp Res. 2013 Feb;37(2):315-24. [FULL TEXT]

Compared with control children, children with heavy prenatal alcohol exposure generated isotonic force signals that were less accurate, more variable, and less complex in the time domain. Specifically, interactions were found between group and visual feedback for response accuracy and signal complexity, suggesting that these children have greater difficulty altering their motor output when visual feedback is low.

Sabatini AM (2000) - **Analysis of postural sway using entropy measures of signal complexity**. Med Biol Eng Comput. 2000 Nov;38(6):617-24. [ABS]

Hadders-Algra M (1997) - **Assessment of spontaneous motor activity in young infants: an effective method for the detection of brain function disorders**]. Ned Tijdschr Geneeskd. 1997 Apr 26;141(17):816-20. [ABS]

> A method for the assessment of the brain function of young infants was recently introduced. It consists of evaluation of the quality of spontaneously generated generalized movements (general movements, GMs). GMs appear at an early stage of pregnancy and persist until approximately the 4th month after term. Normal GMs are characterized by the triad of complexity, variation and fluency. Mildly abnormal GMs. indicating mild dysfunction of the nervous system, are not fluent but jerky or stiff. Markedly abnormal GMs, indicating major nervous system dysfunction, are characterized mostly by absence of complexity and variation of the movements: the movements are monotonous and stereotyped. The quality of the GMs can be evaluated by means of so-called global Gestalt perception. The technique can be learned in a few days. The quality of the GMs has a clear predictive significance for the child's development. Children with normal GMs will be free of handicaps in later life, whereas three-quarters of the children showing clearly abnormal GMs throughout the postnatal GM period do develop handicaps. Assessment of the quality of the GMs is a relatively cheap, non-invasive method of evaluating the current and future brain function of young infants.

Music ▲

Carpentier SM, et al (2020) - **Complexity Matching: Brain Signals Mirror Environment Information Patterns during Music Listening and Reward**. J Cogn Neurosci. 2020 Apr;32(4):734-745. [ABS]

> We can directly assess the correspondence between brain signal complexity and stimulus complexity as an indication of how well the brain reflects the content of the environment in an analysis that we term "complexity matching." Music is an ideal stimulus because it is a multidimensional signal with a rich temporal evolution and because of its emotion- and reward-inducing potential. *When participants focused on acoustic features of music, we found that EEG complexity was lower and more closely resembled the musical complexity compared to an emotional task* that asked them to monitor how the music made them feel. *Music-derived reward scores on the Barcelona Music Reward Questionnaire correlated with less complexity matching but higher EEG complexity*. Compared with perceptual-level processing, emotional and reward responses are associated with additional internal information processes above and beyond those linked to the external stimulus. In other words, the brain adds something when judging the emotional valence of music.

Wollman I, et al (2020) - **Neural entrainment to music is sensitive to melodic spectral complexity.** J Neurophysiol. 2020 Mar 1;123(3):1063-1071. [ABS]

Cameron DJ, et al (2019) - **Neural entrainment is associated with subjective groove and complexity for performed but not mechanical musical rhythms**. Exp Brain Res. 2019 Aug;237(8):1981-1991. [FULL TEXT]

Dolan D, et al (2018) - **The Improvisational State of Mind: A Multidisciplinary Study of an Improvisatory Approach to Classical Music Repertoire Performance**. Front Psychol. 2018 Sep 25;9:1341. [FULL TEXT]

> EEG measurements from 19 scalp locations showed *higher levels of Lempel-Ziv complexity (associated with awareness and alertness) in the improvised version in both performers and audience.* Results are discussed in terms of their potential support for an "*improvisatory state of mind*" which may have aspects of flow (as characterized by Csikszentmihalyi, 1997) and primary states (as characterized by the Entropic Brain Hypothesis of Carhart-Harris et al., 2014). In a group setting, such as a live concert, our evidence suggests that *this state of mind is communicable between performers and audience thus contributing to a heightened quality of shared experience*.

Sakellariou J, et al (2017) - **Maximum entropy models capture melodic styles**. Sci Rep. 2017 Aug 23;7(1):9172. [ABS]

> We validate our Maximum Entropy model by contrasting how much the generated sequences capture the style of the original corpus without plagiarizing it.

Chanwimalueang T, et al (2017) - **Stage call: Cardiovascular reactivity to audition stress in musicians**. PLoS One. 2017 Apr 24;12(4):e0176023. [FULL TEXT]

> The complexity science approaches—namely, multiscale sample entropy and multiscale fuzzy entropy—indicated a statistically significant decrease in structural complexity in HRV from the low- to the high-stress condition and an increase in structural complexity from the pre-performance to performance period, thus confirming the complexity loss theory and a loss in degrees of freedom due to stress. Results from the spectral analyses also suggest that the stress responses in the female participants were more parasympathetically driven than those of the male participants. In conclusion, our findings suggest that interventions to manage stress are best targeted at the sensitive pre-performance period, before an audition begins.

Thammasan N, et al (2017) - **Familiarity effects in EEG-based emotion recognition**. Brain Inform. 2017 Mar;4(1):39-50. [FULL TEXT]

> We conducted an additional experiment using music familiarity in an attempt to recognize emotional states; our empirical results suggested that the use of only songs with low familiarity levels can enhance the performance of EEG-based emotion classification systems that adopt fractal dimension or power spectral density features and support vector machine, multilayer perceptron or C4.5 classifier. This suggests that unfamiliar songs are most appropriate for the construction of an emotion recognition system.

Carpentier SM, et al (2016) - **Short-term Music Training Enhances Complex, Distributed Neural Communication during Music and Linguistic Tasks**. J Cogn Neurosci. 2016 Oct;28(10):1603-12. [FULL TEXT]

> Comparing pre-training with post-training, *musical training was associated with increased EEG complexity at coarse temporal scales during the music and French vowel tasks in widely distributed cortical regions.*

Lebedev AV, et al (2016) - **LSD-induced entropic brain activity predicts subsequent personality change**. Hum Brain Mapp. 2016 Sep;37(9):3203-13. [ABS]

> Personality is known to be relatively stable throughout adulthood. ...Overall, LSD had a pronounced global effect on brain entropy, increasing it in both sensory and hierarchically higher networks across multiple time scales. These shifts predicted enduring increases in trait openness. Moreover, the predictive power of the entropy increases was greatest for the music-listening scans and when "ego-dissolution" was reported during the acute experience.

Vanderlei FM, et al (2016) - **Symbolic analysis of heart rate variability during exposure to musical auditory stimulation**. Altern Ther Health Med. 2016 Mar-Apr;22(2):24-31. [ABS]

> Auditory stimulation with the heavy-metal music reduced the parasympathetic modulation of HRV, whereas no significant changes occurred in cardiac autonomic modulation during exposure to the classical music.

Riganello F, et al (2015) - **How Can Music Influence the Autonomic Nervous System Response in Patients with Severe Disorder of Consciousness?** Front Neurosci. 2015 Dec 10;9:461. [FULL TEXT]

Akar SA, et al (2015) - **Nonlinear analysis of EEGs of patients with major depression during different emotional states.** Comput Biol Med. 2015 Dec 1;67:49-60. [ABS]

> First, higher complexity values were generated by MDD patients relative to controls. Significant differences were obtained in the frontal and parietal scalp locations using KFD ($p<0.001$), HFD ($p<0.05$), and LZC ($p=0.05$). Second, lower complexities were observed only in the controls when they were subjected to music compared to the resting baseline state in the frontal ($p<0.05$) and parietal ($p=0.005$) regions. In contrast, the LZC and KFD values of patients increased in the music period compared to the resting state in the frontal region ($p<0.05$). Third, the patients′ brains had higher complexities when they were exposed to noise stimulus than did the controls′ brains. Moreover, MDD patients′ negative emotional bias was demonstrated by their higher brain complexities during the noise period than the music stimulus.

Rankin SK, et al (2014) - **Fractal structure enables temporal prediction in music**. J Acoust Soc Am. 2014 Oct;136(4):EL256-62. [ABS]

> 1/f serial correlations and statistical self-similarity (fractal structure) have been measured in various dimensions of musical compositions. Musical performances also display 1/f properties in expressive tempo fluctuations, and listeners predict tempo changes when synchronizing. Here the authors show that the 1/f structure is sufficient

for listeners to predict the onset times of upcoming musical events. These results reveal what information listeners use to anticipate events in complex, non-isochronous acoustic rhythms, and this will entail innovative models of temporal synchronization. This finding could improve therapies for Parkinson's and related disorders and inform deeper understanding of how endogenous neural rhythms anticipate events in complex, temporally structured communication signals.

Rankin SK, et al (2014) - **Auditory-motor synchronization with temporally fluctuating sequences is dependent on fractal structure but not musical expertise**. Front Psychol. 2014 Sep 3;5:970. [FULL TEXT]

Hennig H (2014) - **Synchronization in human musical rhythms and mutually interacting complex systems.** Proc Natl Acad Sci U S A. 2014 Sep 9;111(36):12974-9. [FULL TEXT]

> We find that the inter-beat intervals of both laypeople and professional musicians exhibit scale-free (power law) cross-correlations. Surprisingly, the next beat to be played by one person is dependent on the entire history of the other person's interbeat intervals on timescales up to several minutes.
>
> We show that the observed long-term memory phenomenon in rhythmic synchronization can be imitated by fractal coupling of separately recorded or synthesized audio tracks and thus applied in electronic music. Though this study provides an understanding of fundamental characteristics of timing and synchronization at the interbrain level, the mutually interacting complex systems model may also be applied to study the dynamics of other complex systems where scale-free cross-correlations have been observed, including econophysics, physiological time series, and collective behavior of animal flocks.

Williamon A, et al (2013) - **Complexity of physiological responses decreases in high-stress musical performance**. J R Soc Interface. 2013 Sep 25;10(89):20130719. [FULL TEXT]

Vialatte FB, et al (2012) - **Audio representations of multi-channel EEG: a new tool for diagnosis of brain disorders**. Am J Neurodegener Dis. 2012;1(3):292-304. [FULL TEXT]

> The objective of this paper is to develop audio representations of electroencephalographic (EEG) multichannel signals, useful for medical practitioners and neuroscientists
>
> Several characteristics of the audio sequences, including sample entropy, number of notes, and synchrony, are significantly different in MCI patients and control subjects (Mann-Whitney $p < 0.01$). Moreover, the participants of the perception test were able to accurately classify the audio sequences (89% correctly classified).

Shahin AJ, et al (2010) - **Development of auditory phase-locked activity for music sounds**. J Neurophysiol. 2010 Jan;103(1):218-29. [FULL TEXT]

> Phase-locking for theta (4-8 Hz), alpha (8-14 Hz), lower-to-mid beta (14-25 Hz), and upper-beta and gamma (25-70 Hz) bands strengthened with age. Phase-locking in the upper-beta and gamma range matured later than in lower frequencies and was stronger

for music sounds than for pure tones, likely reflecting the maturation of neural networks that code spectral complexity.

Hadjidimitriou S, et al (2010) - **Sensorimotor cortical response during motion reflecting audiovisual stimulation: evidence from fractal EEG analysis**. Med Biol Eng Comput. 2010 Jun;48(6):561-72. [ABS]

> Experimental results from the midline electrode (CZ) based on the Higuchi method showed significant differences between the AMS (advanced music students) and the NM (non-musician) groups, with the former displaying substantial sensorimotor response during auditory stimulation and stronger correlation with the acoustic stimulus than the latter. This observation was linked to mirror neuron system activity, a neurological mechanism that allows trained musicians to detect action-related meanings underlying the structural patterns in musical excerpts.

Rankin SK, et al (2009) - **Fractal Tempo Fluctuation and Pulse Prediction**. Music Percept. 2009 Jun;26(5):401-413. [FULL TEXT]

> ...listeners may exploit long-range correlations and fractal scaling to predict tempo changes in music.

Ventegodt S, et al (2008) - **Human development XIII: the connection between the structure of the overtone system and the tone language of music. Some implications for our understanding of the human brain**. ScientificWorldJournal. 2008 Jul 13;8:643-57. [FULL TEXT]

Bhattacharya J, et al (2001) - **Long-range synchrony in the gamma band: role in music perception.** J Neurosci. 2001 Aug 15;21(16):6329-37. [ABS]

> The degree of spatial synchrony, a measure of signal complexity based on eigen-decomposition method, was also significantly increased in musicians while listening to music. …As compared with non-musicians, the finding of increased long-range synchrony in musicians independent of spectral power is interpreted as a manifestation of a more advanced musical memory of musicians in binding together several features of the intrinsic complexity of music in a dynamical way.

Hsu KJ, et al (1991) - **Self-similarity of the "1/f noise" called music**. Proc. Nati. Acad. Sci. USA. [FULL TEXT]

Hsu KJ, et al (1990) - **Fractal geometry of music**. Proc Natl Acad Sci USA. 1990 Feb 1;87(3):938-41. [FULL TEXT]

Neurosyphillis ▲

Jiang MJ, et al (2019) - **Analysis of EEG Lemple-Ziv complexity and correlative aspects before and after treatment of anti-syphilis therapy for neurosyphilis.** Neurol Res. 2019 Mar;41(3):199-203. [ABS]

> After intensive anti-syphilis therapy, the LZC increased significantly in all patients while the trend and degree of change were consistent with other diagnostic results.

Obsessive-Compulsive Disorder ▲

Altuglu TB, et al (2020) - **Prediction of treatment resistance in obsessive compulsive disorder patients based on EEG complexity as a biomarker**. Clin Neurophysiol. 2020 Mar;131(3):716-724. [ABS]

> *Beta band EEG complexity was lower in the treatment-resistant patients and the severity of OCD, as measured by YBOCS score, was inversely correlated with complexity values.*

Tan O, et al (2017) - **Electroencephalographic Complexity and Decreased Randomness in Drug-Naive Obsessive-Compulsive Patients**. The Journal of Psychiatry and Neurological Sciences 2017;30:101-112. [FULL TEXT]

> OCD is characterized by low EEG complexity, increased regularity, or decreased randomness. Segmentation of EEG signals is useful for their quantitative identification, a smaller window providing a more sensitive characterization of EEG.

Aydin S, et al (2015) - **Classification of obsessive compulsive disorder by EEG complexity and hemispheric dependency measurements.** Int J Neural Syst. 2015 May;25(3):1550010. [ABS]

> "…patients are characterized by lower EEG complexity at both pre-frontal regions and right fronto-temporal locations. *Our results are compatible with imaging studies that define OCD as a sub group of anxiety disorders that exhibited a decreased complexity (such as anorexia nervosa and panic disorder)."*

Okazaki R, et al (2015) - **Changes in EEG complexity with electroconvulsive therapy in a patient with autism spectrum disorders: a multiscale entropy approach.** Front Hum Neurosci. 2015 Feb 26;9:106. [FULL TEXT]

> Autism spectrum disorders (ASD) are heterogeneous neurodevelopmental disorders that are reportedly characterized by aberrant neural networks. Recently developed multiscale entropy analysis (MSE) can characterize the complexity inherent in electroencephalography (EEG) dynamics over multiple temporal scales in the dynamics of neural networks. We encountered an 18-year-old man with ASD whose **refractory catatonic obsessive-compulsive** symptoms were improved dramatically after electroconvulsive therapy (ECT). In this clinical case study, we strove to clarify the neurophysiological mechanism of ECT in ASD by assessing EEG complexity using MSE. Along with ECT, the frontocentral region showed decreased EEG complexity at higher temporal scales, whereas the occipital region expressed an increase at lower temporal scales. Furthermore, these changes were associated with clinical improvement associated with the **elevation of brain-derived neurotrophic factor**, which is a molecular hypothesis of ECT, playing key roles in ASD pathogenesis. Changes in EEG complexity in a region-specific and temporal scale-specific manner that we found might reflect atypical EEG dynamics in ASD. Although MSE is not a direct approach to measuring neural connectivity and the results are from only a single case, they might

reflect specific aberrant neural network activity and the therapeutic neurophysiological mechanism of ECT in ASD.

Parkinson's Disease ▲

Keller SM, et al (2020) - **Cognitive decline in Parkinson's disease is associated with reduced complexity of EEG at baseline.** Brain Commun. 2020 Nov 27;2(2). [FULL TEXT]

Flood MW, et al (2019) - **Increased EMG intermuscular coherence and reduced signal complexity in Parkinson's disease**. Clin Neurophysiol. 2019 Feb;130(2):259-269. [ABS]

> Sample Entropy was significantly lower, in PD patients. Intermuscular coherence was also significantly higher in the PD group in theta, alpha and beta frequency bands. … SampEn decreased with increasing Movement-Disorder-Society UPDRS scores, while theta band coherence was significantly correlated with total MDS-UPDRS scores and torque variance.

Mostile G, et al (2019) - **Complexity of electrocortical activity as potential biomarker in untreated Parkinson's disease.** J Neural Transm (Vienna). 2019 Feb;126(2):167-172. [ABS]

> …the power law exponent β was computed… PD subjects presented overall lower β values among different sites compared to controls, with significant differences for the left fronto-temporal sites. Our findings suggest an increased level of fronto-temporal neuronal organization in untreated PD. We hypothesize a possible role of β as a neurophysiological biomarker for early untreated PD.

Yi GS, et al (2017) - **Complexity of resting-state EEG activity in the patients with early-stage Parkinson's disease**. Cogn Neurodyn. 2017 Apr;11(2):147-160. [ABS]

> Two methods based on the ordinal patterns of the recorded series, i.e., permutation entropy (PE) and order index (OI), were introduced to characterize the complexity of the cortical activities for two groups. It was observed that the resting-state EEG of PD patients showed lower PE and higher OI than healthy controls, which indicated that theearly-stage PD caused the reduced complexity of EEG. We further applied two methods to determine the complexity of EEG rhythms in five sub-bands. The results showed that the gamma, beta and alpha rhythms of PD patients were characterized by lower PE and higher OI, i.e., reduced complexity, than healthy subjects. No significant differences were observed in theta or delta rhythms between two groups. The findings suggested that PE and OI were promising methods to detect the abnormal changes in the dynamics of EEG signals associated with early-stage PD. Further, such changes in EEG complexity may be the early markers of the cortical or subcortical dysfunction caused by PD.

Liu G, et al (2017) - **Complexity Analysis of Electroencephalogram Dynamics in Patients with Parkinson's Disease**. Parkinsons Dis. 2017;2017:8701061. [FULL TEXT]

Park K, et al (2016) **- Effects of aging and Parkinson's disease on joint coupling, symmetry, complexity and variability of lower limb movements during gait**. Clin Biomech (Bristol, Avon). 2016 Mar;33:92-97. [ABS]

> People with Parkinson's disease had the highest asymmetry among the three groups. Aging and Parkinson's disease significantly decreased complexity of hip and ankle joint movements, respectively, while there were no significant differences in variability measures among the three groups.

Afsar O, et al (2016) - **Entropy-based complexity measures for gait data of patients with Parkinson's disease**. Chaos. 2016 Feb;26(2):023115. [ABS]

> …renormalized entropy method for stride time variability of gait is found to correctly identify patients with a sensitivity of 80%, while the Shannon entropy and the Kullback-Leibler relative entropy can do this with a sensitivity of only 26.7% and 13.3%, respectively.

Bertrand JA, et al (2015) - **Brain Connectivity Alterations Are Associated with the Development of Dementia in Parkinson's Disease**. Brain Connect. 2016 Apr;6(3):216-24. [ABS]

> Brain connectivity EEG measures, such as multiscale entropy (MSE) and phase-locking value (PLV) analyses, may be more informative and sensitive to brain alterations leading to dementia than previously used methods. …Patients who developed dementia showed higher signal complexity and lower PLVs in low frequencies (mainly in delta frequency) than patients who remained dementia-free and controls. Conversely, both patient groups showed lower signal variability and higher PLVs in high frequencies (mainly in gamma frequency) compared to controls, with the strongest effect in patients who developed dementia. These findings suggest that specific disruptions of brain communication can be measured before PD patients develop dementia, providing a new potential marker to identify patients at highest risk of developing dementia and who are the best candidates for neuroprotective trials.

Chung CC. et al (2013) - **Multiscale entropy analysis of electroencephalography during sleep in patients with Parkinson disease**. Clin EEG Neurosci. 2013 Jul; 44(3):221-6. [ABS]

> "...increased biosignal complexity, as revealed by MSE analysis, was found in patients with PD during non-REM sleep at high TSFs. This finding might reflect a compensatory mechanism for early defects in neuronal network control machinery in PD." (MSE = Multiscale Entropy)

Pediatrics ▲

Jost K, et al (2017) - **Dynamics and complexity of body temperature in preterm infants nursed in incubators**. PLoS One. 2017 Apr 27;12(4):e0176670. [FULL TEXT]

Dynamics and complexity of body temperature in incubator-nursed preterm infants show considerable associations with gestational age and respiratory morbidity.

Kaffashi F, et al (2013) - **An analysis of the kangaroo care intervention using neonatal EEG complexity: a preliminary study**. Clin Neurophysiol. 2013 Feb; 124(2):238-46. [ABS]

> "Based on the hypothesis that EEG-derived complexity increases with neurophysiological maturation as supported by previously published research, SSC (skin-to-skin contact) accelerates brain maturation in healthy preterm infants as quantified by time series measures of predictability when compared to a similar non-SSC group."

PTSD ▲

Ros T, et al (2017) - **Neurofeedback Tunes Scale-Free Dynamics in Spontaneous Brain Activity**. Cereb Cortex. 2017 Oct 1;27(10):4911-4922. [ABS]

> Here, healthy adults used closed-loop brain training (neurofeedback, NFB) to reduce the amplitude of alpha oscillations, producing a significant increase in spontaneous LRTCs (long-range temporal correlations) post-training. This effect was reproduced in patients with post-traumatic stress disorder, where abnormally random dynamics were reversed by NFB, correlating with significant improvements in hyperarousal.

Channer K, et al (2017) - **Self-Complexity and Perceived Self-Aspect Control in Post-Traumatic Stress Disorder**. Behav Cogn Psychother. 2017 Jul 31:1-16. [ABS]

> It was found that those with PTSD had significantly greater overall self-complexity than those without PTSD. Furthermore, when considering self-description valence, it was found that those with PTSD had significantly greater negative self-complexity than those without PTSD, but the groups did not differ in terms of positive self-complexity. Second, those with PTSD reported significantly less control over their self-aspects. Third, for those with PTSD, lower levels of self-aspect control were significantly correlated with greater negative self-complexity and lower positive self-complexity. Finally, self-aspect control mediated the relationship between self-complexity and PTSD symptoms.

Bodner E, et al (2017) - **A light in a sea of darkness: the moderating role of emotional complexity in the PTSD symptoms-successful aging association**. Aging Ment Health. 2017 May 3:1-8. [ABS]

> ...higher PTSD symptoms were related to less successful aging, both objective and subjective. However, this relationship existed only amongst older adults with low emotional complexity, but not amongst those with high emotional complexity. ...The findings suggest that high emotional complexity buffers against the negative effects of PTSD symptoms on successful aging. Interventions that empower emotional complexity amongst traumatized older adults may attenuate these negative effects.

Nalipay MJ, et al (2016) - **Social complexity beliefs predict posttraumatic growth in survivors of a natural disaster**. Psychol Trauma. 2016 Sep;8(5):559-67. [ABS]

Hoffman JR, et al (2016) - **Exercise Maintains Dendritic Complexity in an Animal Model of PTSD**. Med Sci Sports Exerc. 2016 Jul 12. [ABS]

> The results of this study indicate that 6-weeks of endurance training can protect dendritic length and complexity suggesting a degree of resiliency to stress. This provides further evidence for supporting the inclusion of an exercise regimen for reducing the risk of PTSD.

Chae JH, et al (2004) - **Dimensional complexity of the EEG in patients with posttraumatic stress disorder.** Psychiatry Res. 2004 May 30;131(1):79-89. [ABS]

> "*PTSD patients have globally reduced complexity in their EEG waveforms.* This study supports the hypotheses that PTSD patients exhibit disturbed cortical information processing, and that non-linear dynamical analysis of the EEG can be a tool for detecting changes in neurodynamics of the brain in PTSD."

Psychedelics ▲

Varley TF, et al (2020) - **Serotonergic psychedelics LSD & psilocybin increase the fractal dimension of cortical brain activity in spatial and temporal domains**. Neuroimage. 2020 Jun 30;220:117049. [FULL TEXT]

> Psychedelic drugs, such as psilocybin and LSD, represent unique tools for researchers investigating the neural origins of consciousness. Currently, the most compelling theories of how psychedelics exert their effects is by increasing the complexity of brain activity and moving the system towards a critical point between order and disorder, creating more dynamic and complex patterns of neural activity.
>
> In addition to the fractal measures, we used a well-established, non-fractal measure of signal complexity and show that they behave similarly. We were able to show that both psychedelic drugs significantly increased the fractal dimension of functional connectivity networks, and that LSD significantly increased the fractal dimension of BOLD signals, with psilocybin showing a non-significant trend in the same direction. With both LSD and psilocybin, we were able to localize changes in the fractal dimension of BOLD signals to brain areas assigned to the dorsal-attention network. These results show that psychedelic drugs increase the fractal dimension of activity in the brain and we see this as an indicator that the changes in consciousness triggered by psychedelics are associated with evolution towards a critical zone.

Li D, et al (2019) - **Cortical dynamics during psychedelic and anesthetized states induced by ketamine.** Neuroimage. 2019 Aug 1;196:32-40. [FULL TEXT]

> …the subanesthetic dose of ketamine is associated with an elevated complexity level relative to baseline, while the brain activity following an anesthetic dose of ketamine is characterized by alternating low and high complexity levels until stabilizing at a high level comparable to that during baseline.

Viol A, et al (2017) - **Shannon entropy of brain functional complex networks under the influence of the psychedelic Ayahuasca**. Sci Rep. 2017 Aug 7;7(1):7388. [FULL TEXT]

> We report an increase in the Shannon entropy of the degree distribution of the networks subsequent to Ayahuasca ingestion. We also find increased local and decreased global network integration. Our results are broadly consistent with the entropic brain hypothesis. Finally, we discuss our findings in the context of descriptions of “mind-expansion” frequently seen in self-reports of users of psychedelic drugs.

Schartner MM, et al (2017) - **Increased spontaneous MEG signal diversity for psychoactive doses of ketamine, LSD and psilocybin**. Sci Rep. 2017 Apr 19;7:46421. [FULL TEXT]

> For all three, we find reliably higher spontaneous signal diversity, even when controlling for spectral changes. This increase is most pronounced for the single-channel LZ complexity measure, and hence for temporal, as opposed to spatial, signal diversity. We also uncover selective correlations between changes in signal diversity and phenomenological reports of the intensity of psychedelic experience.
>
> These findings suggest that the sustained occurrence of psychedelic phenomenology constitutes an elevated level of consciousness - as measured by neural signal diversity.

Liechti ME (2017) - **Modern Clinical Research on LSD**. Neuropsychopharmacology. 2017 Apr 27. [ABS]

> LSD acutely induced global increases in brain entropy that were associated with greater trait openness 14 days later. In patients with anxiety associated with life-threatening disease, anxiety was reduced for 2 months after two doses of LSD. In medical settings, no complications of LSD administration were observed.

Lebedev AV, et al (2016) - **LSD-induced entropic brain activity predicts subsequent personality change**. Hum Brain Mapp. 2016 Sep;37(9):3203-13. [ABS]

> Personality is known to be relatively stable throughout adulthood. ...Overall, LSD had a pronounced global effect on brain entropy, increasing it in both sensory and hierarchically higher networks across multiple time scales. These shifts predicted enduring increases in trait openness. Moreover, the predictive power of the entropy increases was greatest for the music-listening scans and when "ego-dissolution" was reported during the acute experience.

Gallimore AR (2015) - **Restructuring consciousness -the psychedelic state in light of integrated information theory**. Front Hum Neurosci. 2015 Jun 12;9:346. [FULL TEXT]

Alonso JF, et al (2015) - **Serotonergic psychedelics temporarily modify information transfer in humans**. Int J Neuropsychopharmacol. 2015 Mar 28;18(8). [FULL TEXT]

> The analysis showed significant changes in the coupling of brain oscillations between anterior and posterior recording sites. Transfer entropy analysis showed that frontal sources decreased their influence over central, parietal, and occipital sites. Conversely, sources in posterior locations increased their influence over signals measured at anterior locations. Exploratory correlations found that anterior-to-posterior transfer

entropy decreases were correlated with the intensity of subjective effects, while the imbalance between anterior-to-posterior and posterior-to-anterior transfer entropy correlated with the degree of incapacitation experienced

Tagliazucchi E, et al (2014) - **Enhanced repertoire of brain dynamical states during the psychedelic experience**. Hum Brain Mapp. 2014 Nov;35(11):5442-56. [ABS]

> …increased signal variability bilaterally in the hippocampi and anterior cingulate cortex. Changes in BOLD signal spectral behavior (including spectral scaling exponents) affected exclusively higher brain systems such as the default mode, executive control, and dorsal attention networks. A novel framework enabled us to track different connectivity states explored by the brain during rest. This approach revealed a wider repertoire of connectivity states post-psilocybin than during control conditions.

Carhart-Harris RL, et al (2014) - **The entropic brain: a theory of conscious states informed by neuroimaging research with psychedelic drugs**. Front Hum Neurosci. 2014 Feb 3;8:20. [FULL TEXT]

> Indeed, since there is a greater repertoire of connectivity motifs in the psychedelic state than in normal waking consciousness, this implies that primary states may exhibit "criticality," i.e., the property of being poised at a "critical" point in a transition zone between order and disorder where certain phenomena such as power-law scaling appear. Moreover, if primary states are critical, then this suggests that entropy is suppressed in normal waking consciousness, meaning that the brain operates just below criticality. It is argued that this entropy suppression furnishes normal waking consciousness with a constrained quality and associated metacognitive functions, including reality-testing and self-awareness. It is also proposed that entry into primary states depends on a collapse of the normally highly organized activity within the default-mode network (DMN) and a decoupling between the DMN and the medial temporal lobes (which are normally significantly coupled).

Schizophrenia / Psychosis ▲

Goshvarpour A, et al (2020) **- Schizophrenia diagnosis using innovative EEG feature-level fusion schemes**. Australas Phys Eng Sci Med. 2020 Jan 2. [ABS]

> … we analyze EEG dynamics using three well-known nonlinear measures, including complexity (Cx), Higuchi fractal dimension (HFD), and Lyapunov exponents (Lya). … Using the proposed algorithm, the classification accuracy increased up to 100%. These results establish the suggested framework as a superior scheme compared to the state-of-the-art EEG schizophrenia diagnosis tool.

Iglesias-Parro S, et al (2020) **- Introspective and Neurophysiological Measures of Mind Wandering in Schizophrenia**. Sci Rep. 2020 Mar 16;10(1):4833. [FULL TEXT]

> …the EEG complexity was lower in patients than in controls in the frontal and temporal areas. This pattern is consistent with previous research that employed HFD as a measure

of complexity, whereas higher values of complexity in patients are usually found when Lempel-Ziv complexity is calculated

Murphy M, et al (2019) - **Electroencephalogram Microstate Abnormalities in Early-Course Psychosis.** Biol Psychiatry Cogn Neurosci Neuroimaging. 2020 Jan;5(1):35-44. [FULL TEXT]

> In control subjects, sample entropy decreased as template length increased, suggesting that sequence of microstate transitions is self-similar across multiple transitions. In patients, sample entropy did not decrease, suggesting a lack of self-similarity in transition sequences. This finding was unrelated to data length or microstate topography. Entropy was elevated in unmedicated patients, and it decreased in patients who were administered medication.

Hager B, et al (2018) - **Neural complexity as a potential translational biomarker for psychosis.** J Affect Disord. 2017 Jul; 216: 89–99. [FULL TEXT]

> These observations support the loss of brain complexity hypothesis in psychotic probands. Furthermore, we found significant differences as well as overlaps of pathologic brain signal complexity between psychotic probands by DSM diagnoses, thus suggesting a biological approach to categorizing psychosis based on functional neuroimaging data.

Cerquera A, et al (2017) - **Comparing EEG Nonlinearity in Deficit and Nondeficit Schizophrenia Patients: Preliminary Data**. Clin EEG Neurosci. 2017 Nov;48(6):376-382. [ABS]

> These findings suggest that cognitive processing occurring in the frontal networks in DS is less complex compared to NDS patients as reflected by EEG complexity measures. The data also suggest that there may be a relationship between the degree of emotionality and the complexity of the frontal EEG signal.

Missonnier P, et al (2017) - **Differences of temporal dynamics and signal complexity of gamma band oscillations in first-episode psychosis during a working memory task**. J Neural Transm (Vienna). 2017 Jul;124(7):853-862. [ABS]

> The present results are consistent with a discoordination of the activity of cortical generators engaged by the stimulus apparition in FEP patients, leading to a global binding deficit. In addition, fractal analysis showing higher complexity of gamma signal, confirmed this deficit. Our results provide evidence for recruitment of supplementary cortical generators as compensating mechanisms and yield further understanding for the pathophysiology cognitive impairments in FEP.

Yu Y, et al (2016) - **Estimation of the cool executive function using frontal electroencephalogram signals in first-episode schizophrenia patients.** Biomed Eng Online. 2016 Nov 25;15(1):131. [FULL TEXT]

Akar SA, et al (2016) - **Analysis of the Complexity Measures in the EEG of Schizophrenia Patients**. Int J Neural Syst. 2016 Mar;26(2):1650008. [ABS]

> The EEG complexity of participants were investigated and compared using approximate entropy (ApEn), Shannon entropy (ShEn), Kolmogorov complexity (KC) and Lempel-Ziv

complexity (LZC). Lower complexity values were obtained in schizophrenia patients. The most significant complexity differences between patients and controls were obtained in especially left frontal (F3) and parietal (P3) regions of the brain when all complexity measures were applied individually. …Moreover, significant inter-hemispheric complexity differences were found in the frontal and parietal areas of schizophrenics' brain.

Kim BS, et al (2014) - **Differential regulation of observational fear and neural oscillations by serotonin and dopamine in the mouse anterior cingulate cortex.** Psychopharmacology (Berl). 2014 Nov;231(22):4371-81. [ABS]

Based on entropy, reduced complexity of ACC neural activity was observed with 5-HT treatment. …The current results demonstrated that DA D2 receptors in the ACC are required for observational fear learning, whereas increased 5-HT levels disrupt observational fear and alter the regularity of ACC neural oscillations.

Peng H, et al (2013) - **A study on validity of cortical alpha connectivity for schizophrenia.** Conf Proc IEEE Eng Med Biol Soc. 2013;2013:3286-90. [ABS]

"It was found that, compared to the controls, anterior alpha Omega and dimensional complexity are higher in schizophrenia patients ($p<0.05$) with the single channel local omega complexity differentials (LCD) also increasing at FP1, FP2, F7 and F8 electrodes. Furthermore, higher left hemisphere dimensional complexity and LCD at T3 point was also found. The results suggest there is lower connectivity in the pre-frontal and left temporal regions with respect to the alpha band in schizophrenia patients."

Fernández A, et al (2013) - **Complexity and schizophrenia.** Prog Neuropsychopharmacol Biol Psychiatry. 2013 Aug 1;45:267-76. [ABS]

Complexity estimators have been broadly utilized in schizophrenia investigation. Early studies reported increased complexity in schizophrenia patients, associated with a higher variability or "irregularity" of their brain signals. However, further investigations showed reduced complexities, thus introducing a clear divergence. Nowadays, *both increased and reduced complexity values are reported*. The explanation of such divergence is a critical issue to understand the role of complexity measures in schizophrenia research.

Carlino E, et al (2012) - **Nonlinear analysis of electroencephalogram at rest and during cognitive tasks in patients with schizophrenia.** J Psychiatry Neurosci. 2012 Jul;37(4):259-66. [FULL TEXT]

A nonlinear measure of complexity was calculated by means of **correlation dimension (D2).** …In controls, increased D2 values were observed during active states (eyes open and the 2 cognitive tasks) compared with baseline conditions. This increase of brain complexity, which can be interpreted as an increase of information processing and integration, was not preserved in the patient population.

Kikuchi M, et al (2011) - **Frontal areas contribute to reduced global coordination of resting-state gamma activities in drug-naïve patients with schizophrenia.** Schizophr Res. 2011 Aug;130(1-3):187-94. [ABS]

> Gamma band oscillations reflect local cortical activities, and the synchronization of these activities among spatially distributed cortical areas has been suggested to play a central role in the formation of networks. …We found that gamma band OC (omega complexity) was significantly higher in drug-naïve patients with schizophrenia compared to control subjects… After neuroleptic treatment, reductions in the contribution of frontal electrodes to global OC in both bands correlated with the improvement of schizophrenia symptomatology.

Fernández A, et al (2010) - **Analysis of brain complexity and mental disorders.** Actas Esp Psiquiatr. 2010 Jul-Aug;38(4):229-38. [ABS]

> … the analysis of brain signals' complexity has been broadly utilized in the investigation of psychiatric disorders. Parameters of EEG-MEG complexity usually estimate the predictability of brain oscillations and/or the number of independent oscillators underlying the observed signals. More importantly, complexity parameters seem to be sensitive to the temporal components of brain activity, and therefore might reflect the dynamical nature of psychiatric disorders.

Takahashi T, et al (2010) - **Antipsychotics reverse abnormal EEG complexity in drug-naive schizophrenia: a multiscale entropy analysis.** Neuroimage. 2010 May 15;51(1):173-82. [ABS]

> "multiscale entropy measures identified abnormal dynamical EEG signal complexity in anterior brain areas in schizophrenia that normalized selectively in fronto-central areas with antipsychotic treatment."

Łatka M, et al (2010) - **The empirical mode decomposition and Lempel-Ziv complexity. The new possibility in diagnosis of EEG in schizophrenic patients**. Przegl Lek. 2010;67(9):674-6. [ABS]

> We find that variability of the third IMF mode is lower in the patients. The statistically significant differences were observed in 14 channels. Interestingly enough, the Fourier power spectra of both cohorts were not statistically different in any of 19 EEG channels. CONCLUSIONS: Unlike traditional spectral analysis, the combination of empirical mode decomposition and Lempel-Ziv complexity enabled us to identify the properties of EEG that are affected by schizophrenia. The future, more extensive, studies should verify the applicability of the proposed algorithm to diagnostics of schizophrenia. Moreover, we would like to link the observed differences in EEG variability to the pathogenesis of this disease.

Peupelmann J, et al (2009) - **Linear and non-linear measures indicate gastric dysmotility in patients suffering from acute schizophrenia.** Prog Neuropsychopharmacol Biol Psychiatry. 2009 Oct 1;33(7):1236-40. [ABS]

Cardiac autonomic dysfunction has been reported in patients suffering from schizophrenia. The aim of the present study was to evaluate gastric electrical activity in unmedicated patients suffering from acute schizophrenia in relation to their symptoms.

Electrogastrography was performed before and after test meal ingestion in 26 patients suffering from schizophrenia and 26 matched controls. The non-linear measure approximate entropy (ApEn) was calculated for the first time from the obtained signal in addition to standardized measures.

A significant difference was observed for slow wave, which represents the dominant frequency of gastric pacemaker activity, indicating gastric dysmotility in our patients. *The elevated ApEn measure points to increased complexity and dysregulation. In addition, we have observed a correlation between delusions and tachygastria.* Sympathetic function seems to be altered in the enteric nervous system of patients suffering from schizophrenia

Raghavendra BS, et al (2009) - **Complexity analysis of EEG in patients with schizophrenia using fractal dimension.** Physiol Meas. 2009 Aug;30(8):795-808. [ABS]

We computed Higuchi's fractal dimension (FD) of resting, eyes closed EEG recorded from 30 scalp locations in 18 male neuroleptic-naïve, recent-onset schizophrenia (NRS) subjects and 15 male healthy control (HC) subjects, who were group-matched for age. Schizophrenia patients showed a diffuse reduction of FD except in the bilateral temporal and occipital regions, with the reduction being most prominent bifrontally. The positive symptom (PS) schizophrenia subjects showed FD values similar to or even higher than HC in the bilateral temporo-occipital regions, along with a co-existent bifrontal FD reduction as noted in the overall sample of NRS. In contrast, this increase in FD values in the bilateral temporo-occipital region was absent in the negative symptom (NS) subgroup. The regional differences in complexity suggested by these findings may reflect the aberrant brain dynamics underlying the pathophysiology of schizophrenia and its symptom dimensions. Higuchi's method of measuring FD directly in the time domain provides an alternative for the more computationally intensive nonlinear methods of estimating EEG complexity.

Flynn G, et al (2008) - **Increased absolute magnitude of gamma synchrony in first-episode psychosis**. Schizophr Res. 2008 Oct;105(1-3):262-71. [ABS]

FEP subjects showed a significant elevation in absolute GPS relative to controls, apparent across the 35-45 Hz range. This elevation was most marked in the left centro-temporal region, across the 800 ms post-stimulus period. In FEP subjects, the elevation in GPS was also greater for target compared to non-target stimuli, while healthy controls did not show a stimulus effect.

These findings complement previous evidence for reductions in peak gamma synchrony, calculated relative to a pre-stimulus baseline, in schizophrenia. The results an excess of absolute GPS in schizophrenia may contribute to an inability to effectively integrate task-relevant information, which underlie psychotic symptoms

Stephane M, et al (2008) - **Temporospatial characterization of brain oscillations (TSCBO) associated with subprocesses of verbal working memory in schizophrenia.** Clin EEG Neurosci. 2008 Oct;39(4):194-202. [ABS]

> Less ERD (event related desynchronization) reflects reduced complexity of the neural activity, while reduced ERS (event related synchronization) reflects failure of the neural systems to resume idle state.

Lee SH, et al (2008) - **Nonlinear analysis of electroencephalogram in schizophrenia patients with persistent auditory hallucination.** Psychiatry Investig. 2008 Jun;5(2):115-20. [FULL TEXT]

> The recent nonlinear analyses of electroencephalogram (EEG) data have shown that the **correlation dimension (D2)** reflects the degree of integration of information processing in the brain. There is now considerable evidence that auditory hallucination (AH) reflects dysfunctional gamma and beta frequency oscillations. Gamma oscillations are thought to reflect internally driven representations of objects, and the occurrence of subsequent beta oscillations can reflect the modification of the neuronal circuitry used to encode the sensory perception.
>
> …The AH patients showed significantly increased gamma frequency D2 in Fp2 and decreased beta frequency D2 in the P3 region compared with the N-AH patients. These results imply that gamma frequency D2 in the right prefrontal cortex is more chaotic and that beta frequency D2 in the left parietal cortex is more coherent (less chaotic) in AH patients than in N-AH patients. CONCLUSION: Our study supports the previous evidence indicating that gamma and beta oscillations are pivotal to AH, and also shows the distinctive dimensional complexity between the right prefrontal and left parietal cortexes as the underlying biological correlates of AH in schizophrenia patients.

Li Y, et al (2008) - **Abnormal EEG complexity in patients with schizophrenia and depression.** Clin Neurophysiol. 2008 Jun;119(6):1232-41. [ABS]

> In all the groups, LZC of EEG decreased during the mental arithmetic compared with those under the resting conditions. Both the schizophrenia and the depression groups had a higher LZC ($p<0.05$) than the controls. Also, the schizophrenia group had a lower LZC ($p<0.05$) than the depression group during the mental arithmetic task as well as during the resting state. Significant differences in LZC, at some symmetrically located loci (FP1/FP2, F7/F8), between the two hemispheres were found in all the patient groups only during the arithmetic task. ONCLUSIONS: *Compared with conventional spectral analysis, LZC was more sensitive to both the power spectrum and the temporal amplitude distribution. LZC was associated with the ability to attend to the task and adapt the information processing system to the cognitive challenge.*

Bob P (2007) - **Chaos, brain and divided consciousness.** Acta Univ Carol Med Monogr. 2007;153:9-80. [ABS]

> Because epileptiform activity has specific chaotic behaviour and calculated information entropy from EDA (electrodermal activity) records reflects the complexity of the deterministic structure in the system there is a relevant assumption that unilaterally

increased complexity may produce interhemispheric disbalance and increased chaoticity which hypothetically may serve as a dynamic source of epileptiform discharges related to trauma induced kindling mechanism.

Bär KJ, et al (2007) - **Acute psychosis leads to increased QT variability in patients suffering from schizophrenia.** Schizophr Res. 2007 Sep;95(1-3):115-23. Epub 2007 Jul 16. [ABS]

Patients with schizophrenia have been reported to experience sudden cardiac death 3 times more likely than individuals from the general population. One important factor related to an increased risk of cardiac arrhythmias and sudden death is the prolongation of the QTc interval. …QTvi (QT variability interval) was significantly higher in patients with schizophrenia compared to controls. While QTvi correlated with the degree of delusions and hallucinations, no correlation with electrolyte concentrations was found. Approximate entropy of heart rate was decreased indicating reduced complexity and decreased vagal tone. In conclusion, increased QT variability in patients with schizophrenia indicates abnormal cardiac repolarization lability, which can result in serious cardiac arrhythmias.

Keshavan MS, et al (2004) - **Decreased nonlinear complexity and chaos during sleep in first episode schizophrenia: a preliminary report.** Schizophr Res. 2004 Dec 1;71(2-3):263-72. [ABS]

Diminished complexity of EEG time series during awake and REM sleep in patients with schizophrenia may underlie the impaired ability to process information in psychotic disorders such as schizophrenia.

Gruzelier JH (2003) - **Theory, methods and new directions in the psychophysiology of the schizophrenic process and schizotypy**. Int J Psychophysiol. 2003 May;48(2):221-45. [ABS]

The recognition that this is a dynamic and fluctuating illness and hence the relevance of functional neurophysiology, including the role of imbalances in hemispheric activation in ontogeny, developmental course, expression of symptoms, the effects of neuroleptics and recovery process, and the influence of stress a precipitant of breakdown. The role of thalamo-cortical activation systems. The particular value of electrocortical measures including the interrelations of electroencephalographic rhythms throughout the spectrum, and relations of gamma, dynamic core neuronal complexity, connectivity and sensory gating with experiences of unreality and disturbances of consciousness.

Jin SH, et al (2003) - **Hemispheric laterality and dimensional complexity in schizophrenia under sound and light stimulation**. Int J Psychophysiol. 2003 Jul;49(1):1-15. [ABS]

Kotini A, et al (2002) - **Detection of non-linearity in schizophrenic patients using magnetoencephalography.** Brain Topogr. 2002 Winter;15(2):107-13. [ABS]

We calculated the correlation dimension, which is a measure of the complexity of the dynamic system, as well as the first Lyapunov exponent that indicates the system's unpredictability. … The analysis of the MEG in the schizophrenic group **showed lower dimension complexity** and moreover the first Lyapunov exponent presented lower values compared with the corresponding ones in the control group, which means lower information processing.

Lee YJ, et al (2001) - **Detection of non-linearity in the EEG of schizophrenic patients.** Clin Neurophysiol. 2001 Jul;112(7):1288-94. [ABS]

> The aim of this study is to detect non-linearity in the EEG of schizophrenia with a modified method of surrogate data. We also want to identify if dimension complexity (correlation dimension using spatial embedding) could be used as a discriminating statistic to demonstrate non-linearity in the EEG. The difference between the attractor dimension of healthy subjects and schizophrenic subjects is expected to be interpreted as reflecting some mechanisms underlying brain wave by views of non-linear dynamics analysis may reflect mechanistic differences. …A decrease of dimension complexity was found in the EEG of schizophrenia compared with controls. We interpreted it as the result of the psychopath's dysfunction overall brain. The surrogating procedure results in a significant increase in D(s). …Moreover, schizophrenic patients' EEGs were compared with controls and a lower dimension complexity was found. The results of our study indicate the possibility of using the methods of non-linear time series analysis to identify the EEGs of schizophrenic patients.

Kim DJ, et al (2000) - **An estimation of the first positive Lyapunov exponent of the EEG in patients with schizophrenia.** Psychiatry Res. 2000 May 15;98(3):177-89. [ABS]

> We studied the complexity of the electroencephalogram (EEG) in schizophrenic patients by estimating the first Lyapunov exponent (L1), which might serve as an indicator of the specific brain function in schizophrenia. …For limited noisy data, this algorithm was strikingly faster and more accurate than previous ones. Our results showed that the schizophrenic patients had lower values of the L1 at the left inferior frontal and anterior temporal regions compared with normal controls. …These suggest that the non-linear analysis of the EEGs such as the estimation of the L1 might be a useful tool in analyzing EEG data to explore the neurodynamics of the brains of schizophrenic patients.

Koukkou M, et al (2000) - **An EEG approach to the neurodevelopmental hypothesis of schizophrenia studying schizophrenics, normal controls and adolescents.** J Psychiatr Res. 2000 Jan-Feb;34(1):57-73. [ABS]

> Within the framework of our model, the results suggest multifactorially elicited imbalances in the level of excitability of neuronal networks in schizophrenia, resulting in network activation at dissociated complexity levels, partially regressed and partially prematurely developed. It is hypothesized that activation of age- and/or state-inadequate representations for coping with realities becomes manifest as productive schizophrenic symptoms. Thus, the results support some aspects of the neurodevelopmental hypothesis.

Friston KJ (1996) - **Theoretical neurobiology and schizophrenia.** Br Med Bull. 1996 Jul;52(3):644-55. [ABS]

> This chapter addresses the idea that schizophrenia is a 'disconnection syndrome' from a theoretical and computational perspective. The distinction between anatomical and functional connectivity is reviewed and used as a framework to introduce empirical and computational evidence that schizophrenia involves, at some level, a disintegration of

neuronal interactions. The chapter concludes with an example of computational neuroscience that relates observations on the dimensional complexity of neuronal dynamics in schizophrenia to the disconnection hypothesis.

Koukkou M, et al (1995) - **EEG reactivity and EEG activity in never-treated acute schizophrenics, measured with spectral parameters and dimensional complexity.** J Neural Transm Gen Sect. 1995;99(1-3):89-102. [ABS]

> Results from our studies on EEG activity and EEG reactivity (= EEG components of a memory-driven, adaptive, non-unitary orienting response) as analyzed with spectral parameters and "chaotic" dimensionality (correlation dimension) are summarized. Both analysis procedures showed a deviant brain functional organization in never-treated first-episode schizophrenia which, within the framework of the model, suggests as common denominator for the pathogenesis of the symptoms a deviation of working memory, the nature of which is functional and not structural.

Koukkou M, et al (1993) - **Dimensional complexity of EEG brain mechanisms in untreated schizophrenia.** Biol Psychiatry. 1993 Mar 15;33(6):397-407. [ABS]

> The higher dimensional complexity of functional brain mechanisms in schizophrenics versus normals is reminiscent of the loosened organization of thought, and of suggestions of certain superior abilities in the patients.

Sleep ▲

Zhao D, et al (2019) - **Comparative analysis of different characteristics of automatic sleep stages**. Comput Methods Programs Biomed. 2019 Jul;175:53-72. [ABS]

> …the SampEn, fuzzy entropy, FD and complexity can achieve ideal sleep staging. … due to the non-stationary and non-linear characteristics of EEG signals, time domain and time-frequency analysis methods all have some limitations. Nonlinear analysis was more effective and practical for the analysis of sleep EEG.

Gonzalez J, et al (2019) - **Decreased electrocortical temporal complexity distinguishes sleep from wakefulness**. Sci Rep. 2019; 9: 18457. [ABS]

> We found that PeEn is maximal during wakefulness (W) and decreases during sleep. These results bring to light the different thalamo-cortical dynamics emerging during sleep-wake states, which are associated with the well-known spectral changes that occur when passing from W to sleep. Moreover, the PeEn analysis allows us to determine behavioral states independently of the electrodes' cortical location, which points to an underlying global pattern in the signal that differs among the cycle states that is missed by classical methods. Consequently, our data suggest that PeEn analysis of a single EEG channel could allow for cheap, easy, and efficient sleep monitoring.

Wielek T, et al (2019) **- On the development of sleep states in the first weeks of life**. PLoS One. 2019; 14(10): e0224521. [FULL TEXT]

> For sleep classification EEG signal complexity was estimated using multi-scale permutation entropy and fed into a machine learning classifier. Interestingly the baby's brain signal complexity (and spectral power) revealed developmental changes in sleep in the first 5 weeks of life, and were restricted to NREM ("quiet") and REM ("active sleep") states…

Miskovic V, et al (2019) - **Changes in EEG multiscale entropy and power-law frequency scaling during the human sleep cycle.** Hum Brain Mapp. 2019 Feb 1;40(2):538-551. [FULL TEXT]

> Slow wave sleep was characterized by reduced entropy at short time scales and increased entropy at long time scales.

Ruffini G, et al (2019) - **Algorithmic Complexity of EEG for Prognosis of Neurodegeneration in Idiopathic Rapid Eye Movement Behavior Disorder (RBD**). Ann Biomed Eng. 2019 Jan;47(1):282-296. [ABS]

> Poor prognosis in RBD appears to be associated with decreased complexity of EEG spectrograms stemming in part from frequency power imbalances and cross-frequency amplitude algorithmic coupling.

Darracq M, et al (2018) - **Characterising the effect of propofol on complexity and stability in the EEG power spectrum**. Br J Anaesth. 2018 Dec;121(6):1368-1369. [FULL TEXT]

> This adds to accumulating evidence suggesting that during unconsciousness the complexity of the spontaneous EEG, and evoked responses, is reduced.

Hou F, et al (2018) - **Complexity of Wake Electroencephalography Correlates with Slow Wave Activity after Sleep Onset.** Front Neurosci. 2018 Nov 13;12:809. [FULL TEXT]

> …lower complexity before sleep onset is associated with decreased sleep latency, indicating a potential facilitating role of reduced pre-sleep complexity in the wake-sleep transition.

Lin D, et al (2018) - **Analysis on Insomniac Electroencephalogram Data after Treatment with Superficial Needling Based on Approximate Entropy and Correlation Dimensionality**. Zhen Ci Yan Jiu 2018 Mar 25;43(3):180-4. [ABS]

> …during superficial needling stimulation of Shangen point, the EEG signals were lowered in complexity, and improved in synchronization, stabilization and ordering, favoring sleep at last.

Ma Y, et al (2018) - **Nonlinear dynamical analysis of sleep electroencephalography using fractal and entropy approaches.** Sleep Med Rev. 2018 Feb;37:85-93. [ABS]

> …nonlinear measures may provide extensive insights into brain activities during sleep.

Bugalho P, et al (2017) - **Heart rate changes according to the complexity of motor events in REM sleep behavior disorder.** Clin Neurophysiol. 2017 Jul;128(7):1317-1318. [ABS]

> Reduced Heart Rate Variability (HRV) is considered a marker of autonomic system dysfunction in REM sleep behavior disorder (RBD) (Fantini et al., 2002; Sorensen et al., 2012). *Blunted Heart Rate (HR) response was described in RBD and Parkinson's Disease*

(PD) patients following limb movements during sleep (Fantini et al., 2002; Sorensen et al., 2012) and in PD after arousals (Sorensen et al., 2012). We found no study on the effect of RBD motor events (ME) on HR. RBD related ME can be classified in two types: short lasting, small amplitude, non-purposeful movements and complex, scenic ones, in which patients enact the content of their dreams, usually negative or violent (Frauscher et al., 2007).

Schartner MM, et al (2017) - **Global and local complexity of intracranial EEG decreases during NREM sleep.** Neurosci Conscious. 2017; 2017(1): niw022. [FULL TEXT]

Mariani S, et al (2016) - **Analysis of the sleep EEG in the complexity domain**. Conf Proc IEEE Eng Med Biol Soc. 2016 Aug;2016:6429-6432. [FULL TEXT]

> We explore a complementary "complexity domain" approach based on multiscale entropy (MSE) analysis of EEG signals and discuss its relationships to standard sleep analysis and to that based on electrocardiogram (ECG)-derived cardiopulmonary coupling (CPC). We observe a progressive decrease in complexity associated with decreased arousability, as measured by both conventional sleep scoring and CPC analysis. Furthermore, complexity analysis supports the contention that stage 2 non-REM sleep has distinct sub-phases that map to CPC high- and low-frequency coupled dynamics.

Abásolo D, et al (2015) - **Lempel-Ziv complexity of cortical activity during sleep and waking in rats.** J Neurophysiol. 2015 Apr 1; 113(7):2742-52. [ABS]

> "…activated brain states-waking and rapid eye movement (REM) sleep are characterized by higher LZC compared with non-rapid eye movement (NREM) sleep."

Zhang C, et al (2015) - **The effect of CPAP treatment on EEG of OSAS patients**. Sleep Breath. 2015 Mar 14. [ABS]

> "After CPAP treatment, FD of EEG in non-rapid eye movement (NREM) sleep decreased significantly ($P < 0.05$), while FD of EEG increased in rapid eye movement (REM) sleep." FD means fractal dimension and is a measure of entropy/complexity.

Immanuel SA, et al (2014) - **Symbolic dynamics of respiratory cycle related sleep EEG in children with sleep disordered breathing**. Conf Proc IEEE Eng Med Biol Soc. 2014; 2014:6016-9. [ABS]

> "Children with SDB (sleep disordered breathing) showed less complex EEG dynamics in non-REM sleep that was unrelated to the respiratory phase. In REM sleep normal children showed a respiratory phase-related reduction in EEG variability during the expiratory phase compared to inspiration, which was not apparent in children with SDB."

Melia U, et al (2015) - **Mutual information measures applied to EEG signals for sleepiness characterization**. Med Eng Phys. 2015 Mar; 37(3):297-308. [ABS]

"Without daytime sleepiness (WDS) group presented more complexity than excessive daytime sleepiness (EDS) in the occipital zone, while a stronger nonlinear coupling between occipital and frontal zones was detected in EDS patients than in WDS."

Melia U. et al (2014) - **Correntropy measures to detect daytime sleepiness from EEG signals**. Physiol Meas. 2014 Oct; 35(10):2067-83. [Abstract]

The without daytime sleepiness (WDS) group presented more complexity in the occipital zone than the excessive daytime sleepiness (EDS) group, while a stronger nonlinear coupling between the occipital and frontal regions was detected in EDS patients than in the WDS group.

Burioka N, et al (2005) - **Approximate entropy in the electroencephalogram during wake and sleep**. Clin EEG Neurosci. 2005 Jan;36(1):21-4. [FULL TEXT]

Approximate entropy (ApEn) of EEG was statistically significantly lower during Stage IV and higher during wake and REM sleep. …We conclude that ApEn measurement can be useful to estimate sleep stages and the complexity in brain activity.

Small World Networks ▲

Smith K, et al (2017) - **The complex hierarchical topology of EEG functional connectivity.** J Neurosci Methods. 2017 Jan 30;276:1-12. [ABS]

By controlling the parameters of our model, the highest complexity is found to arise between a random topology and a strict 'class-based' topology. Further, the model has equivalent complexity to EEG phase-lag networks at peak performance.

Mugisha S, et al (2016) - **Identifying optimal targets of network attack by belief propagation.** Phys Rev E. 2016 Jul;94(1-1):012305. [ABS]

For a network formed by nodes and undirected links between pairs of nodes, the network optimal attack problem aims at deleting a minimum number of target nodes to break the network down into many small components. This problem is intrinsically related to the feedback vertex set problem that was successfully tackled by spin-glass theory and an associated belief propagation-guided decimation (BPD) algorithm. …In the present work we apply the BPD algorithm (which has approximately linear time complexity) to the network optimal attack problem and demonstrate that it has much better performance than a recently proposed collective information algorithm for different types of random networks and real-world network instances. The *BPD-guided attack scheme often induces an abrupt collapse of the whole network, which may make it very difficult to defend*.

Caliandro P, et al (2016) - **Small-World Characteristics of Cortical Connectivity Changes in Acute Stroke.** Neurorehabil Neural Repair. 2017 Jan;31(1):81-94. [ABS]

Functional and dynamic changes of brain connectivity can be reliably analyzed via electroencephalography (EEG) recordings even when they are not yet reflected in structural changes of connections.

Results: Network rearrangements were mainly detected in delta, theta, and alpha bands when patients were compared with healthy subjects. In delta and alpha bands similar findings were observed in both hemispheres regardless of the side of ischemic lesion: bilaterally decreased small-worldness in the delta band and bilaterally increased small-worldness in the alpha2 band. In the theta band, bilaterally decreased small-worldness was observed only in patients with stroke in the left hemisphere. Conclusions After an acute stroke, brain cortex rearranges its network connections diffusely, in a frequency-dependent modality probably in order to face the new anatomical and functional frame.

Ulloa Severino FP. Et al, (2016) - **The role of dimensionality in neuronal network dynamics.** Sci Rep. 2016 Jul 11;6:29640. [FULL TEXT]

Recent results from network theory show that *complexity affects several dynamical properties of networks that favor synchronization.*

After one week, calcium imaging revealed moderately synchronous activity in 2D networks, but the degree of synchrony of 3D networks was higher and had two regimes: a highly synchronized (HS) and a moderately synchronized (MS) regime.

After two weeks, the degree of synchrony in 3D networks decreased, as observed in vivo. These results show that dimensionality determines properties of neuronal networks and that several features of brain dynamics are a consequence of its 3D topology.

John M, et al (2017) - **Graph analysis of structural brain networks in Alzheimer's disease: beyond small world properties.** Brain Struct Funct. 2017 Mar;222(2):923-942. [ABS]

Small worldness diminished with AD only in the sub-network containing the areas of medial temporal lobe known to be heaviest and earliest affected.

Beyond small world properties, complexity and entropy measures indicated that the intricacy of connection patterns and structural diversity decreased in both sub-networks.

Cox MP (2016) - **Small Traditional Human Communities Sustain Genomic Diversity over Microgeographic Scales despite Linguistic Isolation**. Mol Biol Evol. 2016 Sep;33(9):2273-84. [FULL TEXT]

More than 4,000 years after these communities were established during the Neolithic period, most speak different languages and can be distinguished genetically. Yet their nuclear diversity is not reduced, instead being comparable to other, even much larger, regional groups. Modeling reveals a separation of time scales: while languages and culture can evolve quickly, creating social barriers, sporadic migration averaged over many generations is sufficient to keep villages linked genetically…

Man M, et al (2016) - **Quantification of degeneracy in Hodgkin-Huxley neurons on Newman-Watts small world network.** J Theor Biol. 2016 Aug 7;402:62-74. [ABS]

> Degeneracy is a fundamental source of biological robustness, complexity and evolvability in many biological systems. However, degeneracy is often confused with redundancy. …both degeneracy and redundancy increase with complexity for small coupling strengths; however, as coupling strength increases, redundancy decreases with complexity (in contrast to degeneracy, which is relatively invariant). These results suggest that the degeneracy is a general topologic characteristic of neuronal networks, which could be applied quantitatively in neuroscience and connectomics.

Liu H, et al (2015) - **Effects of bursting dynamic features on the generation of multi-clustered structure of neural network with symmetric spike-timing-dependent plasticity learning rule**. Chaos. 2015 Nov;25(11):113108. [ABS]

> …the time consumption of this clustering procedure of the burst-based self-organized neural network (BSON) is much shorter than the spike-based self-organized neural network (SSON). Our results show that the BSON network has more obvious small-world properties, i.e., higher clustering coefficient and smaller shortest path length than the SSON network. Also, the results of larger structure entropy and activity entropy of the BSON network demonstrate that this network has higher topological complexity and dynamical diversity, which benefits for enhancing information transmission of neural circuits. Hence, we conclude that the burst firing can significantly enhance the efficiency of clustering procedure and the emergent clustered structure renders the whole network more synchronous and therefore more sensitive to weak input. This result is further confirmed from its improved performance on stochastic resonance. Therefore, we believe that the multi-clustered neural network which self-organized from the bursting dynamics has high efficiency in information processing.

Zachariou N, et al (2015) - **Generalised Sandpile Dynamics on Artificial and Real-World Directed Networks**. PLoS One. 2015 Nov 25;10(11):e0142685. [FULL TEXT]

> Randomly adding a small proportion of links connecting non adjacent layers in an otherwise layered network takes the system out of the mean field regime to produce non-trivial avalanche-size probability density function.

Wen X, et al (2015) - **Reconfiguration of the Brain Functional Network Associated with Visual Task Demands**. PLoS One. 2015 Jul 6;10(7):e0132518. [FULL TEXT]

> Compared with the resting-state, the functional networks associated with the visual tasks exhibited significantly increased network efficiency and wiring-cost, but decreased modularity and network robustness. The changes in the task-related topological properties were modulated according to the task complexity (i.e., from RS to VSW and VSD). Moreover, at the regional level, we observed that the increased nodal efficiencies in the visual and working memory regions were positively associated with the increase in task complexity.

Chang MC, et al (2014) - **Emergence of dynamical complexity related to human heart rate variability**. Phys Rev E Stat Nonlin Soft Matter Phys. 2014 Dec;90(6):062806. [ABS]

> By tuning the adaptability of the environment and the long-range shortcuts we can increase or decrease the dynamical complexity, thereby modeling trends found in the MSE of a healthy human heart rate in different physiological states. When the shortcut and adaptability values increase, the complexity in the system dynamics becomes uncorrelated.

Kao AB, et al (2014) - **Decision accuracy in complex environments is often maximized by small group sizes**. Proc Biol Sci. 2014 Apr 23;281(1784):20133305. [FULL TEXT]

> …counterintuitively, it is the noise inherent in these small groups that enhances their accuracy, allowing individuals in such groups to avoid the detrimental effects of correlated information while exploiting the benefits of collective decision-making. Our results demonstrate that the conventional view of the wisdom of crowds may not be informative in complex and realistic environments, and that being in small groups can maximize decision accuracy across many contexts.

Brook AH (2014) - **General and craniofacial development are complex adaptive processes influenced by diversity.** Aust Dent J. 2014 Jun;59 Suppl 1:13-22. [ABS]

Esteve-Altava B, et al (2013) - **Grist for Riedl's mill: a network model perspective on the integration and modularity of the human skull.** J Exp Zool B Mol Dev Evol. 2013 Dec;320(8):489-500. [ABS]

> Our overall results show that the human skull is a small-world network, with two well-delimited connectivity modules: one facial organized around the ethmoid bone, and one cranial organized around the sphenoid bone. …Our study also demonstrates the adequacy of network analysis as an innovative tool to understand the morphological complexity of anatomical systems.

Gow DW, et al (2012) - **New levels of language processing complexity and organization revealed by granger causation.** Front Psychol. 2012 Nov 19;3:506. [FULL TEXT]

> …even "early" processes such as speech perception involve interactions of many areas in a strikingly large network that extends well beyond traditional left hemisphere perisylvian cortex that play out over hundreds of milliseconds.

Kaiser M, et al (2011) - **Evolution and development of brain networks: from Caenorhabditis elegans to Homo sapiens.** . Network. 2011;22(1-4):143-7. [ABS]

> Neural networks show a progressive increase in complexity during the time course of evolution. …'Small-world' topology and highly connected regions (hubs) are prevalent across the evolutionary scale, ensuring efficient processing and resilience to internal (e.g. lesions) and external (e.g. environment) changes.

Esteve-Altava B, et al (2011) - **Network models in anatomical systems**. J Anthropol Sci. 2011;89:175-84. [ABS]

Network theory has been extensively used to model the underlying structure of biological processes. From genetics to ecology, network thinking is changing our understanding of complex systems, specifically how their internal structure determines their overall behavior. Concepts such as hubs, scale-free or small-world networks, common in the complexity literature, are now used more and more in sociology, neurosciences, as well as other anthropological fields.

Hu Y, et al (2011) - **Possible origin of efficient navigation in small worlds.** . Phys Rev Lett. 2011 Mar 11;106(10):108701. [ABS]

The small-world phenomenon is one of the most important properties found in social networks. It includes both short path lengths and efficient navigation between two individuals. It is found by Kleinberg that navigation is efficient only if the probability density distribution of an individual to have a friend at distance r scales as P(r) ∼ r(-1). Although this spatial scaling is found in many empirical studies, the origin of how this scaling emerges is still missing. In this Letter, we propose the origin of this scaling law using the concept of entropy from statistical physics and show that this scaling is the result of optimization of collecting information in social networks.

Masucci AP, et al (2011) - **Wikipedia information flow analysis reveals the scale-free architecture of the semantic space.** PLoS One. 2011 Feb 28;6(2):e17333. [FULL TEXT]

In this paper we extract the topology of the semantic space in its encyclopedic acception, measuring the semantic flow between the different entries of the largest modern encyclopedia, Wikipedia, and thus creating a directed complex network of semantic flows. Notably at the percolation threshold the semantic space is characterised by scale-free behaviour at different levels of complexity and this relates the semantic space to a wide range of biological, social and linguistics phenomena. In particular we find that the cluster size distribution, representing the size of different semantic areas, is scale-free. Moreover the topology of the resulting semantic space is scale-free in the connectivity distribution and displays small-world properties. However its statistical properties do not allow a classical interpretation via a generative model based on a simple multiplicative process. After giving a detailed description and interpretation of the topological properties of the semantic space, we introduce a stochastic model of content-based network, based on a copy and mutation algorithm and on the Heaps' law, that is able to capture the main statistical properties of the analysed semantic space, including the Zipf's law for the word frequency distribution.

Telesford QK, et al (2011) - **The brain as a complex system: using network science as a tool for understanding the brain**. Brain Connect. 2011;1(4):295-308. [FULL TEXT]

The field was propelled forward when Watts and Strogatz introduced their small-world network model, which described a network that provided regional specialization with efficient global information transfer. This model is appealing to the study of brain connectivity, as the brain can be viewed as a system with various interacting regions that produce complex behaviors. …These methods necessitate a philosophical shift toward complexity science. In this context, when correctly applied and interpreted,

network scientific methods have a chance to revolutionize the understanding of brain function.

Thiemann C, et al (2010) - **The structure of borders in a small world.** PLoS One. 2010 Nov 18;5(11):e15422. [FULL TEXT]

> The complexity of modern human communication, the ease of long-distance movement, and increased interaction across political borders complicate the operational definition and assessment of geographic borders that optimally reflect the multi-scale nature of today's human connectivity patterns. What border structures emerge directly from the interplay of scales in human interactions is an open question.

Park CY, et al (2010) - **Simultaneous genome-wide inference of physical, genetic, regulatory, and functional pathway components**. PLoS Comput Biol. 2010 Nov 24;6(11):e1001009. [FULL TEXT]

> We analyzed the systems-level network features within all interactomes, verifying the presence of small-world properties and enrichment for recurring network motifs.

Xu J, et al (2011) - **MiRNA-miRNA synergistic network: construction via co-regulating functional modules and disease miRNA topological features**. Nucleic Acids Res. 2011 Feb;39(3):825-36. [FULL TEXT]

> Synergistic regulations among multiple microRNAs (miRNAs) are important to understand the mechanisms of complex post-transcriptional regulations in humans. Complex diseases are affected by several miRNAs rather than a single miRNA…. Here, we constructed a miRNA-miRNA functional synergistic network (MFSN) via co-regulating functional modules that have three features: common targets of corresponding miRNA pairs, enriched in the same gene ontology category and close proximity in the protein interaction network. …We found that the MFSN exhibits a scale free, small world and modular architecture. Furthermore, the topological features of disease miRNAs in the MFSN are distinct from non-disease miRNAs. They have more synergism, indicating their higher complexity of functions and are the global central cores of the MFSN. In addition, miRNAs associated with the same disease are close to each other.

Gaál ZA, et al (2010) - **Age-dependent features of EEG-reactivity - spectral, complexity, and network characteristics.** Neurosci Lett. 2010 Jul 19;479(1):79-84. [ABS]

> Absolute spectral power was higher in the young in the delta, alpha1 and alpha2 bands in the posterior area. The alpha1 peak frequency decreased following eyes opening in the young, while no change was observed in the elderly. Omega-complexity was higher in the elderly especially in the frontal area and increased following eyes opening. Values of the clustering coefficient, path length and that of the "small-world index" decreased as a result of eyes opening, the latter in the fast frequency range. The results suggest reduced reactivity in the elderly as shown by frequency spectra and decreased level of integrative activity particularly in the frontal area probably as a result of reduced interneuronal processing capacity. Indices of network characteristics reveal a shift

towards more random topology especially in the beta frequencies caused by eyes opening.

Kaiser M, et al (2010) - **Optimal hierarchical modular topologies for producing limited sustained activation of neural networks.** Front Neuroinform. 2010 May 14;4:8. [FULL TEXT]

> An essential requirement for the representation of functional patterns in complex neural networks, such as the mammalian cerebral cortex, is the existence of stable regimes of network activation, typically arising from a limited parameter range. In this range of limited sustained activity (LSA), the activity of neural populations in the network persists between the extremes of either quickly dying out or activating the whole network. Hierarchical modular networks were previously found to show a wider parameter range for LSA than random or small-world networks not possessing hierarchical organization or multiple modules. …
>
> For a constant number of node connections, there was a trend for optimal configurations in larger-size networks to possess a larger number of hierarchical levels or more modules. These results may help to explain the trend to greater network complexity apparent in larger brains and may indicate that this complexity is required for maintaining stable levels of neural activation.

Lupyan G (2010) - **Language structure is partly determined by social structure.** PLoS One. 2010 Jan 20;5(1):e8559. [FULL TEXT]

> We conducted a statistical analysis of >2,000 languages… We found strong relationships between linguistic factors related to morphological complexity, and demographic/socio-historical factors …Our findings indicate that just as biological organisms are shaped by ecological niches, language structures appear to adapt to the environment (niche) in which they are being learned and used. As adults learn a language, features that are difficult for them to acquire, are less likely to be passed on to subsequent learners. Languages used for communication in large groups that include adult learners appear to have been subjected to such selection. Conversely, *the morphological complexity common to languages used in small groups increases redundancy which may facilitate language learning by infants.*

Grillari J et al (2010) - **Novel modulators of senescence, aging, and longevity: Small non-coding RNAs enter the stage.** Exp Gerontol. 2010 Apr;45(4):302-11. [ABS]

> During the last decade evidence has accumulated that the aging process is driven by limited allocation of energy to somatic maintenance resulting in accumulation of stochastic damage. This damage, affecting molecules, cells, and tissues, is counteracted by genetically programmed repair, the efficiency of which thus importantly determines the life and 'health span' of organisms. Therefore, understanding the regulation of gene expression during cellular and organismal aging as well as upon exposure to various damaging events is important to understand the biology of aging and to positively influence the health span. The recent identification of small non-coding RNAs (ncRNAs), has added an additional layer of complexity to the regulation of gene expression with the classes of endogenous small inhibitory RNAs (siRNAs), PIWI-interacting RNAs

(piRNAs), QDE1-interacting RNAs (qiRNAs) and microRNAs (miRNAs). Some of these ncRNAs have not yet been identified in mammalian cells and are dependent on RNA-dependent RNA polymerases. The first mammalian enzyme with such activity has only now emerged and surprisingly consists of the catalytic subunit of telomerase (hTERT) together with RMPR, an alternative RNA component. The so far most studied small non-coding RNAs, miRNAs, however, are now increasingly found to operate in the complex network of cellular aging. Recent findings show that (i) miRNAs are regulated during cellular senescence in vitro, (ii) they contribute to tissue regeneration by regulation of stem cell function, and (iii) at least one miRNA modulates the life span of the model organism C. elegans. Additionally, (iv) they act as inhibitors of proteins mediating the insulin/IGF1 and target of rapamycin (TOR) signalling, both of which are conserved modulators of organism life span.

Bullmore E (2009) - **Generic aspects of complexity in brain imaging data and other biological systems.** Neuroimage. 2009 Sep;47(3):1125-34. [ABS]

A key challenge for systems neuroscience is the question of how to understand the complex network organization of the brain on the basis of neuroimaging data. Similar challenges exist in other specialist areas of systems biology because complex networks emerging from the interactions between multiple non-trivially interacting agents are found quite ubiquitously in nature, from protein interactomes to ecosystems. We suggest that one way forward for analysis of brain networks will be to quantify aspects of their organization which are likely to be generic properties of a broader class of biological systems. In this introductory review article we will highlight four important aspects of complex systems in general: fractality or scale-invariance; criticality; small-world and related topological attributes; and modularity.

Hori N, et al (2009) - **Folding energy landscape and network dynamics of small globular proteins.** Proc Natl Acad Sci U S A. 2009 Jan 6;106(1):73-8. [FULL TEXT]

Dynamics in the denatured part of the network exhibited basin-hopping itinerancy among many conformations, whereas the protein reached relatively well-defined final stages that led to their native states. We also found that the folding network has the hierarchic nature characterized by the scale-free and the small-world properties.

Shanahan M (2008) - **Dynamical complexity in small-world networks of spiking neurons.** Phys Rev E Stat Nonlin Soft Matter Phys. 2008 Oct;78(4 Pt 1):041924. [ABS]

The results broadly support the hypothesis that small-world topology promotes dynamical complexity, but reveal a narrow parameter range within which this occurs for the network topology under investigation, and suggest an inverse correlation with phase synchrony inside this range.

Siri B, et al () - **Effects of Hebbian learning on the dynamics and structure of random networks with inhibitory and excitatory neurons.** J Physiol Paris. 2007 Jan-May;101(1-3):136-48. [ABS]

We show that the application of such Hebbian learning leads to drastic changes in the network dynamics and structure. In particular, the learning rule contracts the norm of

the weight matrix and yields a rapid decay of the dynamics complexity and entropy. In other words, the network is rewired by Hebbian learning into a new synaptic structure that emerges with learning on the basis of the correlations that progressively build up between neurons. We also observe that, within this emerging structure, the strongest synapses organize as a small-world network. The second effect of the decay of the weight matrix spectral radius consists in a rapid contraction of the spectral radius of the Jacobian matrix. This drives the system through the "edge of chaos" where sensitivity to the input pattern is maximal. Taken together, this scenario is remarkably predicted by theoretical arguments derived from dynamical systems and graph theory.

Ferri R, et al (2007) - **Small-world network organization of functional connectivity of EEG slow-wave activity during sleep.** Clin Neurophysiol. 2007 Feb;118(2):449-56. [ABS]

The network organization of the EEG slow-wave synchronization during sleep shows features characteristic of small-world networks (high Cp combined with low Lp); this type of organization is slightly but significantly more evident during the CAP A1 subtypes. SIGNIFICANCE: Our results show feasibility of using graph theoretical measures to characterize the complexity of brain networks during sleep and might indicate sleep, and the A1 phases of CAP in particular, as a period during which slow-wave synchronization shows optimal network organization for information processing.

Broad KD, et al (2006) - **Mother-infant bonding and the evolution of mammalian social relationships**. Philos Trans R Soc Lond B Biol Sci. 2006 Dec 29;361(1476):2199-214. [FULL TEXT]

With the evolutionary increase of neocortex seen in monkeys and apes, there has been a corresponding increase in the complexity of social relationships and bonding strategies together with a significant redundancy in hormonal priming for motivated behavior. Olfactory recognition and olfactory inputs to areas of the brain concerned with social reward are downregulated and recognition is based on integration of multimodal sensory cues requiring an expanded neocortex, particularly the association cortex. This emancipation from olfactory and hormonal determinants of bonding has been succeeded by the increased importance of social learning that is necessitated by living in a complex social world and, especially in humans, a world that is dominated by cultural inheritance.

Mellars P (2006) - **Why did modern human populations disperse from Africa ca. 60,000 years ago? A new model.** Proc Natl Acad Sci U S A. 2006 Jun 20;103(25):9381-6. [FULL TEXT]

Studies of both the mitochondrial DNA (mtDNA) mismatch patterns in modern African populations and related mtDNA lineage-analysis patterns point to a major demographic expansion centered broadly within the time range from 80,000 to 60,000 B.P., probably deriving from a small geographical region of Africa. Recent archaeological discoveries in southern and eastern Africa suggest that, at approximately the same time, there was a major increase in the complexity of the technological, economic, social, and cognitive behavior of certain African groups, which could have led to a major demographic expansion of these groups in competition with other, adjacent groups. It is suggested that this complex of behavioral changes (possibly triggered by the rapid environmental

changes around the transition from oxygen isotope stage 5 to stage 4) could have led not only to the expansion of the L2 and L3 mitochondrial lineages over the whole of Africa but also to the ensuing dispersal of these modern populations over most regions of Asia, Australasia, and Europe, and their replacement (with or without interbreeding) of the preceding "archaic" populations in these regions.

Stam CJ, et al (2007) - **Small-world networks and functional connectivity in Alzheimer's disease.** Cereb Cortex. 2007 Jan;17(1):92-9. [ABS]

> A longer path length with a relatively preserved cluster coefficient suggests a loss of complexity and a less optimal organization. The present study provides further support for the presence of "small-world" features in functional brain networks and demonstrates that AD is characterized by a loss of small-world network characteristics. Graph theoretical analysis may be a useful approach to study the complexity of patterns of interrelations between EEG channels.

Mrowka R, et al (2004) - **Sequence-related human proteins cluster by degree of evolutionary conservation.** Phys Rev E Stat Nonlin Soft Matter Phys. 2004 Nov;70(5 Pt 1):051908. [ABS]

> We gain further insight into structural properties of N by studying the relationship between the connectivity distribution and the phylogenetic conservation of proteins in bacteria, plants, invertebrates, and vertebrates. We find that (iv) the proportion of sequence-related proteins increases with increasing extent of evolutionary conservation. Our results support that small-world network properties constitute a footprint of an evolutionary mechanism and extend the traditional interpretation of protein families.

Smell / Aromatherapy ▲

Omam S, et al (2020) - **Complexity-based decoding of brain-skin relation in response to olfactory stimuli**. Comput Methods Programs Biomed. 2020 Feb;184:105293. [ABS]

> ...the complexity of GSR (galvanic skin response – electrodermal response) signal changes with the complexity of EEG signal in case of different stimuli, where by increasing the molecular complexity of olfactory stimuli, the complexity of EEG and GSR signals increases. The results of statistical analysis showed the significant effect of stimulation on variations of complexity of GSR signal. In addition, based on effect size analysis, fourth odor with greatest molecular complexity had the greatest effect on variations of complexity of EEG and GSR signals.

Namazi H, et al (2016) - **The Analysis of the Influence of Odorant's Complexity on Fractal Dynamics of Human Respiration.** Sci Rep. 2016 May 31;6:26948. [FULL TEXT]

> The results show for the first time that more structurally complex a monomolecular odorant will result in less fractal respiratory signal. On the other hand, odorant with higher entropy will result the respiratory signal with lower entropy.

Stroke ▲

Popa LL, et al (2020) - **The Role of Quantitative EEG in the Diagnosis of Neuropsychiatric Disorders.** Med Life. Jan-Mar 2020;13(1):8-15. [FULL TEXT]

> QEEG has brought new techniques of EEG signals feature extraction: analysis of specific frequency band and signal complexity, analysis of connectivity, and network analysis. The clinical application of QEEG is extensive, including neuropsychiatric disorders, epilepsy, stroke, dementia, traumatic brain injury, mental health disorders, and many others. …to date, the role of QEEG is not necessarily to pinpoint an immediate diagnosis but to provide additional insight …and specific treatment response evaluation.

Zeng H, et al (2017) - **A Novel Nonlinear Dynamic Method for Stroke Rehabilitation Effect Evaluation Using EEG.** IEEE Trans Neural Syst Rehabil Eng. [ABS]

> …mean nonlinearly separable complexity degree (Mean_NLSD), to efficiently and accurately evaluate therapy effect of stroke patients.

Kielar A, et al (2016) - **Identifying Dysfunctional Cortex: Dissociable Effects of Stroke and Aging on Resting State Dynamics in MEG and fMRI.** Front Aging Neurosci. 2016; 8: 40. [FULL TEXT]

> …MEG signal complexity offers a sensitive index of neural dysfunction in perilesional tissue in chronic stroke, and that these effects are clearly distinguishable from those associated with healthy aging.

Liu S, et al (2016) - **Abnormal EEG Complexity and Functional Connectivity of Brain in Patients with Acute Thalamic Ischemic Stroke**. Comput Math Methods Med. 2016;2016:2582478. [FULL TEXT]

> Results showed that patients had increased mean LZC and SampEn than the controls, which implied the stroke group has higher EEG complexity. For the brain network, the stroke group displayed a trend of weaker cortical connectivity, which suggests a functional impairment of information transmission in cortical connections in stroke patients. These findings suggest that nonlinear analysis and brain network could provide essential information for better understanding the brain dysfunction in the stroke and assisting monitoring or prognostication of stroke evolution.

Chen CH, et al (2015) - **Complexity of Heart Rate Variability Can Predict Stroke-In-Evolution in Acute Ischemic Stroke Patients.** Sci Rep. 2015 Dec 1;5:17552. [FULL TEXT]

> After adjustment for clinical variables, patients with higher complexity index values were significantly less likely to have stroke-in-evolution (SIE) ... In summary, early assessment of HRV by MSE can be a potential predictor of SIE in ICU-admitted non-AF ischemic stroke patients.

Chu RK (2015) **- MEG-based detection and localization of perilesional dysfunction in chronic stroke.** Neuroimage Clin. 2015 Apr 8; 8:157-69. [FULL TEXT]

"Perilesional tissue exhibited a general slowing of the power spectrum (increased delta/theta, decreased beta) as well as a reduction in MSE." - Multi-Scale Entropy.

Placek MM, et al (2015) - **Complexity of cerebral blood flow velocity and arterial blood pressure in subarachnoid hemorrhage using time-frequency analysis**. Conf Proc IEEE Eng Med Biol Soc. 2015;2015:7700-3. [ABS]

> We investigated changes of time-frequency (TF) complexity, in terms of Rényi entropy and a measure of concentration, of middle cerebral blood flow velocity (CBFV) and arterial blood pressure in relation to the development of cerebral vasospasm in 15 patients after aneurysmal subarachnoid hemorrhage. Interhemispheric differences in the period of no vasospasm and vasospasm were also compared. Results show reduced complexity of TF representations of CBFV on the side of aneurysm before vasospasm was identified. This potentially can serve as an early-warning indicator of future derangement of cerebral circulation.

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> After adjustment for clinical variables, patients with higher complexity index values were significantly less likely to have stroke-in-evolution (SIE) ... In summary, early assessment of HRV by MSE can be a potential predictor of SIE in ICU-admitted non-AF ischemic stroke patients.

Goh S, et al (2015) - **Failure of Arm Movement Control in Stroke Patients, Characterized by Loss of Complexity**. PLoS One. 2015 Nov 4;10(11):e0141996. [FULL TEXT]

> This study provides an integrated framework for the origin of the loss of complexity in the dynamics of patients as well as the coupling structure in the arm-posture dynamics.

Zappasodi F, et al (2014) - **Fractal dimension of EEG activity senses neuronal impairment in acute stroke**. PLoS One. 2014 Jun 26; 9(6):e100199. [FULL TEXT]

> Higuchi Fractal Dimensionality "decrease was associated to alpha increase and beta decrease of oscillatory activity power. ... This picture is coherent with neuronal activity complexity decrease paired to a reduced repertoire of functional abilities."

Nenadovic V, et al (2014) - **Phase synchronization in electroencephalographic recordings prognosticates outcome in paediatric coma**. PLoS One. 2014 Apr 21; 9(4): e94942. [ABS]

> Children who had a poor outcome following brain injury secondary to cardiac arrest, TBI or stroke, had ... a lower spatial complexity of the synchrony patterns and a lower temporal variability.

Video Mind-Training Games ▲

Li X, et al (2019) - **Study on the improvement of brain cognitive function status by mind-control game training**. Sheng Wu Yi Xue Gong Cheng Xue Za Zhi. 2019 Jun 25;36(3):364-370. [ABS]

> The results showed that after two training sessions, the continuous complexity of EEG signal of the subject… the cognitive function of brain improved significantly and state was stable. The results of this paper may show that mind-control game training can improve the status of the brain cognitive function, which may provide support and help for the future intervention of cognitive dysfunction.

Amjad I, et al (2018) - **Xbox 360 Kinect Cognitive Games Improve Slowness, Complexity of EEG, and Cognitive Functions in Subjects with Mild Cognitive Impairment: A Randomized Control Trial**. Games Health J. 2019 Apr;8(2):144-152. [ABS]

> After one session of game intervention, delta, theta and EEG complexity impr9ved significantly in eyes closed recording. There was continued improvement at 6 weeks not seen in the control group.

Voice ▲

Ahamed MRA, et al (2020) - **Complexity-based decoding of the relation between human voice and brain activity**. Technol Health Care. 2020 Mar 13 [ABS]

> The results indicate that the activity of human voice is related to brain activity, where the variations of the complexity of EEG signal are linked to the variations of the complexity of voice signal. In addition, the EEG and voice signal complexities are related to the molecular complexity of applied odors

Ecternach M, et al (2017) - **Laryngeal evidence for the first and second passaggio in professionally trained sopranos**. PLoS One. 2017; 12(5): e0175865. [FULL TEXT]

> Audible register transitions (in both the first and second passaggi) generally coincided with higher sample entropy values and higher open quotient variance through the respective passaggi.

Locke JL (2017) - **Emancipation of the voice: Vocal complexity as a fitness indicator**. Psychon Bull Rev. 2017 Feb;24(1):232-237. [ABS]

Simonyan K, et al (2016) - **New Developments in Understanding the Complexity of Human Speech Production**. J Neurosci. 2016 Nov 9;36(45):11440-11448. [FULL TEXT]

Gustison ML, et al (2016) - **Vocal complexity influences female responses to gelada male calls**. Sci Rep. 2016; 6: 19680. [FULL TEXT]

APPENDIX 1 – Conclusions ▲

Would it surprise you to learn that the EEG signal complexity increases in proportion to the complexity of the path you walk? The complexity of your EEG and GSR increase in proportion to the complexity of the odors around you? The complexity of your EEG increases with the complexity of the music you listen to. Thus how we adjust our lives has a great bearing on our adaptation and wellness behavior.

By looking at the categories of references in this document you will understand why I say that complexification is a transdiagnostic biomarker of the movement away from sickness behavior. To be truly transdiagnostic it must be not only insensitive to ICD or DSM category but insensitive to the type of physiological signal measured as well. This is the beauty of a good theory. It can summarize a great deal of data. Please follow the links in Appendix 2 to see how this theory applies to other physiological signals.

When the diagnosis is unknown, uncertain, or confounded a transdiagnostic biomarker and an adaptogen can constitute a therapeutic trial.

APPENDIX 2 – Imaging & 1/f Signal Types ▲

Blood Glucose Levels

Godat E, et al (2020) - **Dynamic properties of glucose complexity during the course of critical illness: a pilot study**. J Clin Monit Comput. 2020 Apr;34(2):361-370. [ABS]

> …a complexity loss of the blood glucose signal is linked to poor clinical outcomes.

Rodriquez de Castro C, et al (2017) - **Glucose time series complexity as a predictor of type 2 diabetes.** Diabetes Metab Res Rev. 2017 Feb;33(2). [FULL TEXT]

Blood Pressure, Blood Flow, Oxygenation

Gibson LE, et al (2020) - **Comparison of invasive and noninvasive blood pressure measurements for assessing signal complexity and surgical risk in cardiac surgical patients.** Anesth Analg. 2020 Jun;130(6):1653-1660. [ABS]

> Beat-to-beat fluctuations in noninvasive ABP measurements were not random but complex; however, their degree of complexity was lower than that of fluctuations in invasively obtained ABP signals…The complexity of noninvasive ABP time series, like that of invasive time series, was inversely associated with estimated surgical risk in patients undergoing cardiovascular operations.

Kuliga KZ, et al (2018) - **Time-Dependent Behavior of Microvascular Blood Flow and Oxygenation: A Predictor of Functional Outcomes**. IEEE Trans Biomed Eng. 2018 May;65(5):1049-1056. [ABS]

> Recent evidence strongly suggests that the inability of microvascular networks to adapt to an imposed stressor is symptomatic of disease risk which might be assessed via BF and OXY via the combination signal analysis techniques described here.

Gao L, et al (2016) - **Cerebrovascular Signal Complexity Six Hours after Intensive Care Unit Admission Correlates with Outcome after Severe Traumatic Brain Injury**. J Neurotrauma. 2016 Nov 15;33(22):2011-2018. [ABS]

> Our results demonstrate that as early as 6 h into monitoring, complexity measures from easily attainable vital signs, such as heart rate and mean arterial pressure, in addition to intracranial pressure, can help triage those who require more intensive neurological management at an early stage.

Adjei T, et al (2016) - **Characterisation of the complexity of intracranial pressure signals measured from idiopathic and secondary normal pressure hydrocephalus patients.** Healthc Technol Lett. 2016 Jul 5;3(3):226-229. [FULL TEXT]

Placek MM, et al (2015) - **Complexity of cerebral blood flow velocity and arterial blood pressure in subarachnoid hemorrhage using time-frequency analysis**. Conf Proc IEEE Eng Med Biol Soc. 2015;2015:7700-3. [ABS]

> We investigated changes of time-frequency (TF) complexity, in terms of Rényi entropy and a measure of concentration, of middle cerebral blood flow velocity (CBFV) and arterial blood pressure in relation to the development of cerebral vasospasm in 15 patients after aneurysmal subarachnoid hemorrhage. Interhemispheric differences in the period of no vasospasm and vasospasm were also compared. Results show reduced complexity of TF representations of CBFV on the side of aneurysm before vasospasm was identified. This potentially can serve as an early-warning indicator of future derangement of cerebral circulation.

Center of Pressure / Gravity

Bauer CM, et al (2017) - **The effect of muscle fatigue and low back pain on lumbar movement variability and complexity**. J Electromyogr Kinesiol. 2017 Apr;33:94-102. [ABS]

The effects indicate that pain free participants showed more complex and less predictable lumbar movement with a lower degree of structure in its variability following fatigue while participants suffering from LBP did not. This may be physiological responses to avoid overload of fatigued tissue, increase endurance, or a consequence of reduced movement control caused by fatigue

Niermeyer MA, et al (2017) - **Motor sequencing in older adulthood: relationships with executive functioning and effects of complexity**. Clin Neuropsychol. 2017 Apr;31(3):598-618. [ABS]

These results clarify prior findings by showing (a) more aspects of motor sequencing relate to executive functioning for older compared to younger adults and (b) for these unique relationships, executive functioning is only related to action during the generation of sequences that are complex.

Yamagata M, et al (2017) - **Correlation between movement complexity during static standing and balance function in institutionalized older adults**. Clin Interv Aging. 2017 Mar 8;12:499-503. [FULL TEXT]

Sample entropy (SampEn) is an analysis to evaluate movement complexity of the center of pressure (COP). A lower value of SampEn indicates lower complexity of COP variability, that is, rigidity, and lower degrees of freedom. Previous studies reported the association of increased SampEn with improved standing balance ability in young subjects. Lower SampEn implies rigidity for postural control. In the present study, it was found that lower SampEn in the sagittal plane was related to a higher balance function, which suggests that older adults utilized body rigidity to maintain postural stability as a compensative strategy.

Fino PC, et al (2016) - **Decreased high-frequency center-of-pressure complexity in recently concussed asymptomatic athletes**. Gait Posture. 2016 Oct;50:69-74. [ABS]

This decrease in entropy may associate with reported increases in intra-cortical inhibition. Furthermore, a single-case study suggested high frequency MV-CompMSE may be a useful clinical tool for concussion management.

Busa MA, et al (2016) - **Multiscale entropy identifies differences in complexity in postural control in women with multiple sclerosis**. Gait Posture. 2016 Mar;45:7-11. [ABS]

Loss of postural center-of-pressure complexity (COP complexity) has been associated with reduced adaptability that accompanies disease and aging.

The key dependent variable was the complexity index (CI) of the center of pressure. We observed a lower CI in the MS group compared to controls in both anterior-posterior (AP) and medio-lateral (ML) directions (p's<0.002), during the performance of maximal self-regulated leans (AP: p<0.001; ML: p=0.018), and under limited vision

Decreased cutaneous sensitivity was associated with lower CI values in the AP direction among those with MS. MS is associated with diminished COP complexity under both normal and challenging postures, and (2) complexity is strongly correlated with

cutaneous sensitivity, suggesting the unique contribution of impaired somatosensation on postural control deficits in persons with MS.

Negahban H, et al (2016) - **Complexity and variability of the center of pressure time series during quiet standing in patients with knee osteoarthritis**. Clin Biomech (Bristol, Avon). 2016 Feb;32:280-5. [ABS]

> The complexity loss was observed in patients compared with healthy controls. The observed increase in the variability coupled with a decrease in the complexity could be explained by the exploratory behavior of postural control system to gather information during difficult postural conditions relative to the easy ones. Moreover, the observed increase in the complexity coupled with the decrease in the amount of variability may enhance the flow of information to facilitate the perceptual control of standing balance during dual-task conditions.

Ko JH, et al (2016) - **Aging and the complexity of center of pressure in static and dynamic postural tasks**. Neurosci Lett. 2016 Jan 1;610:104-9. [ABS]

> Multi-scale entropy (MSE) and detrended fluctuation analysis showed that the complexity of COP in the old adults was lower compared to the young in the constant target, whereas it was higher in the sine-wave target. The task dependent age-related bi-directional change of COP complexity is counter to the hypothesis of a universal loss of complexity with aging but shows that there is loss of adaptive change in complexity driven by the COP dynamics.

Wayne PM, et al (2014) - **Complexity-Based Measures Inform Effects of Tai Chi Training on Standing Postural Control: Cross-Sectional and Randomized Trial Studies**. PLoS One. 2014 Dec 10;9(12):e114731 [FULL TEXT]

Sabatini AM (2000) - **Analysis of postural sway using entropy measures of signal complexity**. Med Biol Eng Comput. 2000 Nov;38(6):617-24. [ABS]

Hadders-Algra M (1997) - **Assessment of spontaneous motor activity in young infants: an effective method for the detection of brain function disorders**]. Ned Tijdschr Geneeskd. 1997 Apr 26;141(17):816-20. [ABS]

> A method for the assessment of the brain function of young infants was recently introduced. It consists of evaluation of the quality of spontaneously generated generalized movements (general movements, GMs). GMs appear at an early stage of pregnancy and persist until approximately the 4th month after term. Normal GMs are characterized by the triad of complexity, variation and fluency. Mildly abnormal GMs. indicating mild dysfunction of the nervous system, are not fluent but jerky or stiff. Markedly abnormal GMs, indicating major nervous system dysfunction, are characterized mostly by absence of complexity and variation of the movements: the movements are monotonous and stereotyped. The quality of the GMs can be evaluated by means of so-called global Gestalt perception. The technique can be learned in a few days. The quality of the GMs has a clear predictive significance for the child's development. Children with normal GMs will be free of handicaps in later life, whereas

three-quarters of the children showing clearly abnormal GMs throughout the postnatal GM period do develop handicaps. Assessment of the quality of the GMs is a relatively cheap, non-invasive method of evaluating the current and future brain function of young infants.

Electromyographic (EMG) Signal

Flood MW, et al (2019) - **Increased EMG intermuscular coherence and reduced signal complexity in Parkinson's disease**. Clin Neurophysiol. 2019 Feb;130(2):259-269. [ABS]

> Sample Entropy was significantly lower, in PD patients. Intermuscular coherence was also significantly higher in the PD group in theta, alpha and beta frequency bands. … SampEn decreased with increasing Movement-Disorder-Society UPDRS scores, while theta band coherence was significantly correlated with total MDS-UPDRS scores and torque variance.

Shafer RL, et al (2019) - **Visual feedback during motor performance is associated with increased complexity and adaptability of motor and neural output**. Behav Brain Res. 2019 Dec 30;376:112214. [ABS]

> Consistent with previous literature, motor performance and its complexity were higher when visual feedback was provided relative to when it was withheld. The complexity of the neural signal was also higher when visual feedback was provided. This was most robust at frequency bands (alpha and beta) and scalp regions (parietal and occipital) associated with sensorimotor processing. The findings show that visual feedback increases the information available to the brain when generating complex, adaptive motor output.

Kamal SM, et al (2019) - **Decoding of the relationship between human brain activity and walking paths**. Technol Health Care. 2019 Nov 14. [ABS]

> The results of the analysis show that *the complexity of brain activity increases with the increment of complexity of path of movement.* The method of analysis employed in this research can also be employed to analyze the reaction of the human heart and respiration when subjects move on paths with different complexities.

Fino PC, et al (2016) - **Decreased high-frequency center-of-pressure complexity in recently concussed asymptomatic athletes**. Gait Posture. 2016 Oct;50:69-74. [ABS]

> This decrease in entropy may associate with reported increases in intra-cortical inhibition. Furthermore, a single-case study suggested high frequency MV-CompMSE may be a useful clinical tool for concussion management.

Bisi MC, et al (2016) - **Complexity of human gait pattern at different ages assessed using multiscale entropy: From development to decline**. Gait Posture. 2016 Jun;47:37-42. [ABS]

From young adults to elderlies a slight increase in sample entropy (SEN) values was shown although not statistically significant. While performance gait parameters showed adolescent gait similar to the one of adults, SEN highlighted that their gait maturation is not complete yet.

In conclusion, present results suggest that the *complexity of gait, evaluated on the sagittal plane, can be used as a characterizing parameter of the maturation of gait control.*

See also the section on the Center of Gravity signal and also the earlier section on movement and posture.

Galvanic Skin (Electrodermal) Response

Omam S, et al (2020) - **Complexity-based decoding of brain-skin relation in response to olfactory stimuli**. Comput Methods Programs Biomed. 2020 Feb;184:105293. [ABS]

> ...the complexity of GSR signal changes with the complexity of EEG signal in case of different stimuli, where by increasing the molecular complexity of olfactory stimuli, the complexity of EEG and GSR signals increases. The results of statistical analysis showed the significant effect of stimulation on variations of complexity of GSR signal. In addition, based on effect size analysis, fourth odor with greatest molecular complexity had the greatest effect on variations of complexity of EEG and GSR signals.

Visnovcova Z, et al (2016) - **The complexity of electrodermal activity is altered in mental cognitive stressors.** Comput Biol Med. 2016 Dec 1;79:123-129. [ABS]

> The SCA, SIE and ApEn were significantly increased during mental loads and decreased during recovery periods. However, SCA remained significantly elevated during recovery periods versus baseline, and SIE and ApEn decreased significantly during recovery versus baseline. The frequency of NS-EDR had no significant changes during stress. The EDA is a sensitive marker for evaluation of changes during the activation of sympathetic nervous system under the influence of a load. Detailed knowledge of EDA regulatory mechanisms associated with stress could provide important information associated with autonomic dysregulation.

Svetlak M, et al (2010) - **Electrodermal complexity during the Stroop colour word test.** Auton Neurosci. 2010 Jan 15;152(1-2):101-7. [ABS]

> Complexity analysis applied to EDA was performed using Skinner's algorithm for pointwise correlation dimension (PD2). … subjects with low initial PD2 tended to respond to experimental stress by its increase and subjects with high initial PD2 values tended to respond by its decrease.

Bob P (2007) - **Chaos, brain and divided consciousness.** Acta Univ Carol Med Monogr. 2007;153:9-80. [ABS]

> Because epileptiform activity has specific chaotic behaviour and calculated information entropy from EDA (electrodermal activity) records reflects the complexity of the deterministic structure in the system there is a relevant assumption that unilaterally increased complexity may produce interhemispheric disbalance and increased chaoticity which hypothetically may serve as a dynamic source of epileptiform discharges related to trauma induced kindling mechanism.

Heart Rate Variability

Padley JR, et al (2018) - **Low pre-operative heart rate variability and complexity are associated with hypotension after anesthesia induction in major abdominal surgery**. J Clin Monit Comput. 2018 Apr;32(2):245-252. [ABS]

> … post-induction hypotension and lower HRV may be associated with severity of illness or poor physiological reserve. Pre-operative HRV was a useful screening tool in identifying patients undergoing major abdominal surgery who were at risk of haemodynamic instability after anesthesia induction.

Varley T, et al (2020) - **Fractal dimension of cortical functional connectivity networks & severity of disorders of consciousness**. PLoS One. 2020 Feb 13;15(2):e0223812. [FULL TEXT]

> These results suggest that cortical functional connectivity networks display fractal character and that this is associated with level of consciousness in a clinically relevant population, with higher fractal dimensions (i.e. more complex) networks being associated with higher levels of consciousness. This supports the hypothesis that level of consciousness and system complexity are positively associated, and is consistent with previous EEG, MEG, and fMRI studies.

Fiskum C, et al (2017) - **Cardiac complexity and emotional dysregulation in children.** Int J Psychophysiol. 2017 Nov;121:38-45. [ABS]

> Sample entropy (SampEn) gives an estimate of signal complexity in cardiac time series and can give information beyond linear heart rate variability. Lower cardiac SampEn is associated with psychopathology in adults. Emotional dysregulation is widely present in adult psychopathology and a forerunner to later mental problems in children.

Chen CH, et al (2015) - **Complexity of Heart Rate Variability Can Predict Stroke-In-Evolution in Acute Ischemic Stroke Patients**. Sci Rep. 2015 Dec 1;5:17552. [FULL TEXT]

> After adjustment for clinical variables, patients with higher complexity index values were significantly less likely to have stroke-in-evolution (SIE) ... In summary, early assessment of HRV by MSE can be a potential predictor of SIE in ICU-admitted non-AF ischemic stroke patients.

Lin P-F, et al (2014) - **Correlations between the Signal Complexity of Cerebral and Cardiac Electrical Activity: A Multiscale Entropy Analysis**. PLoS ONE 9(2): e87798. [FULL TEXT]

> With the deterioration of health conditions, the change in dynamic patterns of biological signals is characterized by *loss of complexity and development of stereotypy*...

Bennett AJ, et al (2001) - **Initial ethanol exposure results in decreased heart rate variability in ethanol-naive rhesus monkeys.** Eur J Pharmacol. 2001 Dec 21;433(2-3):169-72. [ABS]

Magneto-Encephalography

Varley T, et al (2020) - **Fractal dimension of cortical functional connectivity networks & severity of disorders of consciousness**. PLoS One. 2020 Feb 13;15(2):e0223812. [FULL TEXT]

> These results suggest that cortical functional connectivity networks display fractal character and that this is associated with level of consciousness in a clinically relevant population, with higher fractal dimensions (i.e. more complex) networks being associated with higher levels of consciousness. This supports the hypothesis that level of consciousness and system complexity are positively associated, and is consistent with previous EEG, MEG, and fMRI studies.

Schartner MM, et al (2017) - **Increased spontaneous MEG signal diversity for psychoactive doses of ketamine, LSD and psilocybin**. Sci Rep. 2017 Apr 19;7:46421. [FULL TEXT]

> For all three, we find reliably higher spontaneous signal diversity, even when controlling for spectral changes. This increase is most pronounced for the single-channel LZ complexity measure, and hence for temporal, as opposed to spatial, signal diversity. We also uncover selective correlations between changes in signal diversity and phenomenological reports of the intensity of psychedelic experience.
>
> These findings suggest that the sustained occurrence of psychedelic phenomenology constitutes an elevated level of consciousness - as measured by neural signal diversity.

Azami H, et al (2015) - **Evaluation of resting-state magnetoencephalogram complexity in Alzheimer's disease with multivariate multiscale permutation and sample entropies**. Conf Proc IEEE Eng Med Biol Soc. 2015;2015:7422-5. [ABS]

> Alzheimer's disease (AD) is one of the fastest growing neurological diseases in the world. We evaluate multivariate multiscale sample entropy (mvMSE) and multivariate multiscale permutation entropy (mvMPE) approaches to distinguish resting-state magnetoencephalogram (MEG) signals of 36 AD patients from those of 26 normal controls.
>
> In most scale factors, the average of the mvMPE and mvMSE values of AD patients are lower than those of controls.

Chu RK (2015) **- MEG-based detection and localization of perilesional dysfunction in chronic stroke.** Neuroimage Clin. 2015 Apr 8; 8:157-69. [FULL TEXT]

> "Perilesional tissue exhibited a general slowing of the power spectrum (increased delta/theta, decreased beta) as well as a reduction in MSE." - Multi-Scale Entropy.

Fernández A, et al (2010) - **Analysis of brain complexity and mental disorders.** Actas Esp Psiquiatr. 2010 Jul-Aug;38(4):229-38. [ABS]

> Parameters of EEG-MEG complexity usually estimate the predictability of brain oscillations and/or the number of independent oscillators underlying the observed signals. More importantly, complexity parameters seem to be sensitive to the temporal components of brain activity, and therefore might reflect the dynamical nature of psychiatric disorders.

Kotini A, et al (2002) - **Detection of non-linearity in schizophrenic patients using magnetoencephalography.** Brain Topogr. 2002 Winter;15(2):107-13. [ABS]

> We calculated the correlation dimension, which is a measure of the complexity of the dynamic system, as well as the first Lyapunov exponent that indicates the system's unpredictability. … The analysis of the MEG in the schizophrenic group **showed lower dimension complexity** and moreover the first Lyapunov exponent presented lower values compared with the corresponding ones in the control group, which means lower information processing.

Magnetic Resonance Imaging

Zheng H, et al (2020) - **Reduced Dynamic Complexity of BOLD Signals Differentiates Mild Cognitive Impairment from Normal Aging**. Front Aging Neurosci. 2020; 12: 90. [ABS]

> Notably, the reduction of BOLD signal complexity in the rostral anterior cingulate cortex was significantly associated with greater risk of progression to AD. The present study thus identified Multi-Scale Entropy as a potential imaging biomarker for the early diagnosis of pre-clinical Alzheimer's disease and provides further insights into the neuropathology of cognitive decline in prodromal AD

Sevel L, et al (2020) - **Acute Alcohol Intake Produces Widespread Decreases in Cortical Resting Signal Variability in Healthy Social Drinkers**. Alcohol Clin Exp Res. 2020 May 29. [ABS]

> Findings indicate that alcohol intake produces diffuse reductions in fMRI resting signal variability among structures associated with attentional processes. Within these structures, signal complexity was also reduced in a subset of frontal regions. Neurobehavioral effects of acute alcohol consumption may be partially driven by disruption of intraregional neural dynamics among regions involved in higher-order cognitive and attentional processes.

Easson AK, et al (2019) - **BOLD signal variability and complexity in children and adolescents with and without autism spectrum disorder**. Dev Cogn Neurosci. 2019 Apr;36:100630. [FULL TEXT]

> Negative correlations were observed between each brain measure and the severity of ASD behaviors across all participants.

Dong J, et al (2018) - **Hurst Exponent Analysis of Resting-State fMRI Signal Complexity across the Adult Lifespan.** Front Neurosci. 2018; 12: 34. [FULL TEXT]

> …healthy aging is accompanied by a loss of complexity in frontal and parietal lobe and increased complexity in insula, limbic, and temporal lobe. …Hurst Exponent Analysis may serve as a new parameter to assess healthy aging process.

Hager B, et al (2018) - **Neural complexity as a potential translational biomarker for psychosis.** J Affect Disord. 2017 Jul; 216: 89–99. [FULL TEXT]

> These observations support the loss of brain complexity hypothesis in psychotic probands. Furthermore, we found significant differences as well as overlaps of pathologic brain signal complexity between psychotic probands by DSM diagnoses, thus suggesting a biological approach to categorizing psychosis based on functional neuroimaging data.

Dona O, et al (2017) - **Temporal fractal analysis of the rs-BOLD signal identifies brain abnormalities in autism.** PLoS One. 2017; 12(12). [FULL TEXT]

> In this study, we were able to find regions in the brain with reported decreased signal complexity using the FD methodology. These regions have been previously reported as dysfunctional for ASD patients and correlated with behavioral assessments.

Dona O, et al (2017) - **Fractal Analysis of Brain Blood Oxygenation Level Dependent (BOLD) Signals from Children with Mild Traumatic Brain Injury (mTBI).** PLoS One. 2017; 12(1): e0169647. [FULL TEXT]

> …we were able to find regions in the brain that despite not showing any abnormality in an anatomical scan, reported decreased signal complexity using FD methodology. These regions have been previously reported as dysfunctional for mTBI patients. The method we have proposed is able to provide additional information of mTBI in a non-invasive and fast manner and could hopefully help in the design of future treatment plans.

Ho P-S, et al (2017) - **Complexity analysis of resting state fMRI signals in depressive patients**. Conf Proc IEEE Eng Med Biol Soc. [ABS]

Kielar A, et al (2016) - **Identifying Dysfunctional Cortex: Dissociable Effects of Stroke and Aging on Resting State Dynamics in MEG and fMRI.** Front Aging Neurosci. 2016; 8: 40. [FULL TEXT]

> …MEG signal complexity offers a sensitive index of neural dysfunction in perilesional tissue in chronic stroke, and that these effects are clearly distinguishable from those associated with healthy aging.

Temperature / Infrared spectroscopy / fNIRS

Perpetuini D, et al (2019) - **Autonomic impairment in Alzheimer's disease is revealed by complexity analysis of functional thermal imaging signals during cognitive tasks**. Physiol Meas. 2019 Mar 22;40(3):034002. [ABS]

> AD patients exhibited lower complexity of fIRI (functional infrared imaging) signals during the tests, which could be indicative of a stronger sympathetic activity with respect to HC. No significant effects were found at rest. No differences were found on employing frequency-based analysis.

Jin L, et al (2019) - **Differences in brain signal complexity between experts and novices when solving conceptual science problem: a functional near-infrared spectroscopy study**. Neurosci Lett. 2019 Apr 23;699:172-176. [ABS]

(During testing) the permutation entropy values in the inferior frontal gyrus were smaller for experts, especially in the right IFG.

Li X, et al (2018) - **Decreased resting-state brain signal complexity in patients with mild cognitive impairment and Alzheimer's disease: a multiscale entropy analysis.** Biomed Opt Express. 2018 Apr 1; 9(4): 1916–1929. [FULL TEXT]

> The quantitative analysis of MSE revealed that reduced brain signal complexity in AD patients in several networks, namely, the default, frontoparietal, ventral and dorsal attention networks. For the default and ventral attention networks, the MSE values also showed significant positive correlations with cognitive performances. These findings demonstrated that the MSE-based analysis method could serve as a novel tool for fNIRS study in characterizing and understanding the complexity of abnormal cortical signals in AD cohorts.

Costa CS, et al (2017) - **Complexity of brain signals is associated with outcome in preterm infants**. J Cereb Blood Flow Metab. 2017 Oct; 37(10). [FULL TEXT]

> Here, we apply Multiscale Entropy (MSE) analysis to assess the complexity of systemic and cerebral near-infrared spectroscopy (NIRS) signals… Decreased complexity of brain signals was associated with mortality and brain injury. Measurement of brain signal complexity in preterm infants is feasible and could represent a significant advance in the brain-oriented care.

Soltanlou M, et al (2017) - **Increased arithmetic complexity is associated with domain-general but not domain- specific magnitude processing in children: A simultaneous fNIRS-EEG study**. Cogn Affect Behav Neurosci. 2017 May 4. [ABS]

> We investigated 24 children undergoing one-digit and two-digit multiplication tasks while simultaneously recording functional near-infrared spectroscopy (fNIRS) and electroencephalography (EEG) data. FNIRS data indicated that one-digit multiplication was associated with brain activity in the left superior parietal lobule (SPL) and intraparietal sulcus (IPS) extending to the left motor area, and two-digit multiplication was associated with activity in bilateral SPL, IPS, middle frontal gyrus (MFG), left inferior parietal lobule (IPL), and motor areas. Oscillatory EEG data indicated theta increase and alpha decrease in parieto-occipital sites for both one-digit and two-digit multiplication. The contrast of two-digit versus one-digit multiplication yielded greater activity in right MFG and greater theta increase in frontocentral sites. Activation in frontal areas and theta band data jointly indicate additional domain-general cognitive control and working memory demands for heightened arithmetic complexity in children. The similarity in parietal activation between conditions suggests that children rely on domain-specific magnitude processing not only for two-digit but-in contrast to adults-also for one-digit multiplication problem solving.

Gu Y, et al (2017) - **Complexity analysis of fNIRS signals in ADHD children during working memory task**. Sci Rep. 2017 Apr 11;7(1):829. [FULL TEXT]

> We found that PE (permutation entropy) values exhibited significantly negative correlation with the cortical activations (r = −0.515, p = 0.003), and the PE values of right dorsolateral prefrontal cortex in ADHD children were significantly larger than those in normal controls (p = 0.027). In addition, the PE values of right dorsolateral prefrontal cortex were positively correlated to the ADHD index (r = 0.448, p = 0.012). These results suggest that complexity analysis of fNIRS signals could be a promising tool in diagnosing children with ADHD.

Jost K, et al (2017) - **Dynamics and complexity of body temperature in preterm infants nursed in incubators**. PLoS One. 2017 Apr 27;12(4):e0176670. [FULL TEXT]

> Dynamics and complexity of body temperature in incubator-nursed preterm infants show considerable associations with gestational age and respiratory morbidity.

Kaiyala KJ (2016) - **Fractal analysis of thermoregulatory complexity**. Temperature (Austin). 2016; 3(3): 364–365. [FULL TEXT]

Appendix 3 - General Complexity Resources ▲

Jannesari M, et al (2020) - **Stability of neuronal avalanches and long-range temporal correlations during the first year of life in human infants**. Brain Struct Funct. 2020; 225(3): 1169–1183. [FULL TEXT]

Yang AC, et al (2020) - **Editorial: Advances in Multi-Scale Analysis of Brain Complexity**. Front Neurosci. 2020 Apr 15;14:337. [FULL TEXT]

> The complexity of regional neural signals may serve as an index of the brain's capacity of information processing—increased complexity may indicate greater transition or exploration between different states of brain networks, thereby indicating a greater propensity for information processing.

Godat E, et al (2020) - **Dynamic properties of glucose complexity during the course of critical illness: a pilot study**. J Clin Monit Comput. 2020 Apr;34(2):361-370. [ABS]

> …a complexity loss of the blood glucose signal is linked to poor clinical outcomes.

Popa LL, et al (2020) - **The Role of Quantitative EEG in the Diagnosis of Neuropsychiatric Disorders.** Med Life. Jan-Mar 2020;13(1):8-15. [FULL TEXT]

> QEEG has brought new techniques of EEG signals feature extraction: analysis of specific frequency band and signal *complexity*, analysis of connectivity, and network analysis. The clinical application of QEEG is extensive, including neuropsychiatric disorders, epilepsy, stroke, dementia, traumatic brain injury, mental health disorders, and many others. …to date, *the role of QEEG is not necessarily to pinpoint an immediate diagnosis but to provide additional insight* …and specific treatment response evaluation.

Parameshwaran D, et al (2019) - **Waveform complexity: A new metric for EEG analysis.** J Neurosci Methods. 2019 Sep 1;325:108313. [ABS]

> …we demonstrate that when applied to eyes closed EEG recordings in subjects taken immediately prior to taking a Raven's progressive matrix test, this measure had a high correlation to participant's scores.

Paul JK, et al (2019) - **Characterization of fibromyalgia using sleep EEG signals with nonlinear dynamical features**. Comput Biol Med.2019 Aug;111:103331. [ABS]

Spasić SZ, et al (2019) - **Nonlinearity in Living Systems: Theoretical and Practical Perspectives on Metrics of Physiological Signal Complexity**. Front Physiol. 2019; 10: 298. [FULL TEXT]

Nascimento DC, et al (2019) - **Entropy Analysis of High-Definition Transcranial Electric Stimulation Effects on EEG Dynamics.** Brain Sci. 2019 Aug 20;9(8):208. [FULL TEXT]

> We demonstrated that entropy analysis could identify intervention-related change in EEG data, supporting that entropy can be a useful "summary" statistic in non-linear dynamical systems.

Zhou L, et al (2019) - **Research of the Regulation effect of Cooling Stimulation on Vigilance**. Conf Proc IEEE Eng Med Biol Soc. 2019 Jul;2019:3127-3130. [ABS]

> Results showed that there was a significant difference concerning behavior and EEG power (the relative power RPβ, the power ratios Pα/β and P(θ+α)/β), but not for Lempel-Ziv Complexity (LZC). Our results suggest that forehead-cooling stimulation may be an effective method to increase vigilance.

Meng J, et al (2019) - **EEG Complexity and Functional Connectivity during Precise Timing Prediction**. Conf Proc IEEE Eng Med Biol Soc. 2019 Jul;2019:2909-2912. [ABS]

> Significant lower EEG complexity and stronger brain functional connectivity were observed when the stimulus matches the timing prediction. The current observation may shed light on the modeling of the precise predictive timing process.

Ibáñez-Molina AJ, et al (2019) **- Differential Effects of Simulated Cortical Network Lesions on Synchrony and EEG Complexity.** Int J Neural Syst. 2019 May;29(4):1850024. [ABS]

> We found a general negative correlation between EEG complexity metrics and synchrony but Sample Entropy and Lempel-Ziv showed a positive correlation with synchrony when the edges of the network were deleted. This suggests an intricate relationship between synchrony of the system and its estimated complexity. Hence, complexity seems to depend on the multiple states of interaction between the oscillators of the system. Our results can contribute to the interpretation of the functional meaning of EEG complexity.

Vaghefi M, et al (2019) - **Nonlinear Analysis of Electroencephalogram Signals while Listening to the Holy Quran**. J Med Signals Sens. 2019 Apr-Jun; 9(2): 100–110. [FULL TEXT]

> Consciously listening to the Holy Quran decreases self-similarity and correlation of brain signal and instead increases complexity and dynamicity in the brain.

Yu Y, et al (2019) - **Nonlinear analysis of local field potentials and motor cortex EEG in spinocerebellar ataxia 3.** J Clin Neurosci. 2019 Jan;59:298-304. [ABS]

…it was possible to distinguish between the two groups by the LZ complexity of their alpha and theta bands.

Croce P, et al (2018) - **Circadian Rhythms in Fractal Features of EEG Signals**. Front Physiol. 2018 Nov 12;9:1567. [FULL TEXT]

Complexity and the persistence of temporal correlations of brain rhythms change during daytime, parallel to changes in alertness and performance.

Dimitriadis SI (2018) - **Complexity of brain activity and connectivity in functional neuroimaging**. J Neurosci Res. 2018 Nov;96(11):1741-1757. [ABS]

…we succeeded to totally discriminate healthy controls from schizophrenic using FI and dynamic reconfiguration of DICM. Anaesthesia independently of the drug caused a global decreased of complexity in all frequency bands with the exception in δ…

Portnova GV, et al (2018) - **Nonlinear EEG parameters of emotional perception in patients with moderate traumatic brain injury, coma, stroke and schizophrenia**. AIMS Neurosci. 2018 Nov 7;5(4):221-235. [FULL TEXT]

The Hjorth parameters were negatively correlated with irritation. The fractal dimension was positively correlated with arousal and empathy levels.

Gao F, et al (2018) - **Microstate and Omega Complexity Analyses of the Resting-state Electroencephalography**. J Vis Exp. 2018; (136): 56452. [FULL TEXT]

These two EEG measures could complement each other to investigate the brain complexity from the temporal and spatial domain respectively.

Yin Y, et al (2018) - **Multiscale permutation Rényi entropy and its application for EEG signals**. PLoS One. 2018 Sep 4;13(9):e0202558. [FULL TEXT]

Si J, et al (2018) - **Spinal Cord Stimulation Frequency Influences the Hemodynamic Response in Patients with Disorders of Consciousness**. Neurosci Bull. 2018 Aug; 34(4): 659–667. [FULL TEXT]

…functional connectivity between prefrontal and occipital areas was significantly improved with SCS at 70 Hz.

Hasegawa C, et al (2018) - **Developmental Trajectory of Infant Brain Signal Variability: A Longitudinal Pilot Study**. Front Neurosci. 2018 Aug 14;12:566. [FULL TEXT]

…signal complexity predominantly increased from 5 to 15 months of age at higher temporal scales, whereas the complexity at lower temporal scales was constant across age, except in one infant who showed decreased complexity.

Bohara G, et al (2018) - **Bridging Waves and Crucial Events in the Dynamics of the Brain**. Front. Physiol., 29 August 2018. [FULL TEXT]

Baravalle R, et al (2018) - **Rhythmic activities of the brain: Quantifying the high complexity of beta and gamma oscillations during visuomotor tasks.** Chaos. 2018 Jul;28(7):075513. [ABS]

…enhanced complexity in the gamma 1, gamma 2, and beta 1 bands allows us to distinguish motor-visual memory tasks from control conditions.

Keshmiri S, et al (2018) - **Bodily-Contact Communication Medium Induces Relaxed Mode of Brain Activity While Increasing Its Dynamical Complexity: A Pilot Study**. Front Psychol. 2018 Jul 9;9:1192. [FULL TEXT]

> …we find a significant reduction of overall power of the EEG signals of the individuals. …Additionally, multiscale entropy (MSE) analysis of our data implies that such a medium increases the level of complexity that is exhibited by EEG time series of our participants, thereby suggesting their sustained sense of involvement in their course of communication.

Kuliga KZ, et al (2018) - **Time-Dependent Behavior of Microvascular Blood Flow and Oxygenation: A Predictor of Functional Outcomes**. IEEE Trans Biomed Eng. 2018 May;65(5):1049-1056. [ABS]

> Recent evidence strongly suggests that the inability of microvascular networks to adapt to an imposed stressor is symptomatic of disease risk which might be assessed via BF and OXY via the combination signal analysis techniques described here.

Portnova GV, et al (2018) - **Correlation of BOLD Signal with Linear and Nonlinear Patterns of EEG in Resting State EEG-Informed fMRI**. Front Hum Neurosci. 2018 Jan 9;11:654. [FULL TEXT]

> …EEG dynamic complexity as measured by the HFD of the 2–20 Hz EEG frequency range significantly correlated with the activation of cortical and subcortical limbic system areas.

Zhu B, et al (2017) - **Competitive pressures affect sexual signal complexity in Kurixalus odontotarsus: insights into the evolution of compound calls**. Biol Open. 2017 Dec 15; 6(12): 1913–1918. [FULL TEXT]

> Using male evoked vocal response experiments, we found that competition influences the temporal structure and complexity of vocal signals produced by males. ...This means that the evolution of sexual signal complexity in frogs may be susceptible to selection …

Kim JH, et al (2017) - **Applying fractal analysis to pupil dilation for measuring complexity in a process monitoring task.** Appl Ergon. 2017 Nov;65:61-69. [ABS]

> The participants showed a higher fractal dimension when they performed a low complexity multitasking scenario. The findings of this research help us to advance our understanding of how to evaluate the complexity level of real-world applications by using pupillary responses.

Costa CSd, et al (2017) - **Complexity of brain signals is associated with outcome in preterm infants**. J Cereb Blood Flow Metab. 2017 Oct; 37(10). [FULL TEXT]

> Decreased complexity of brain signals was associated with mortality and brain injury. Measurement of brain signal complexity in preterm infants is feasible and could represent a significant advance in the brain-oriented care.

Grundy JG, et al (2017) - **Bilinguals Have More Complex EEG Brain Signals in Occipital Regions than Monolinguals**. Neuroimage. 2017 Oct 1; 159: 280–288. [FULL TEXT]

Saraiva GFR, et al (2017) - **Osmotic stress decreases complexity underlying the electrophysiological dynamic in soybean.** Plant Biol (Stuttg). 2017 Sep;19(5):702-708. [ABS]

> Non-linear time series analyses methods were used as follows: auto-correlation and cross-correlation function, power spectra density function, and complexity of the time series estimated as Approximate Entropy (ApEn). Using Approximate Entropy analysis we found that the level of temporal complexity of the electrical signals was affected by the environmental conditions, decreasing when the plant was subjected to a low osmotic potential. Electrical spikes observed only after stimuli followed a power law distribution, which is indicative of scale invariance. Our results suggest that changes in complexity of the electrical signals could be associated with water stress conditions in plants. We hypothesised that the power law distribution of the spikes could be explained by a self-organised critical state (SOC) after osmotic stress.

Conrad CD, et al (2017) - **Chronic stress and hippocampal dendritic complexity: Methodological and functional considerations**. Physiol Behav. 2017 Sep 1;178:66-81. [ABS]

> ...this review systematically outlines the basic neuroanatomy of relevant hippocampal features to help clarify how chronic stress or glucocorticoids impact hippocampal dendritic complexity and how these changes occur in parallel with spatial cognition. Chronic stress often leads to hippocampal CA3 apical dendritic retraction first with other hippocampal regions (CA3 basal dendrites, CA1, dentate gyrus, DG) showing dendritic retraction when chronic stress is sufficiently robust or long lasting. The stress-induced reduction in hippocampal CA3 apical dendritic arbor complexity often coincides with impaired hippocampal function, such as spatial learning and memory. Yet, when chronic stress ends and a post-stress recovery period ensues, the atrophied dendritic arbors and poor spatial abilities often improve. However, this process differs from a simple reversal of chronic stress-induced deficits. Recent reports suggest that this return to baseline-like functioning is uniquely different from non-stressed controls, emphasizing the need for further studies to enhance our understanding of how a history of stress subsequently alters an organism's spatial abilities.

O'Farrell K, et al (2017) - **Inhibition of the kynurenine pathway protects against reactive microglial-associated reductions in the complexity of primary cortical neurons**. Eur J Pharmacol. 2017 Sep 5;810:163-173. [ABS]

Liu AP, et al (2017) - **The big and intricate dreams of little organelles: Embracing complexity in the study of membrane traffi**c. Traffic. 2017 Sep;18(9):567-579. [ABS]

Yue Q, et al (2017) **- Brain Modularity Mediates the Relation between Task Complexity and Performance.** J Cogn Neurosci. 2017 Sep;29(9):1532-1546. [ABS]

> ...high-modularity networks favor performance on simple tasks whereas low-modularity networks favor performance on more complex tasks**.**

Shariff M, et al (2017) - **Binge-like sucrose consumption reduces the dendritic length and complexity of principal neurons in the adolescent rat basolateral amygdala**. PLoS One. 2017 Aug 16;12(8):e0183063. [FULL TEXT]

Peters FJ, et al (2017) - **The human brain from above: an increase in complexity from environmental stimuli to abstractions.** Cogn Neurodyn. 2017 Aug;11(4):391-394. [ABS]

> Contrary to common belief, the brain appears to increase the complexity from the perceived object to the idea of it. Topological models predict indeed that: (a) increases in anatomical/functional dimensions and symmetries occur in the transition from the environment to the higher activities of the brain, and (b) informational entropy in the primary sensory areas is lower than in the higher associative ones. To demonstrate this novel hypothesis, we introduce a straightforward approach to measuring island information levels in fMRI neuroimages, via Rényi entropy derived from tessellated fMRI images. This approach facilitates objective detection of entropy and corresponding information levels in zones of fMRI images generally not taken into account. We found that the Rényi entropy is higher in associative cortices than in the visual primary ones. This suggests that the brain lies in dimensions higher than the environment and that it does not concentrate, but rather dilutes messages coming from external inputs.

Li X, et al (2017) - **Impact of low-dose chronic exposure to Bisphenol A (BPA) on adult male zebrafish adaption to the environmental complexity**: Disturbing the color preference patterns and reliving the anxiety behavior. Chemosphere. 2017 Aug 1;186:295-304. [ABS]

Schiffmann Y (2017) - **The non-equilibrium basis of Turing Instability and localised biological work**. Prog Biophys Mol Biol. 2017 Aug;127:12-32. [ABS]

Buezas G, et al (2017) - **Cranial suture complexity in caviomorph rodents (Rodentia; Ctenohystrica)**. J Morphol. 2017 Aug;278(8):1125-1136. [ABS]

> Due to their flexibility, sutures are regions that experience greater strains than the surrounding rigid cranial bones. Cranial sutures differ in their degree of interdigitation or complexity. There is evidence indicating that a more convoluted suture better enables the absorption of high stresses coming from dynamic masticatory forces, and other functions. ...The reconstruction of the ancestral character state, on family and species phylogeny, points toward low suture interdigitation (i.e., low length ratio) as a likely ancestral state for interfrontal, premaxillofrontal and maxillofrontal sutures. Interspecific differences in suture morphology shown here might represent adaptations to different mechanical demands (i.e., soft vs. tough foods) or behaviors (e.g., chisel-tooth digging), which evolved in close association with the diverse environments…

Xu J, et al (2017) - **Local complexity predicts global synchronization of hierarchically networked oscillators**. Chaos. 2017 Jul;27(7):073116. [ABS]

> Under weak inter-subsystem couplings, we demonstrate that the synchronization between subsystems is highly correlated with the number of attractors in uncoupled subsystems. Among the network motifs, perfect anti-symmetric ones are unique to generate both single and multiple attractors depending on the activities of oscillators. The flexible local complexity can make global synchronization controllable.

Bhat R, et al (2017) - **Complexity: the organizing principle at the interface of biological (dis)order**. J Genet. 2017 Jul;96(3):431-444. [ABS]

> We propose that the complexity of living systems can be understood through two interdependent structural properties: multiscalarity of interconstituent mechanisms and excitability of the biological materials. The answer to whether a system becomes more or less complex over time depends on the potential for its constituents to interact in novel ways and combinations to give rise to new structures and functions, as well as on the evolution of excitable properties that would facilitate the exploration of interconstituent organization in the context of their microenvironments and macroenvironments.

Hearne LJ, et al (2017) - **Reconfiguration of brain network architectures between resting state and complexity-dependent cognitive reasoning**. J Neurosci. 2017 Jul 31. pii: 0485-17. [ABS]

> Specifically, resting state and null-task demand conditions were associated with more segregated brain network topology, whereas increases in reasoning complexity resulted in merging of resting state modules. Further increments in task complexity did not change the established modular architecture, but impacted selective patterns of connectivity between fronto-parietal, subcortical, cingulo-opercular and default-mode networks. Larger increases in network efficiency within the newly established task modules were associated with higher reasoning accuracy. Our results shed light on the network architectures that underlie external task engagement, and highlight selective changes in brain connectivity supporting increases in task complexity.

Montai C, et al (2017) - **The X-Linked Intellectual Disability Protein IL1RAPL1 Regulates Dendrite Complexity**. J Neurosci. 2017 Jul 12;37(28):6606-6627. [ABS]

Papoutsi A, et al (2017) - **Basal tree complexity shapes functional pathways in the prefrontal cortex**. J Neurophysiol. 2017 Jul 12:jn.00099.2017. [ABS]

Bhat R, et al (2017) - **Complexity: the organizing principle at the interface of biological (dis)order**. J Genet. 2017 Jul;96(3):431-444. [ABS]

> We propose that the complexity of living systems can be understood through two interdependent structural properties: multiscalarity of interconstituent mechanisms and excitability of the biological materials. The answer to whether a system becomes more or less complex over time depends on the potential for its constituents to interact in novel ways and combinations to give rise to new structures and functions, as well as on the evolution of excitable properties that would facilitate the exploration of interconstituent organization in the context of their microenvironments and macroenvironments.

Ribeiro HV, et al (2017) - **Characterizing time series via complexity-entropy curves**. Phys Rev E. 2017 Jun;95(6-1):062106. [ABS]

Sanchez-Vives MV, et al (2017) - **Shaping the Default Activity Pattern of the Cortical Network**. Neuron. 2017 Jun 7;94(5):993-1001. [FULL TEXT]

> Slow oscillations have been suggested as the default emergent activity of the cortical network. This is a low complexity state that integrates neuronal, synaptic, and connectivity properties of the cortex. Shaped by variations of physiological parameters,

slow oscillations provide information about the underlying healthy or pathological network. We review how this default activity is shaped, how it acts as a powerful attractor, and how getting out of it is necessary for the brain to recover the levels of complexity associated with conscious states. We propose that slow oscillations provide a robust unifying paradigm for the study of cortical function.

Heim NA, et al (2017) **- Hierarchical complexity and the size limits of life**. Proc Biol Sci. 2017 Jun 28;284(1857). pii: 20171039. [ABS]

Komatsu K, et al (2017) - **Geometrical complexity of cortical microvascularization in moyamoya disease**. World Neurosurg. 2017 Jun 27. pii: S1878-8750(17)31019-7. [ABS]

Cortical microvascularization in moyamoya disease exhibited increased fractal dimension and dilatation of the pial arteries. In moyamoya disease, cortical microvascularization is associated with the clinical and radiological factors. This microvascularization might be a compensatory mechanism in the ischemic condition in moyamoya disease.

Kim J, et al (2017) - **The order of complexity of visuomotor learning**. BMC Neurosci. 2017 Jun 12;18(1):50. [FULL TEXT]

van der Woude E, et al (2017) - **Maximized complexity in miniaturized brains: morphology and distribution of octopaminergic, dopaminergic and serotonergic neurons in the parasitic wasp,** Trichogramma evanescens. Cell Tissue Res. 2017 Jun 9. [ABS]

Mikhalevich I, et al (2017) - **Is behavioural flexibility evidence of cognitive complexity? How evolution can inform comparative cognition**. Interface Focus. 2017 Jun 6;7(3):20160121. [FULL TEXT]

Behavioural flexibility is often treated as the gold standard of evidence for more sophisticated or complex forms of animal cognition, such as planning, metacognition and mindreading. However, the evidential link between behavioural flexibility and complex cognition has not been explicitly or systematically defended. Such a defence is particularly pressing because observed flexible behaviours can frequently be explained by putatively simpler cognitive mechanisms. This leaves complex cognition hypotheses open to 'deflationary' challenges that are accorded greater evidential weight precisely because they offer putatively simpler explanations of equal explanatory power. This paper challenges the blanket preference for simpler explanations, and shows that once this preference is dispensed with, and the full spectrum of evidence—including evolutionary, ecological and phylogenetic data—is accorded its proper weight, an argument in support of the prevailing assumption that behavioural flexibility can serve as evidence for complex cognitive mechanisms may begin to take shape. An adaptive model of cognitive-behavioural evolution is proposed, according to which the existence of convergent trait–environment clusters in phylogenetically disparate lineages may serve as evidence for the same trait–environment clusters in other lineages. This, in turn, could permit inferences of cognitive complexity in cases of experimental underdetermination, thereby placing the common view that behavioural flexibility can serve as evidence for complex cognition on firmer grounds.

Budi EH, et al (2017) - **Transforming Growth Factor-β Receptors and Smads: Regulatory Complexity and Functional Versatility.** Trends Cell Biol. 2017 May 25. [ABS]

D'Andola M, et al (2017) - **Bistability, Causality, and Complexity in Cortical Networks: An In Vitro Perturbational Study**. Cereb Cortex. 2017 May 19:1-10. [ABS]

> Measuring the spatiotemporal complexity of cortical responses to direct perturbations provides a reliable index of the brain's capacity for consciousness in humans under both physiological and pathological conditions. Upon loss of consciousness, the complex pattern of causal interactions observed during wakefulness collapses into a stereotypical slow wave, suggesting that cortical bistability may play a role. Bistability is mainly expressed in the form of slow oscillations, a default pattern of activity that emerges from cortical networks in conditions of functional or anatomical disconnection. Here, we employ an in vitro model to understand the relationship between bistability and complexity in cortical circuits. We adapted the perturbational complexity index applied in humans to electrically stimulated cortical slices under different neuromodulatory conditions. At this microscale level, we demonstrate that perturbational complexity can be effectively modulated by pharmacological reduction of bistability and, albeit to a lesser extent, by enhancement of excitability, providing mechanistic insights into the macroscale measurements performed in humans.

Kim C, et al (2017) - **Dynamics of analyst forecasts and emergence of complexity: Role of information disparity**. PLoS One. 2017 May 12;12(5):e0177071. [FULL TEXT]

Nippold MA, et al (2017) - **Spoken Language Production in Young Adults: Examining Syntactic Complexity**. J Speech Lang Hear Res. 2017 May 24;60(5):1339-1347. [ABS]

> Both the narrative and critical-thinking tasks elicited significantly greater syntactic complexity than the conversational task. It was also found that syntactic complexity was significantly greater during the narrative task than the critical-thinking task. ...Syntactic complexity was best revealed by a narrative task that involved fables. The study offers benchmarks for language development during early adulthood.

Ziegler C, et al (2017) - **The More the Merrier-Complexity in Long Non-Coding RNA Loci**. Front Endocrinol (Lausanne). 2017 Apr 25;8:90. [FULL TEXT]

Cohen AL, et al (2017) - **The impacts of spatial and temporal complexity across landscapes on biological control: a review**. Curr Opin Insect Sci. 2017 Apr;20:13-18. [ABS]

Garner AJP, et al (2017) **- Thermodynamics of complexity and pattern manipulation**. Phys Rev E. 2017 Apr;95(4-1):042140. [ABS]

> Many organisms capitalize on their ability to predict the environment to maximize available free energy and reinvest this energy to create new complex structures. This functionality relies on the manipulation of patterns-temporally ordered sequences of data. Here, we propose a framework to describe pattern manipulators-devices that convert thermodynamic work to patterns or vice versa-and use them to build a "pattern engine" that facilitates a thermodynamic cycle of pattern creation and consumption. We show that the least heat dissipation is achieved by the provably simplest devices, the

ones that exhibit desired operational behavior while maintaining the least internal memory. We derive the ultimate limits of this heat dissipation and show that it is generally nonzero and connected with the pattern's intrinsic crypticity-a complexity theoretic quantity that captures the puzzling difference between the amount of information the pattern's past behavior reveals about its future and the amount one needs to communicate about this past to optimally predict the future.

Wilsenach J, et al (2017) - **Evolutionary fields can explain patterns of high-dimensional complexity in ecology**. Phys Rev E. 2017 Apr;95(4-1):042401. [ABS]

One of the properties that make ecological systems so unique is the range of complex behavioral patterns that can be exhibited by even the simplest communities with only a few species. Much of this complexity is commonly attributed to stochastic factors that have very high-degrees of freedom. Orthodox study of the evolution of these simple networks has generally been limited in its ability to explain complexity, since it restricts evolutionary adaptation to an inertia-free process with few degrees of freedom in which only gradual, moderately complex behaviors are possible. We propose a model inspired by particle-mediated field phenomena in classical physics in combination with fundamental concepts in adaptation, which suggests that small but high-dimensional chaotic dynamics near to the adaptive trait optimum could help explain complex properties shared by most ecological datasets, such as aperiodicity and pink, fractal noise spectra. By examining a simple predator-prey model and appealing to real ecological data, we show that this type of complexity could be easily confused for or confounded by stochasticity, especially when spurred on or amplified by stochastic factors that share variational and spectral properties with the underlying dynamics

Wang XZ, et al (2017) - **Discovering the Relationship between Generalization and Uncertainty by Incorporating Complexity of Classification**. IEEE Trans Cybern. 2017 Apr 24. [ABS]

It concludes that the generalization ability of a classifier is statistically becoming better with the increase of uncertainty when the complexity of the classification problem is relatively high, and the generalization ability is statistically becoming worse with the increase of uncertainty when the complexity is relatively low. This paper tries to provide some useful guidelines for improving the generalization ability of classifiers by adjusting uncertainty based on the problem complexity.

Gauvrit N, et al (2017) - **Human behavioral complexity peaks at age 25**. PLoS Comput Biol. 2017 Apr 13;13(4):e1005408. [FULL TEXT]

Our main finding is that the developmental curve of the estimated algorithmic complexity of responses is similar to what may be expected of a measure of higher cognitive abilities, with a performance peak around 25 and a decline starting around 60, suggesting that RIG tasks yield good estimates of such cognitive abilities. Our study illustrates that very short strings of, i.e., 10 items, are sufficient to have their complexity reliably estimated and to allow the documentation of an age-dependent decline in the approximate sense of complexity

Balietto G, et al (2017) - **Density-based clustering: A 'landscape view' of multi-channel neural data for inference and dynamic complexity analysis**. PLoS One. 2017 Apr 3;12(4):e0174918. [FULL TEXT]

Farzan F, et al (2017) - **Brain temporal complexity in explaining the therapeutic and cognitive effects of seizure therapy.** Brain. 2017 Apr 1;140(4):1011-1025. [ABS]

Ruiz-Contreras AE, et al (2017) - **Because difficulty is not the same for everyone: the impact of complexity in working memory is associated with cannabinoid 1 receptor genetic variation in young adults**. Memory. 2017 Mar;25(3):335-343. [ABS]

Souza GM, et al (2017) - **Plant "electrome" can be pushed toward a self-organized critical state by external cues: Evidences from a study with soybean seedlings subject to different environmental conditions.** Plant Signal Behav. 2017 Mar 4;12(3):e1290040. [ABS]

> Herein, to work on a specific framework to settle this type of the study, we are adopting the term "electrome" as a reference to the totality of electrical activity measured. Taking into account the non-linear dynamic of the plants electrophysiology, we have hypothesized that the stimuli, as applied in a constant way, could push the system to a critical state, exhibiting spikes without a characteristic size, indicating self-organized criticality (SOC). The results from the power spectral density analysis (PSD), showed that the interval of the large majority of the β exponents were between 1.5 and 3, indicating that the time series, regardless environmental conditions, showed long-range temporal correlation (long memory for $\beta \neq 0$ and $\beta \neq 2$)..... Overall, our results have confirmed that the temporal dynamic of the electrical signaling shows a complex non-linear behavior with long-range persistence. Moreover, the hypothesis that plant electrome can exhibit a self-organized critical state evoked by environmental cues, dissipating energy by bursts of electrical spikes without a characteristic size, was reinforced.

Krencik R, et al (2017) - **Human astrocytes are distinct contributors to the complexity of synaptic function**. Brain Res Bull. 2017 Mar;129:66-73. [ABS]

> Cellular components of synaptic circuits have been adjusted for increased human brain size, neural cell density, energy consumption and developmental duration. How does the human brain make these accommodations? There is evidence that astrocytes are one of the most divergent neural cell types in primate brain evolution and it is now becoming clear that they have critical roles in controlling synaptic development, function and plasticity. Yet, we still do not know how the precise developmental appearance of these cells and subsequent astrocyte-derived signals modulate diverse neuronal circuit subtypes. Here, we discuss what is currently known about the influence of glial factors on synaptic maturation and focus on unique features of human astrocytes including their potential roles in regenerative and translational medicine. Human astrocyte distinctiveness may be a major contributor to high level neuronal processing of the human brain and act in novel ways during various neuropathies ranging from autism spectrum disorders, viral infection, injury and neurodegenerative conditions.

Mougi A (2017) - **Spatial complexity enhances predictability in food webs**. Sci Rep. 2017 Feb 27;7:43440. [FULL TEXT]

DSantangelo A, et al (2017) - **Brain histamine depletion enhances the behavioural sequences complexity of mice tested in the open-field: Partial reversal effect of the dopamine D2/D3 antagonist sulpiride.** Neuropharmacology. 2017 Feb;113(Pt A):533-542. [ABS]

> Our results provide new insights on the role of histamine on repetitive behavioural sequences of freely moving mice. Histamine deficiency is correlated with a general enhancement of pattern complexity. This study supports a putative involvement of histamine in the pathophysiology of tics and related disorders.

Fruter C, et al (2017) - **Repeated evolution of soldier sub-castes suggests parasitism drives social complexity in stingless bees**. Nat Commun. 2017 Feb 23;8(1):4. [FULL TEXT]

Mayfield MM, et al (2017) - **Higher-order interactions capture unexplained complexity in diverse commu**nities. Nat Ecol Evol. 2017 Feb 17;1(3):62. [ABS]

Gursky ZH, et al (2017) - **Wheel Running and Environmental Complexity as a Therapeutic Intervention in an Animal Model of FASD**. J Vis Exp. 2017 Feb 2;(120). [ABS]

Rodriquez de Castro C, et al (2017) - **Glucose time series complexity as a predictor of type 2 diabetes.** Diabetes Metab Res Rev. 2017 Feb;33(2). [FULL TEXT]

Okanoya K (2017) **- Sexual communication and domestication may give rise to the signal complexity necessary for the emergence of language: An indication from songbird studies.** Psychon Bull Rev. 2017 Feb;24(1):106-110. [ABS]

Bai Y, et al (2017) - **Spinal cord stimulation modulates frontal delta and gamma in patients of minimally consciousness state**. j.neuroscience.2017.01.036. [ABS]

Jia H, et al (2017) - **The relationship between ERP components and EEG spatial complexity in a visual Go/Nogo task**. J Neurophysiol. 2017 Jan 1;117(1):275-283. [ABS]

> We found that with the increase of spatial complexity level, the latencies of N1 and N2 component were shortened and the amplitudes of N1, N2, and P3 components were decreased. The anterior Go/Nogo N2 effect and the Go/Nogo P3 effect were also found to be decreased with the increase of EEG spatial complexity. In addition, the reaction times in high spatial complexity trials were significantly shorter than those of medium and low spatial complexity trials when the time interval used to estimate the EEG spatial complexity was extended to 0~1,000 ms after stimulus onset. These results suggest that high spatial complexity may be associated with faster cognitive processing and smaller postsynaptic potentials that occur simultaneously in large numbers of cortical pyramidal cells of certain brain regions. The EEG spatial complexity is closely related with demands of certain cognitive processes and the neural processing efficiency of human brain.
>
> The EEG spatial complexity is closely related to demands of certain cognitive processes and could reflect the neural processing efficiency of human brain. Obtaining the single-trial ERP features through single-trial spatial complexity may be a more efficient approach than traditional methods.

Kew W, et al (2017) - **Chemical Diversity and Complexity of Scotch Whisky as Revealed by High-Resolution Mass Spectrometry**. J Am Soc Mass Spectrom. 2017 Jan;28(1):200-213. [FULL TEXT]

> Here, we present a thorough overview of the chemistry of Scotch whisky as observed by Fourier transform ion cyclotron resonance mass spectrometry (FT-ICR MS). Eighty-five whiskies, representing the majority of Scotch whisky produced and sold, were analyzed by untargeted high-resolution mass spectrometry. Thousands of chemical formulae were assigned for each sample based on parts-per-billion mass accuracy of FT-ICR MS spectra. FT-ICR MS analysis of Scotch whisky was shown to be of significant potential in further understanding of the complexity of mature spirit drinks and as a tool for investigating the chemistry of the maturation processes.

Fuertinger S, et al (2016) - **Stability of Network Communities as a Function of Task Complexity**. J Cogn Neurosci. 2016 Dec;28(12):2030-2043. [ABS]

Visnovcova Z, et al (2016) - **The complexity of electrodermal activity is altered in mental cognitive stressors.** Comput Biol Med. 2016 Dec 1;79:123-129. [ABS]

> The SCA, SIE and ApEn were significantly increased during mental loads and decreased during recovery periods. However, SCA remained significantly elevated during recovery periods versus baseline, and SIE and ApEn decreased significantly during recovery versus baseline. The frequency of NS-EDR had no significant changes during stress. The EDA is a sensitive marker for evaluation of changes during the activation of sympathetic nervous system under the influence of a load. Detailed knowledge of EDA regulatory mechanisms associated with stress could provide important information associated with autonomic dysregulation.

Te Velde AA, et al (2016) - **Embracing Complexity beyond Systems Medicine: A New Approach to Chronic Immune Disorders.** Front Immunol. 2016 Dec 12;7:587. [FULL TEXT]

LaBar T, et al (2016) - **Different Evolutionary Paths to Complexity for Small and Large Populations of Digital Organisms**. PLoS Comput Biol. 2016 Dec 6;12(12):e1005066. [FULL TEXT]

Zamora-Lopez G, et al (2016) - **Functional complexity emerging from anatomical constraints in the brain: the significance of network modularity and rich-clubs**. Sci Rep. 2016 Dec 5;6:38424. [FULL TEXT]

> A comparison between simulated and empirically obtained resting-state functional connectivity indicates that the human brain, at rest, lies in a dynamical state that reflects the largest complexity its anatomical connectome can host. Last, we generalise the topology of neural connectomes into a new hierarchical network model that successfully combines modular organisation with rich-club forming hubs. This is achieved by centralising the cross-modular connections through a preferential attachment rule. Our network model hosts more complex dynamics than other hierarchical models widely used as benchmarks.

Kamhi JF, et al (2016) - **Social complexity influences brain investment and neural operation costs in ants**. Proc Biol Sci. 2016 Oct 26;283(1841). pii: 20161949. [ABS]

However, superorganism phenotypes may lower cognitive demands on behaviorally specialized workers resulting in selection for decreased brain size and/or energetic costs of brain metabolism.

Aslankoohi E, et al (2016) - **Non-Conventional Yeast Strains Increase the Aroma Complexity of Bread**. PLoS One. 2016 Oct 24;11(10):e0165126. [FULL TEXT]

Labra FA, et al (2016) - **Nonlinear temperature effects on multifractal complexity of metabolic rate of mice**. PeerJ. 2016 Oct 20;4:e2607. [FULL TEXT]

Delignieres D, et al (2016) - **Multifractal signatures of complexity matching**. Exp Brain Res. 2016 Oct;234(10):2773-85. [ABS]

Delignieres D, et al (2016) - **Multifractal signatures of complexity matching**. Exp Brain Res. 2016 Oct;234(10):2773-85. [ABS]

The complexity matching effect supposes that synchronization between complex systems could emerge from multiple interactions across multiple scales and has been hypothesized to underlie a number of daily-life situations. Complexity matching suggests that coupled systems tend to share similar scaling properties, and this phenomenon is revealed by a statistical matching between the scaling exponents that characterize the respective behaviors of both systems. However, some recent papers suggested that this statistical matching could originate from local adjustments or corrections, rather than from a genuine complexity matching between systems. In the present paper, we propose an analysis method based on correlation between multifractal spectra, considering different ranges of time scales. We analyze several datasets collected in various situations (bimanual coordination, interpersonal coordination, and walking in synchrony with a fractal metronome). Our results show that this method is able to distinguish between situations underlain by genuine statistical matching and situations where statistical matching results from local adjustments.

Lopez-Domenech G, et al (2016) - **Loss of Dendritic Complexity Precedes Neurodegeneration in a Mouse Model with Disrupted Mitochondrial Distribution in Mature Dendrites**. Cell Rep. 2016 Oct 4;17(2):317-327. [FULL TEXT]

Miro1 deletion leads to depletion of mitochondria from distal dendrites but not axons, accompanied by a marked reduction in dendritic complexity. Disrupting postnatal mitochondrial distribution in vivo by deleting Miro1 in mature neurons causes a progressive loss of distal dendrites and compromises neuronal survival. Thus, the local availability of mitochondrial mass is critical for generating and sustaining dendritic arbors, and disruption of mitochondrial distribution in mature neurons is associated with neurodegeneration.

Pearcy N, et al (2016) - **Complexity and robustness in hypernetwork models of metabolism**. J Theor Biol. 2016 Oct 7;406:99-104. [ABS]

Moreover, we performed a site percolation analysis on a large cohort of bacterial metabolic networks and found that hypernetworks that evolved in more variable environments displayed increased levels of robustness and topological complexity.

Behzadfar N, et al (2016) - **Low-Complexity Discriminative Feature Selection from EEG Before and After Short-Term Memory Task.** Clin EEG Neurosci. 2016 Oct;47(4):291-297. [ABS]

> ...the permutation entropy significantly increased in frontal lobe and the occipital second lower alpha band activity decreased during memory task. These 2 features reflect the same mental task; however, their correlation with memory task varies in different intervals.

Larsen DS, et al (2016) - **Increased textural complexity in food enhances satiation.** Appetite. 2016 Oct 1;105:189-94. [ABS]

Timme NM, et al (2016) - **Criticality Maximizes Complexity in Neural Tissue.** Front Physiol. 2016 Sep 27;7:425. [FULL TEXT]

> We found evidence that neural systems operate at or near a critical point and that neural complexity is optimized in these neural systems at or near the critical point. Surprisingly, we found evidence that complexity in neural systems is dependent upon avalanche profiles and neuron firing rate, but not precise spiking relationships between neurons.

Corriveau KH, et al (2016) - **Preschoolers' Preference for Syntactic Complexity Varies by Socioeconomic Status**. Child Dev. 2016 Sep;87(5):1529-37. [ABS]

Tang J, et al (2016) - **The effect of textural complexity of solid foods on satiation**. Physiol Behav. 2016 Sep 1;163:17-24. [ABS]

Yau SY, et al (2016) - **Chronic corticosterone administration reduces dendritic complexity in mature, but not young granule cells in the rat dentate gyrus**. Restor Neurol Neurosci. 2016 Sep 21;34(5):849-57. [FULL TEXT]

Cassarino M, et al (2016) - **Complexity as Key to Designing Cognitive-Friendly Environments for Older People**. Front Psychol. 2016 Aug 30;7:1329. [FULL TEXT]

> The present paper reviews a selection of studies which have explored complexity in relation to perceptual load, environmental preference and perceived usability to propose a framework which explores direct and indirect environmental influences on cognition, and to understand these influences in relation to aging processes. We identify ways to define complexity at different environmental scales, going from micro low-level perceptual features of scenes, to design qualities of proximal environments (e.g., streets, neighborhoods), to broad geographical areas (i.e., natural vs. urban environments). We propose that studying complexity at these different scales will provide new insight into the design of cognitive-friendly environments.

Rosenblueth DA (2016) - **Editorial: Computational Methods for Understanding Complexity: The Use of Formal Methods in Biology**. Front Bioeng Biotechnol. 2016 Aug 22;4:68. [FULL TEXT]

Gravel D, et al (2016) - **Stability and complexity in model meta-ecosystems**. Nat Commun. 2016 Aug 24;7:12457. [FULL TEXT]

> We find that stability criteria from classic theory are relaxed in direct proportion to the number of ecologically distinct patches in the meta-ecosystem. Further, we find the

stabilizing effect of dispersal is maximal at intermediate intensity. Our results highlight how biodiversity can be vulnerable to factors, such as landscape fragmentation and habitat loss that isolate local communities.

Fasoli D, et al (2016) - **The Complexity of Dynamics in Small Neural Circuits**. PLoS Comput Biol. 2016 Aug 5;12(8):e1004992. [FULL TEXT]

Cui Y, et al (2016) - **The Exposome: Embracing the Complexity for Discovery in Environmental Health. Environ Health Perspect**. 2016 Aug; 124(8): A137–A140. [FULL TEXT]

Adjei T, et al (2016) - **Characterisation of the complexity of intracranial pressure signals measured from idiopathic and secondary normal pressure hydrocephalus patients.** Healthc Technol Lett. 2016 Jul 5;3(3):226-229. [FULL TEXT]

Friedenberg J, et al (2016) - **Perceived beauty of random texture patterns: A preference for complexity**. Acta Psychol (Amst). 2016 Jul;168:41-9. [ABS]

Cipresso P, et al (2016) - **Computational Psychometrics Meets Hollywood: The Complexity in Emotional Storytelling**. Front Psychol. 2016; 7: 1753. [FULL TEXT]

Grainger DC (2016) - **The unexpected complexity of bacterial genomes**. Microbiology. 2016 Jul;162(7):1167-1172. [ABS]

Marshall DJ, et al (2016) - **Global change, life-history complexity and the potential for evolutionary rescue.** Evol Appl. 2016 Jun 30;9(9):1189-1201. [FULL TEXT]

We found that increasing the complexity of the life history generally reduces the evolutionary potential of taxa to cope with environmental change. Our model also predicted that genetic correlations in stress tolerance between stages, levels of genetic variance in each stage, and the relative plasticity of different stages, all interact to affect the maximum rate of environmental change that will permit species persistence.

Marshall N, et al (2016) - **Analysis of Power Laws, Shape Collapses, and Neural Complexity: New Techniques** and MATLAB Support via the NCC Toolbox. Front Physiol. 2016 Jun 27;7:250. [FULL TEXT]

Sokunbi MO (2016) - **BOLD fMRI complexity predicts changes in brain processes, interactions and patterns, in health and disease**. Journal of the Neurological Sciences 367 (2016) 347–348. [FULL TEXT]

Durand PM, et al (2016) - **Programmed Cell Death and Complexity in Microbial Systems**. Curr Biol. 2016 Jul 11;26(13):R587-93. [FULL TEXT]

DeFelipe J, et al (2016) - **Comments and General Discussion on "The Anatomical Problem Posed by Brain Complexity and Size: A Potential Solution".** Front Neuroanat. 2016; 10: 60. [FULL TEXT]

Kim SH, et al (2016) - **Development of cortical shape in the human brain from 6 to 24months of age via a novel measure of shape complexity**. Neuroimage. 2016 Jul 15;135:163-76. [FULL TEXT]

Torday JS (2016) - **Life Is Simple - Biologic Complexity Is an Epiphenomenon**. Biology (Basel). 2016 Apr 27;5(2). pii: E17. [FULL TEXT]

> Life originated from unicellular organisms by circumventing the Second Law of Thermodynamics using the First Principles of Physiology, namely negentropy, chemiosmosis and homeostatic regulation of calcium and lipids. It is hypothesized that multicellular organisms are merely contrivances or tools, used by unicellular organisms as agents for the acquisition of epigenetic inheritance. The First Principles of Physiology, which initially evolved in unicellular organisms are the exapted constraints that maintain, sustain and perpetuate that process. To ensure fidelity to this mechanism, we must return to the first principles of the unicellular state as the determinants of the primary level of selection pressure during the life cycle. The power of this approach is reflected by examples of its predictive value. This perspective on life is a "game changer", mechanistically rendering transparent many dogmas, teleologies and tautologies that constrain the current descriptive view of Biology.

Mohibbullah M, et al (2016) - **The Edible Red Seaweed Gracilariopsis chorda Promotes Axodendritic Architectural Complexity in Hippocampal Neurons**. J Med Food. 2016 Jul;19(7):638-44. [ABS]

Lafontain MP, et al (2016) - **Brain signal complexity rises with repetition suppression in visual learning**. Neuroscience. 2016 Jun 21;326:1-9. [ABS]

> Results revealed RS over occipito-temporal electrode sites during learning, reflected by a decrease in signal energy, a measure of amplitude. Simultaneously, as signal energy decreased, brain signal complexity, as estimated with multiscale entropy (MSE), increased.

Koorehdavoudi H, et al (2016) - **A Statistical Physics Characterization of the Complex Systems Dynamics: Quantifying Complexity from Spatio-Temporal Interactions**. Sci Rep. 2016 Jun 14;6:27602. [FULL TEXT]

Soshnev AA, et al (2016) - **Greater Than the Sum of Parts: Complexity of the Dynamic Epigenome**. Mol Cell. 2016 Jun 2;62(5):681-94. [FULL TEXT]

Namazi H, et al (2016) - **The Analysis of the Influence of Odorant's Complexity on Fractal Dynamics of Human Respiration.** Sci Rep. 2016 May 31;6:26948. [FULL TEXT]

> The results show for the first time that more structurally complex a monomolecular odorant will result in less fractal respiratory signal. On the other hand, odorant with higher entropy will result the respiratory signal with lower entropy.

Bies AJ, et al (2016) - **Aesthetic Responses to Exact Fractals Driven by Physical Complexity**. Front Hum Neurosci. 2016 May 20;10:210. [FULL TEXT]

Fregnac Y, et al (2016) - **The Visual Brain: Computing through Multiscale Complexity**. In: Micro-, Meso- and Macro-Dynamics of the Brain [Internet]. Cham (CH): Springer; 2016. 2016 May 3 [FULL TEXT]

Raijmakers M, et al (2016) - **Experimental febrile seizures increase dendritic complexity of newborn dentate granule cells**. Epilepsia. 2016 May;57(5):717-26. [ABS]

> Experimental FS increase dendritic complexity and the number of mushroom-type spines in post-FS born DGCs, demonstrating a more mature phenotype and suggesting increased incoming excitatory information. The consequences of this hyperconnectivity to signal processing in the DG and the output of the hippocampus remain to be studied.

Kaiyala KJ (2016) - **Fractal analysis of thermoregulatory complexity**. Temperature (Austin). 2016; 3(3): 364–365. [FULL TEXT]

Mougi A, et al (2016) - **Food-web complexity, meta-community complexity and community stability**. Sci Rep. 2016 Apr 13;6:24478. [FULL TEXT]

Zhang Y, et al (2016) - **Exploiting Complexity Information for Brain Activation Detection**. PLoS One. 2016 Apr 5;11(4):e0152418. [FULL TEXT]

Groenwoud F, et al (2016) - **Predation risk drives social complexity in cooperative breeders**. Proc Natl Acad Sci U S A. 2016 Apr 12;113(15):4104-9. [FULL TEXT]

Slone E, et al (2016) - **Environmental layout complexity affects neural activity during navigation in humans**. Eur J Neurosci. 2016 May;43(9):1146-55. [ABS]

> The results showed that navigation in the simpler, less interconnected environment was faster and more accurate relative to the complex environment, and such performance was associated with increased activity in a number of brain areas (i.e. precuneus, retrosplenial cortex, and hippocampus) known to be involved in mental imagery, navigation, and memory. These findings provide novel evidence that environmental complexity not only affects navigational behaviour, but also modulates activity in brain regions that are important for successful orientation and navigation.

Bokov P, et al (2016) - **Increased ventilatory variability and complexity in patients with hyperventilation disorder**. J Appl Physiol (1985). 2016 May 15;120(10):1165-72. [FULL TEXT]

Metzler-Baddeley C, et al (2016) - **Task complexity and location specific changes of cortical thickness in executive and salience networks after working memory training**. Neuroimage. 2016 Apr 15;130:48-62. [FULL TEXT]

Buhrman H, et al (2016) - **Quantum communication complexity advantage implies violation of a Bell inequality**. Proc Natl Acad Sci U S A. 2016 Mar 22;113(12):3191-6. [FULL TEXT]

Tonoyan Y, et al (2016) - **Discriminating Multiple Emotional States from EEG Using a Data-Adaptive, Multiscale Information-Theoretic Approach**. Int J Neural Syst. 2016 Mar;26(2):1650005. [FULL TEXT]

> … multiscale sample entropy is a promising technique to discriminate multiple emotional states from EEG recordings.

Barbieri M (2016) - **A new theory of development: the generation of complexity in ontogenesis**. Philos Trans A Math Phys Eng Sci. 2016 Mar 13;374(2063). [ABS]

Hebets EA, et al (2016) - **A systems approach to animal communication**. Proc Biol Sci. 2016 Mar 16;283(1826):20152889. [FULL TEXT]

Farzan F, et al (2016) - **Enhancing the Temporal Complexity of Distributed Brain Networks with Patterned Cerebellar Stimulation**. Sci Rep. 2016 Mar 24;6:23599. [FULL TEXT]

Gucloturk Y, et al (2016) - **Liking versus Complexity: Decomposing the Inverted U-curve**. Front Hum Neurosci. 2016 Mar 18;10:112. [FULL TEXT]

Zenil H, et al (2016) - **Methods of information theory and algorithmic complexity for network biology**. Semin Cell Dev Biol. 2016 Mar;51:32-43. [ABS]

Burge SK, et al (2016) - **Using complexity science to examine three dynamic patterns of intimate partner violence**. Fam Syst Health. 2016 Mar;34(1):4-14. [ABS]

> The partner violence literature describes 3 dominant models of dynamics of partner aggression: cycle of violence, family systems theory, and Duluth model (power and control wheel). Complexity science describes 3 patterns of system dynamics: periodic, chaotic, and random.

Brantsaeter M, et al (2016) - **Exposure to Increased Environmental Complexity during Rearing Reduces Fearfulness and Increases Use of Three-Dimensional Space in Laying Hens (Gallus gallus domesticus).** Front Vet Sci. 2016 Feb 29;3:14. [FULL TEXT]

Pande V (2016) - **Understanding the Complexity of Epigenetic Target Space**. J Med Chem. 2016 Feb 25;59(4):1299-307. [ABS]

Hahn K, et al (2016) - **A new method to measure complexity in binary or weighted networks and applications to functional connectivity in the human brain**. BMC Bioinformatics. 2016 Feb 13;17:87. [FULL TEXT]

Lane N, et al (2016) **- Mitochondria, complexity, and evolutionary deficit spending**. Proc Natl Acad Sci U S A. 2016 Feb 9; 113(6): E666. [FULL TEXT]

Dorfman A, et al (2016) - **Traveling Companions Add Complexity and Hinder Performance in the Spatial Behavior of Rats**. PLoS One. 2016 Jan 4;11(1):e0146137. [FULL TEXT]

Uversky VN (2016) - **Paradoxes and wonders of intrinsic disorder: Complexity of simplicity. Intrinsically Disord Proteins**. 2016 Jan 8;4(1):e1135015. [FULL TEXT]

Escudero J, et al (2015) - **Effect of the average delay and mean connectivity of the Kuramoto model on the complexity of the output electroencephalograms**. Conf Proc IEEE Eng Med Biol Soc. 2015;2015:7873-6. [ABS]

> Here, we inspected the dependency of two widespread nonlinear complexity markers, Sample Entropy (SampEn) and Lempel-Ziv Complexity (LZC), on EEG activity generated with a Kuramoto phase model where the time delay and connectivity strength among oscillators varied. We also added different levels of noise to the electroencephalogram (EEG) signals. Our results indicated that both complexity metrics reflected the changes in the delays and global synchrony levels, but we found that SampEn was slightly more sensitive to the state transition and its results were less affected by the presence of

noise. These results help in the effort to understand the dynamics of EEG recordings and their relationship to large-scale networks.

Burns T, et al (2015) - **Combining complexity measures of EEG data: multiplying measures reveal previously hidden information**. F1000Res. 2015 Jun 1;4:137. [FULL TEXT]

> The complexity measures did not all significantly correlate, suggesting that different measures were measuring unique features of the EEG signals and thus revealing information which other measures were unable to detect. Therefore, the results from this analysis suggests that combinations of complexity measures reveal unique information which is in addition to the information captured by other measures of complexity in EEG data.

Budday S, et al (2015) - **Secondary instabilities modulate cortical complexity in the mammalian brain**. Philos Mag (Abingdon). 2015;95(28-30):3244-3256. [FULL TEXT]

Lin P-F, et al (2014) - **Correlations between the Signal Complexity of Cerebral and Cardiac Electrical Activity: A Multiscale Entropy Analysis**. PLoS ONE 9(2): e87798. [FULL TEXT]

> With the deterioration of health conditions, the change in dynamic patterns of biological signals is characterized by loss of complexity and development of stereotypy...
>
> Previous evidence showing decreased EEG complexity in dementia only used statistics for group comparison... but we found a proportional relationship between the brain signal variability and cognitive test score at electrode F8.

Khairuddin HR, et al (2013) - **Analysis of EEG signals regularity in adults during video game play in 2D and 3D.** Conf Proc IEEE Eng Med Biol Soc. 2013;2013:2064-7. [ABS]

> Two parameters were used to measure signal complexity for time series data: i) Hjorth-Complexity and ii) Composite Permutation Entropy Index (CPEI). Based on these two parameters, our results showed that the complexity level increased from eyes closed to eyes open condition; and further increased in the case of 3D as compared to 2D game play.

Souza GM, et al (2004) - **Approximate Entropy as a measure of complexity in sap flow temporal dynamics of two tropical tree species under water deficit.** An Acad Bras Cienc. 2004 Sep;76(3):625-30. [ABS]

Andino SLG, et al (2000) - **Measuring the complexity of time series: an application to neurophysiological signals**. Hum Brain Mapp. 2000 Sep;11(1):46-57. [ABS]

> …this measure conforms closely to our visual notion of complexity since low complexity values are obtained for signals formed by a small number of "components".

Klonowski W, et al (1999) - **Quantitative measure of complexity of EEG signal dynamics**. Acta Neurobiol Exp (Wars). 1999;59(4):315-21. [Full Text]

> Karhunen-Loeve KI-complexity of the signal differs profoundly for the signals registered in different EEG channels, from about 5-8 for signals in frontal channels up to 40 and more in occipital ones. But no consistency in the influence of Diazepam administration

on KL-complexity is observed. We also estimated the embedding dimension of the EEG signals of the same subjects, which turned to be between 7 and 11, so endorsing the presumption about existence of low-dimensional chaotic attractor.

Stoddard PK (1999) - **Predation enhances complexity in the evolution of electric fish signals**. Nature. 1999 Jul 15;400(6741):254-6. [ABS]