Review Article

The Fractal Nature of the Brain: EEG Data Suggests That the Brain Functions as a "Quantum Computer" in 5-8 Dimensions

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Abstract

The brain has been traditionally viewed as a deterministic machine where certain inputs give rise to certain outputs. However, there is a growing body of work that suggests this is not the case. The high importance of initial inputs suggests that the brain may be working in the realms of chaos, with small changes in initial inputs leading to the production of strange attractors. This may also be reflected in the physical structure of the brain, which may also be fractal. EEG data is a good place to look for the underlying patterns of chaos in the brain since it samples many millions of neurons simultaneously. Several studies have arrived at a fractal dimension of between 5 and 8 for human EEG data. This suggests that the brain operates in a higher dimension than the 4 of traditional space-time. These extra dimensions suggest that quantum gravity may play a role in generating consciousness.

Key Words: fractal, electroencephalography, quantum gravity, consciousness

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Fractals and the brain

The brain has traditionally been viewed as acting according to laws that tie behavioural responses to environmental variables (reviewed in Maye *et al.*, 2007). However, there are numerous examples of neural systems that appear well understood but still produce variable output with no variations in input. It has been suggested that this noise is due to a number of factors, but an alternative explanation suggests that at least some of this variability is adaptive and irreducible (Maye *et al.*, 2007). Such instability is a property of many nonlinear systems, possibly including the brain (Ashwin and Timme, 2005). Even in flies it appears that there is a nonlinear signature suggesting deterministic endogenous processes involved in generating behavioural variability. Due to its sensitivity to initial conditions this initiator renders genuine spontaneity as a biological trait even in flies (Maye *et al.*, 2007). In humans there also appears to be a default network of stimulus-independent thought (Mason *et al.*, 2007), again suggesting that there is a nonlinear process at work. Such studies demonstrate that consciousness itself may have a fractal component. Indeed an analysis of different brain wave frequencies shows that there is a fractal small-world component of these waves that scales between 2-37Hz (Bassett *et al.*, 2006).

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The fractal physical nature of the brain

Most analyses of the fractal physical nature of the brain have focussed on either the gross physical nature of the brain using such techniques as MRI (Sandu *et al.,* 2007), or examined the shape of individual neurons (Milosevic *et al.,* 2007). However, both these approaches ignore the subcellular structure of neurons, which also contributes to the physical fractal nature of these structures. In a previous paper we suggested that the concept of tensegrity may be useful in understanding the physical structure of the brain (Gardiner *et al.,* 2008). Tensegrity architecture is based around a self-stable structure of tensional and compression-resistant components. In the cell it has been traditionally thought that actin microfilaments act as the tensional components and microtubules as the compression-resistant components (Wang *et al.,* 1993). However, each of these structures is also composed of amino acids which may also fold according to tensegrity principles (Zanotti and Guerra, 2003). One of the main tenets of tensegrity theory is that the underlying building block of any tensegrity system is the triangle. Thus on smaller and smaller scales the triangle is the basic building block. This suggests a structure in the brain perhaps similar to the Sierpinski triangle, which is also a triangular fractal with based upon ever smaller triangles.

Calvin's concept of consciousness and fractals

William Calvin has constructed a model whereby hexagonal clusters of neurons interact with one another in a competitive fashion to produce consciousness. He makes an interesting proposal as to how this may work in the brain (Calvin, 1993; 1995; 1996). In this model most efficient anatomy would be six equally-spaced axon branches from the same cell (Calvin, 1993), or a triangular mosaic. In the dorsocaudal region of medial entorhinal cortex (dMEC) cells, spatial firing fields show a hexagonal grid pattern, with grid cells that are activated whenever the animal's position coincides with any vertex of a regular grid of equilateral triangles spanning the surface of the environment, thus providing experimental support for Calvin's hypothesis (Fyhn *et al.,* 2004; Hafting *et al.,* 2005). Calvin goes on to suggest that there may be "basins of attraction", or strange attractors, within each of the hexagonal components. The output from each hexagonal component might then reflect the current position of the trajectory of the strange attractor through different possible states within the hexagon itself. Thus, even on the scale of neurons there may be an underlying fractal nature to consciousness. Indeed mapping of event-related desynchronization (ERD) on the cortical surface has revealed transitions from spatially diffuse to focused and somatotopically specific patterns of alpha wave suppression (Crone et al 1998), consistent with the picture of spontaneous cortical states being driven into stimulus specific configurations of correlated neural activity (Tsodyks *et al.,* 1999). Since brain activity measures show robust scaling behaviour, it has been suggested that normally neural networks operate in a critical state, thereby making them capable of quick reorganisation (Linkenkaer-Hansen *et al.,* 2001). Another example supporting Calvin's hypothesis is that of neuronal avalanches. These avalanches reflect fast propagation of local synchrony. The statistical organisation of pattern sizes in the avalanches is invariant to the choice of spatial scale, again suggesting a fractal organisation of the brain (Plenz and Thiagarajan, 2007).

Freeman's evidence for chaos in the brain

Freeman's work on olfactory perception and palaeocortical EEG suggests that chaos exists in cortical neurodynamics, and this may be the property that makes perception possible allowing flexible and coherent responses to perceptual stimuli. He concluded that the olfactory system uses bursts of chaotic gamma band activity to signal the perception of an odour to the animal. The chaotic attractor for this signal is thus a representation of a particular odour and these attractors and their basins of attraction are not invariant. The learning of a new odour creates a new attractor and modifies other pre-existing attractors as well. The brain thus has to switch reliably between different attractors and Freeman sees this as either bifurcations or phase transitions in a noisy environment. Thus he sees the brain as essentially chaotic whereby rapid transition between attractors, or the creation of new attractors, is generated by small changes of input (Dafili *et al.,* 2001)

EEG data and the high dimensionality of consciousness

Electroencephalogram (EEG) electrodes placed on the scalp record the aggregate electrical activity from up to 6cm^2 of brain surface, and hence many millions of neurons (Cooper *et al.,* 1965). As such, they provide a good place to look for chaos in the brain since they represent a global sampling of brain activity. Various studies have found that the fractal dimension of EEG data from the brain has a fractal dimension of greater than four. A study of the fractal dimension of EEG recordings from healthy subjects measured over a 2.5 second period consistently revealed a fractal dimension of close to 5 (Stam *et al.,* 1995) and another study using the point correlation dimension PD2 algorithm found a value between 5.2 and 5.9 (Tomberg, 1999). This study also found that the fractal dimension increased to 6.6-6.9 in the Wernicke areas during reading, suggesting that the fractal dimension of EEG data does reflect the complexity of underlying brain function. Yet another study again found fractal dimensions of greater than 5 in EEG data (Preiβl *et al.,* 1997) and a fourth study found a value of 6.5 in healthy subjects (Stam et al 1994). A study of the fractal dimension in sleep and waking found a value of around 7.5 during wakefulness with this falling during different stages of sleep (Pereda *et al.,* 1999). Although there is some discrepancy between the results of these studies, they all arrived at somewhat similar values greater than four, thus suggesting that consciousness indeed occurs in greater than four dimensions. Interestingly, a study of EEG patterns in the lizard *Gallotia galloti* found a fractal dimension of around 6, similar to the results of human studies (González *et al.,* 1999).

Possible objections to this analysis

It has been generally thought that the fractal dimension of EEG data is just a mathematical construct, albeit one which is useful for probing brain function. However, this does not answer the question of why EEG data has a fractal dimension that appears to vary according to the complexity of underlying neural processes. All signals that behave as fractals appear to require a physical fractal nature in order to generate the fractal signal in the first instance. A landmark study of the repeated occurrence of the fourth power in allometric scaling of organisms found that fractal-like networks (in three dimensions) endow life with an additional fourth dimension (West *et al.,* 1999). It has even been suggested that this fourth dimension may represent time itself although this has not been proven (Hainsworth, 1981). Similarly, we suggest that the high dimensionality of EEG data may demonstrate an underlying physical reality similar to that seen in the allometric scaling of organisms, with the higher dimensions corresponding to yet to be proven dimensions of quantum gravity.

Consciousness and quantum gravity

It has been suggested that the missing link in our understanding of consciousness is the same as the missing link between the 'submicroscopic' world of quantum physics and the macro-world where classical physics is effective (Penrose, 1989). Penrose argues that this link is the same as the missing link between quantum theory and Einstein's general relativity, or 'quantum gravity'. A proposal has been put forward whereby quantum gravity includes an extra, fifth, dimension (Randall *et al.,* 1999; Kisselev *et al.,* 2005). Other theories of quantum gravity also include five or more dimensions. Thus consciousness, with more than four dimensions, may reflect the underlying nature of the universe including the extra dimension or dimensions of quantum gravity. Penrose and Hameroff (1995) have also suggested that microtubules may be the sites of quantum gravitational effects that can magnify themselves up to the level of the structure and function of the brain, although this remains controversial. Indeed it has been suggested that tubulin heterodimers may act as computational components, switching between two or more states depending upon their relationship with their six neighbouring tubulin heterodimers (Rasmussen *et al.,* 1990). Here classical computing leads to the emergence of quantum coherent superposition in the organisation of tubulin heterodimers which in turn causes self collapse of the coherent superposition and thus conscious thought. There is perhaps a parallel with the work of Calvin, who envisages that hexagonal groups of neurons in the cerebral cortex may interact with one another in consciousness. It is possible that the order in complexity seen by Calvin may, in turn, reflect the hexagonal tiling of tubulin heterodimers in the microtubule. This heterodimer tiling may be under the influence of the extra dimension, or dimensions, of quantum gravity, and thus provide a link between quantum gravity and consciousness.

Fractals and the brain in disease

Alzheimer's disease is a degenerative dementia whose exact cause remains elusive, although recent work has shown that the amyloid deposits seen in Alzheimer's disease may contribute to the cell death that is seen (Necula *et al.,* 2007). (Magnetoencephalogram recordings from the brains of both Alzheimer's patients and normal controls show that the recordings are nonlinear and that the complexity of the signal is reduced in the Alzheimer's patients using Higuchi's fractal dimension (Gómez et al 2008). Another study found that the fractal dimension of EEG readings from brains of both Parkinson's and Alzheimer's disease patients, with the dimension being lower in the readings of Alzheimer's patients than Parkinson's patients (Stam *et al.,* 1995). A fractal dimension analysis of electroencephalogram data might also prove useful in the diagnosis of Alzheimer's disease (Henderson *et al.,* 2006). This reduction in the fractal dimension of EEG recording from dementia patients suggests that the fractal complexity of the brain and consciousness decreases when the underlying structure of the brain, which is also fractal, is compromised.

Conclusions

It appears likely that the brain does operate as a fractal system, with ever-increasing layer s of scalable self-similarity at smaller and smaller scales. This may give rise to strange attractors at different scales that regulate thought and consciousness. Indeed, it has been suggested that outward manifestations of the fractal nature of our brains may be seen in places such as Gothic architecture, which also has porous, scale-free structures (Goldberger, 1996). Even the hexagonal honeycomb made by bees might also reflect the underlying structure of their brains. EEG data suggests that the fractal dimension of consciousness is somewhere between 5 and 8. This is a greater figure than the 4 dimensions of normal space and time. This suggests that extra dimensions, perhaps reflecting the extra dimensions of quantum gravity, are required to fully explain consciousness. This in turn suggests that the brain does function as a "quantum computer" as has been previously suggested.

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References

Ashwin P, Timme M. Nonlinear dynamics: when instability makes sense. Nature 2005; 436: 36-37.

Bassett DS, Meyer-Lindenberg A, Achard S, Duke T, Bullmore E. Adaptive reconfiguration of fractal small-world human brain functional networks. PNAS 2006; 103: 19518-19523.

Calvin WH. Error-correcting codes: coherent hexagonal copying from fuzzy neuroanatomy. World Congress on Neural Networks 1993; 1: 101-104.

Calvin WH. Cortical columns, modules and Hebbian cell assemblies. In: 1995; The Handbook of Brain Theory and Neural Networks. Ed: Michael A Arbib, Bradford Books/MIT Press, Cambridge Massachusetts.

Calvin WH. 1996; The Cerebral Code. Bradford Books/MIT Press. Cambridge Massachusetts.

Cooper R, Winter AL, Crow HJ, Walter WG. Comparison of subcortical, cortical and scalp activity using chronically indwelling electrodes in man. Electroencephalogr Clin Neurophysiol 1965; 18: 217-228.

Crone NE, Miglioretti DL, Gordon B, Sieracki JM, Wilson MT, Uematsu S, Lesser RP. Functional mapping of human sensorimotor cortex with electrocorticographic spectral analysis. Brain 1998; 121: 2271-2299.

Dafilis MP, Liley DTJ, Cadusch PJ. Robust chaos in a model of the electroencephalogram: implications for brain dynamics. Chaos 2001; 11: 474-478.

Fyhn M, Molden S, Witter MP, Moser EI, Moser MB. Spatial representation in the entorhinal cortex. Science 2004; 305: 1258-1265.

Gardiner J, Marc J, Overall R. Cytoskeletal thermal ratchets and cytoskeletal tensegrity: determinants of brain asymmetry and symmetry? Front Biosci 2008; 13: 4649-4656.

Goldberger AL. Fractals and the birth of Gothic: reflections on the biologic basis of creativity. Mol Psychiatry 1996; 1: 99-104.

Gómez C, Mediavilla A, Hornero R, Abásolo D, Fernández A. Use of Higuchi's fractal dimension for the analysis of MEG recordings from Alzheimer's disease patients. Med Eng Phys 2008; epub ahead of print.

González J, Gamundi A, Rial R, Nicolau MC, de Vera L, Pereda E. Nonlinear, fractal, and spectral analysis of the EEG of lizard, *Gallotia galloti*. Am J Physiol Regul Integr Comp Physiol 1999; 277: R86-R93.

Hafting T, Fyhn M, Molden S, Moser MB, Moser EI. Microstructure of a spatial map in the entorhinal cortex. Nature 2005; 436: 801-806.

Hainsworth FR. Animal Physiology; Adaptations in Function. Addison-Wesley, Reading MA. 1981; p.170.

Hameroff S, Marcer P. Quantum computation in brain microtubules? The Penrose-Hameroff 'Orch OR' model of consciousness [and discussion]. Phil Trans: Math, Phys, Eng Sci 1998; 356: 1869-1896.

Henderson G, Ifeachor F, Hudson N, Goh C, Outram N, Wimalaratna S, Del Percio C, Vecchio F. Development and assessment of methods for detecting dementia using the human electroencephalogram. IEEE Trans Biomed Eng 2006; 53: 1557-1568.

Kisselev AV, Petrov VA, Ryutin RA. 5-dimensional quantum gravity effects in exclusive double diffractive events. Physics Letters B 2005; 630: 100-107.

Linkenkaer-Hansen K, Nikouline VV, Palva JM, Hmoniemi RJ. Long-range temporal correlations and scaling behaviour in human brain oscillations. J Neurosci 2001; 21: 1370-1377.

Mason MF, Norton MI, Van Horn JD, Wegner DM, Grafton ST, Macrae CN. Wandering minds: the default network and stimulus-independent thought. Science 2007; 315: 393-395.

Maye A, Hsieh C-h, Sugihara G, Brembs B. Order in spontaneous behaviour. PLoS ONE 2007; 2: e443

Milosević NT, Ristanović D, Gudović R, Rajković K, Marić D. Application of fractal analysis to neuronal dendritic arborisation patterns of the monkey dentate nucleus. Neuroscience Letters 2007; 425: 23-27.

Necula M, Breydo L, Milton S, Kayed R, van der Veer WE, Tone P, Glabe CG. Methylene blue inhibits amyloid Abeta oligomerization by promoting fibrillization. Biochemistry 2007; 46: 8850-8860.

Penrose R. The emperor's new mind. Oxford University Press. 1989.

Penrose R, Hameroff SR. What gaps? Reply to Grush and Churchland. Journal of Consciousness Studies 1995; 2: 99-112.

Pereda E, Gamundi A, Nicolau MC, Rial R, González J. Intrahemispheric difference in awake and sleep human EEG: a comparison between non-linear and spectral measures. Neuroscience Letters 1999; 263: 37-40.

Plenz D, Thiagarajan TC. The organizing principles of neuronal avalanches: cell assemblies in the cortex? Trends Neurosci 2007; 30: 101-110.

Preiβl H, Lutzenberger W, Pulverműller F, Birbaumer N. Fractal dimensions of short EEG time series in humans. Neuroscience Letters 1997; 225: 77-80.

Randall L, Sundrum R. Large mass hierarchy from a small extra dimension. Physical Review Letters 1999; 83 :3370-3373.

Rasmussen S, Karampurwala H, Vaidyanath R, Jensen KS, Hameroff S. Computational connectionism within neurons: a model of cytoskeletal automata subserving neural networks. Physica D: Nonlinear Phenomena 1990; 42: 428-449.

Sandu AL, Rasmussen IA Jr., Lundervold A, Kreuder F, Neckelmann G, Hugdahl K, Specht K. Fractal dimension analysis of MR images reveals grey matter structure irregularities in schizophrenia. Comput Med Imaging Graph 2007; 32: 150-158.

Stam KJ, Tavy DL, Jelles B, Achtereekte HA, Slaets JP, Keunen RW. Non-linear dynamical analysis of multichannel EEG: clinical applications in dementia and Parkinson's disease. Brain Topogr 1994; 7: 141-150.

Stam CJ, Jelles B, Achtereekte HAM, Rombouts SARB, Slaets JPJ, Keunen RWM. Investigation of EEG non-linearity in dementia and Parkinson's disease. Electroencephal Clin Neurophysiol 1995; 95: 309-317.

Tomberg C. Focal enhancement of chaotic strange attractor dimension in the left sematic (Wernicke) human cortex during reading without concomitant change in vigilance level. Neurosci Lett 1999; 263: 177-180.

Tsodyks M, Kenet T, Grindvald A, Arieli A. Linking spontaneous activity of single cortical neurons and the underlying functional architecture. Science 1999; 286: 1943-1946.

Wang N, Butler JP, Ingber DE. Mechanotransduction across the cell surface and through the cytoskeleton. Science 1993; 260: 1124-1127.

West GB, Brown JH, Enquist BJ. The fourth dimension of life: fractal geometry and allometric scaling of organisms. Science 1999; 284: 1677-1679.

Zanotti G, Guerra C. Is tensegrity a unifying concept of protein folds? FEBS Lett 2003; 534: 7-10.