From molecules to mindfulness

How vertically convergent fractal time fluctuations unify cognition and emotion*

Carl M. Anderson
Harvard Medical School

Fractal time fluctuations of the spectral "1/f" form are universal in natural self-organizing systems. Neurobiology is uniquely infused with fractal fluctuations in the form of statistically self-similar clusters or bursts on all levels of description from molecular events such as protein chain fluctuations, ion channel currents and synaptic processes to the behaviors of neural ensembles or the collective behavior of Internet users. It is the thesis of this essay that the brain self-organizes via a vertical collation of these spontaneous events in order to perceive the world and generate adaptive behaviors. REM sleep, which coalesces from self-similar clusters of burst-within-burst behavior during ontogeny, is essential to cognitive-emotional function, and has recurrent fractal organization. Empirical fMRI observations further support the association of fractal fluctuations in the temporal lobes, brainstem and cerebellum during the expression of emotional memory, spontaneous fluctuations of thought and meditative practice. Cognitive-emotional integration arises as amygdaloid-brainstem-cerebellar systems harmonize the vertical "1/f" symphony of coupled isochronous cortical oscillations in the pursuit of mindfulness.

Keywords: 1/f noise, amygdala, attention, cerebellar vermis, development, dynamical systems, fractal, emotion, REM sleep, meditation, self-organized criticality, stochastic resonance

"The great field for new discoveries…is always the unclassified residuum. Round about the accredited and orderly facts of every science there ever floats a sort of

Consciousness & Emotion 1:2 (2000), **193–226.** ISSN 1566–5836

> *dust-cloud of exceptional observations, of occurrences minute and irregular and seldom met with, which it always proves more easy to ignore than to attend to. The idea of every science is that of a closed and completed system of truth…. Phenomena unclassifiable within the system are paradoxical absurdities, and must be held untrue… One neglects or denies them with the best of scientific consciences… Any one will renovate his science who will steadily look after the irregular phenomena. And when the science is renewed, its new formulas often have more of the voice of the exception in them than of what were supposed to be the rules[1].*"
>
> –William James

Introduction

In creating a science of the irregular, Benoit Mandelbrot began a renaissance in the way order is perceived in nature, particularly in the spontaneous irregular patterns of neural activity that underlie cognition and emotion. Central to the Mandelbrot renaissance is the concept that patterns termed "fractal" or "self-similar" have recurrent irregularity in space or time repeated like the layers of an onion at different levels or scales. Spontaneous behavioral phenomena at all levels of organisms from ion channel currents to the foraging patterns of animals to reaction time fluctuations generated by subjects in cognitive science experiments exhibit these recurrent fluctuations. Fluctuations, once tacitly overlooked and excluded as noisy, random outliers, reveal a previously hidden fractal or self-similar order in time that is transforming the way the brain is conceptualized by a growing number of investigators.

Of principal interest are ubiquitous self-similar burst-within-burst patterns, observed in membrane potential fluctuations, neuronal firing patterns, episodes of fetal rapid-eye-movement sleep (REMS), and traffic patterns both on expressways and over computer networks such as the World-Wide-Web (WWW) as well as fMRI images. "Self-similarity" refers to a similarity between patterns of organization at one phase of a system, and the patterns of organization at a different phase of the same system. Burst or clustering patterns are, in fact, familiar to anyone who has driven in or observed highway traffic from a passing airliner. Rush hour traffic slows to a standstill due to the tendency of nearby automobiles to spontaneously cluster, forming super clusters or jams, despite and as a result of the efforts of drivers to find some open road. From the perspective of a passenger in an aircraft, individual vehicles appear to cluster into larger groups, dynamically jumping from cluster to cluster over a larger expanse of roadway. The pervasiveness of self-similar burst-within-burst patterns becomes quickly apparent when commuters arrive at work and find slow access times on the internet. Although the self-organized fractal burst patterns common to both situations appear to be only epiphenomena, they place fundamental constraints on traffic flow.

Biological systems, in sharp contrast, appear to thrive and grow via self-organized fractal burst patterns. These spontaneous, impulsive, apparently random movements common to all embryonic animals during development have long been enigmatic to researchers. Recently, a spontaneous fetal behavior, nuchal atonia, associated with REMS, the predominant *in utero* state, has been shown to contain intrinsic recurrent fractal burst patterns. Developmentally, bouts of spontaneous activity, such as limb movements or the occurrence of Active (REM) Sleep or fetal breathing, exhibit self-similar bursting analogous to traffic patterns and appear to be associated with the development of lungs, motor systems and the maturation of the brainstem and cerebellar vermis. Burst patterns appear to provide a means to synchronize the linkage of movements in the fetus with other neural-motor events such as the ingestion of amniotic fluid, allowing long- and short-range coordination among different emerging behaviors. In fact, as new evidence shows, developmental disorders resulting from maternal separation or *in utero* exposure to drugs of abuse, and autism appear to be associated with chronic alterations in these normally stable bursting patterns and the brain regions supporting this activity.

Bursting patterns over a wide range of temporal periods can be characterized by a small number of relatively simple statistical measures, examples of which are the Hurst, wavelet and Lévy exponents. Hurst's rescaled range analysis and wavelet-based methods provide information about correlations among bursts over all times. On the other hand, the Lévy exponent, alpha, is a measure of the probability distribution of events, specifically the tail or the variance associated with burst events. Concordance among exponents derived from all three methods has been demonstrated for fetal behavior, WWW traffic and fMRI data.

Wavelet analysis is also useful in functional brain imaging. It is widely known that much of the variance in fMRI signals is due to background fluctuations emanating from the subject and not the scanner. Preliminary wavelet analysis of these task-related fMRI fluctuations reveals that brain regions, such as the temporal lobes, brainstem and cerebellum have self-similar patterns of fluctuations over multiple time scales. Self-similar fluctuations may also exist at faster scanning times and higher spatial resolutions. In the following, I will describe how the idea of fractal fluctuations in physical and neural processes is relevant to current theories concerned with the vertical integration of cognitive and emotional processes.

Recently, the variability of neural processes has become a point of concern for cortical physiologists who want to precisely define the characteristics of cortical populations or individual neurons during cognitive tasks. Relationships between the variability of individual neurons and populations of neurons have been found to show much stronger correlations than previously thought; fluctuations of single units are self-similar to the large scale fluctuations of populations. Response fluctuations of single neurons to repeated stimulation are mirrored in population fluctuations, leading some researchers to conclude that the "noise" in ongoing cortical activity is an integral aspect of cortical function. Although the complete meaning of these findings is not yet known, this burst-within-burst characteristic of brain activity is reminiscent of the spontaneous bursting behavior of fetal animals which enhances long and short range neural-motor synchronization during development. Parsimoniously, task-specific self-organization of functional relationships among cortical and subcortical regions in adults observed with wavelet analysis of fMRI may parallel the integrative dynamics of fetal neural-motor development, as well as provide an integrated understanding of the role of REM sleep and meditative practice in emotional-cognitive coherence.

Extensive descriptions of self-similar patterns of behavior at many levels of neural, behavioral, and social organization point to a new foundation upon which theoretical and experimental investigations of brain function can be unified. Clearly, the key question for the 21st century remains how the cognitive neurosciences will, in the words of William James "…steadily look after the irregular phenomena" (fractal fluctuations) and incorporate these comprehensive observations of the spontaneous self-organization of behavior to "…renovate…" the sciences of mind.

Spontaneous irregular patterns of neural activity: noise or signal?

Science often progresses through the cross fertilization of ideas between very different fields of investigation. One example, the concept of "signal to noise ratio", originally developed and used in radar detection, is employed widely in descriptions of activity in the nervous system. This concept is commonly used in cognitive neuroscience to describe, for example, how release of the neurotransmitter norepinephrine in frontal cortex reduces the spontaneous background neural "noise" and enhances detection of "signal" at the cellular level of a network (see for example Posner & Raichle, 1994, pp. 224). Although this use seems appropriate for conceptualizing neural events and linking them to cognitive functions such as attention, it tacitly assumes that the spontaneous background "noise" is a random uncorrelated component of neural activity, much like the hiss of static between radio stations, which can be conveniently ignored in models of function or subtracted away from signal in experimental investigations.

Is this spontaneous background neural "noise" really noise? The famous comparative neuroscientist Theodore Holmes Bullock in his 1977 classic *Introduction to Nervous Systems* doesn't completely neglect or deny a role for neural noise in brain function:

> There are certainly sources of meaningless fluctuation, including threshold fluctuations, the convergence of independent rhythms, spontaneous activity, and other events with good causes but no [apparent] signal value to the system. This is true *noise,* and it may be large or small in proportion to signals; highly structured, or quasirandom. Since it is defined not by its causes or structure, but its lack of meaning or value, it is difficult to identify in any given case. We rarely know the system well enough to be confident of what has no value. Heuristically it is better not to label unexplained activity or fluctuation as noise or uncertainty. Calling it something like "unexplained variation" may encourage the search for both causes and possible significance (Bullock, 1977, p. 236).

That this "unexplained variation" is not restricted to neurons, but could conceivably be an important element in the overall behavior of organisms is implicit in Bullock's words. Kenneth Roeder, a respected insect physiologist, makes this point passionately in his 1955 article "Spontaneous activity and behavior" describing his observations of a variety of insect behaviors strongly associated with spontaneous bursting patterns:

> Many years of teaching neurophysiology along Sherringtonian lines, research on the insect nervous system in which spontaneous nerve activity is practically universal, and the observation of the unpredictability of most animal behavior have led me to seek reconciliation of these apparently contradictory aspects of nerve activity and behavior (Roeder, 1955, p. 362).

Roeder went on to propose that spontaneous neural activity was the major drive for the appetitive, or searching component of insect behavioral patterns, as opposed to the prevailing view of reflex driven behavior.

Recently, through the application of perspectives and methods derived from and inspired by Benoit Mandelbrot's science of the irregular, fractal geometry, the assumption that spontaneous background "noise" in neural activity is orderless and uncorrelated can no longer be categorically accepted as true. In passing, this seems only a minor correction. However, this observation of unrevealed structure in spontaneous background activity has profound implications not only for the interpretation of many of the commonly used experimental methods and statistical procedures in the sciences of the mind, but also for the very way that the biological foundations of consciousness are conceptualized.

Some of the developmental implications are:

- Spontaneous phasic activity associated with REM sleep may vertically integrate fluctuations from ion channels to muscle contractions and therefore, plays a fundamental role synchronizing the developmental linkage between neural and motor systems.
- Just as sensory representations have been found to be more plastic than previously thought, associational loops such as cortical-subcortical-cerebellar pathways may have a more plastic organization when examined from the developmental perspective of vertically integrative spontaneous patterns.
- One function of REM sleep may be to periodically present developmentally invariant fractal patterns to the adult brain, facilitating the consolidation of synaptic and large scale network changes associated with emotional-cognitive learning.

Some of the implications for cognitive neuroscience are:

- Experimental procedures such as BOLD fMRI that incorporate averaging, subtraction and statistical procedures and neurophysiological procedures such as interevent-interval histograms are insensitive to the time structure present in spontaneous neural activity.
- Neural activity and communication occur over a broad spectrum of timescales.
- Spontaneous fractal activity may underlie efficient searching strategies in animal behavior and human cognition.
- Neural-organizational strategies based on spontaneous activity during CNS development, may play a role in the organization of dynamic functional connectivity in the CNS of adults.

Other conceptual and experimental implications are briefly summarized in the following table:

Experimental implications of non-random spontaneous background activity

Random Uncorrelated	**Long-range correlations**
– Noise is Gaussian	– Non-Gaussian
– Noise can be eliminated by averaging	– Average may depend on sample size
– Variance decreases with sample size	– Variance increases with sample size

Conceptual implications of non-random spontaneous background activity

Random Uncorrelated	**Long-range correlations**
– Noise degrades order	– Order arises from noise
– Noise degrades signals	– Noise enhances the signal
– Neural systems are organized to filter out noise	– Neural systems are self-organized by noise

This essay will review fractal concepts and explore the evidence for these surprising implications, as well as present the authors's work on the ontogeny and role of REM sleep during development and the functional imaging of behavioral-state-dependent spontaneous fluctuations. In addition, findings of spontaneous behavior resulting from fractal fluctuations at many levels of neural organization will be reviewed. These diverse spontaneous behaviors appear surprisingly similar, and may vertically sum or converge across levels, creating the functional unity of consciousness.

The recurrent theme of this essay, that order can exist over a multitude of timescales in data that at first glance appears to be only random fluctuations, cannot be fully appreciated in the context of the current scientific paradigm that places greater emphasis on a linear view of brain function in which independent elements can be isolated and dealt with separately. When this linear approach is used in complex interactive situations with long-range correlations (for example, the nervous system), the wider context that lends these fluctuations their unity is obscured. Linear approaches, to remain successful, must be cross-integrated within the context of realistic, "practically universal" naturally noisy or variable behavior.

All melodic music, because it is self-similar with the characteristic way our world changes in time, has a 1/f spectral form (Hsj & Hsj, 1991, pp. 3507–3509). The essential idea common to the wide range of examples given in this essay is that minds, like music, require activity at a multitude of timescales. Only by expanding our point of view to encompass a whole range of timescales in experimental or conceptual investigations of neural behavioral processes, can we more accurately grasp their functional organization and the essential nature of our consciousness.

The fractal renaissance and the sciences of mind

What is unique about the fractal geometry of nature? Why should neurobiology in general and cognitive neuroscience in particular take notice of a new geometric view of the natural world that places emphasis on invariant properties derived from measurements over many scales of time or space?

We are now living in an age of scientific and technological renaissance, which, like the original Renaissance, is a time of accelerated change and advances in many areas of human thought, particularly in the sciences of the mind. Dr. Rhonda Shearer proposed in her 1995 article, *From Flatland To Fractaland — New Geometries In Relationship To Artistic And Scientific Revolution*, that the appearance of new perceptions of geometry, such as the development of perspective during the Renaissance, heralds the appearance of changes in thought and social values, foreshadowing innovations in science and art. *Flatland*, Edwin A. Abbott's 1884 book, referred to in the title of Shearer's work, depicts a two-dimensional world peopled by lines, squares and multi-sided polygons in a rigid hierarchal society with no concept of higher dimensions. When a three-dimensional sphere being appears as a circle in *Flatland*, his very existence plants the perceptual seeds of a scientific and cultural revolution. Shearer credits Abbott with the formal insight later attributed to Thomas Kuhn, author of *The Structure of Scientific Revolutions*, that scientific thinking is linked to the individual's perceptual of conceptual change.

If a new geometric perspective inspires innovative approaches to fundamental scientific questions, then the importance of adopting and incorporating the fractal perspective should not be underestimated. It is the contention of the author that without this well-rounded viewpoint on the spontaneous aspects of brain and behavior at all levels of description the sciences of mind might become trapped in a kind of conceptual and experimental "Flatland."

What is a fractal and why should we be mindful of it?

Benoit Mandelbrot coined the word *fractal* from the Latin adjective *fractus*, infinitive *frangere*, meaning "to break" and create irregular fragments. Mandelbrot happily points out, "It is therefore sensible — and how appropriate for our needs! — that, in addition to 'fragmented' (as in *fraction* or *refraction*), fractus should also mean 'irregular', both meanings being preserved in *fragment*" (Mandelbrot, 1983, p. 4).

The concept is perhaps even more multi-faceted. The World-Wide-Web (WWW) is possibly the best place to see and learn about fractal concepts in general[2], and their applications in biology and psychology[3] or just to educate the eye to the endless possibilities of fractal forms[4].

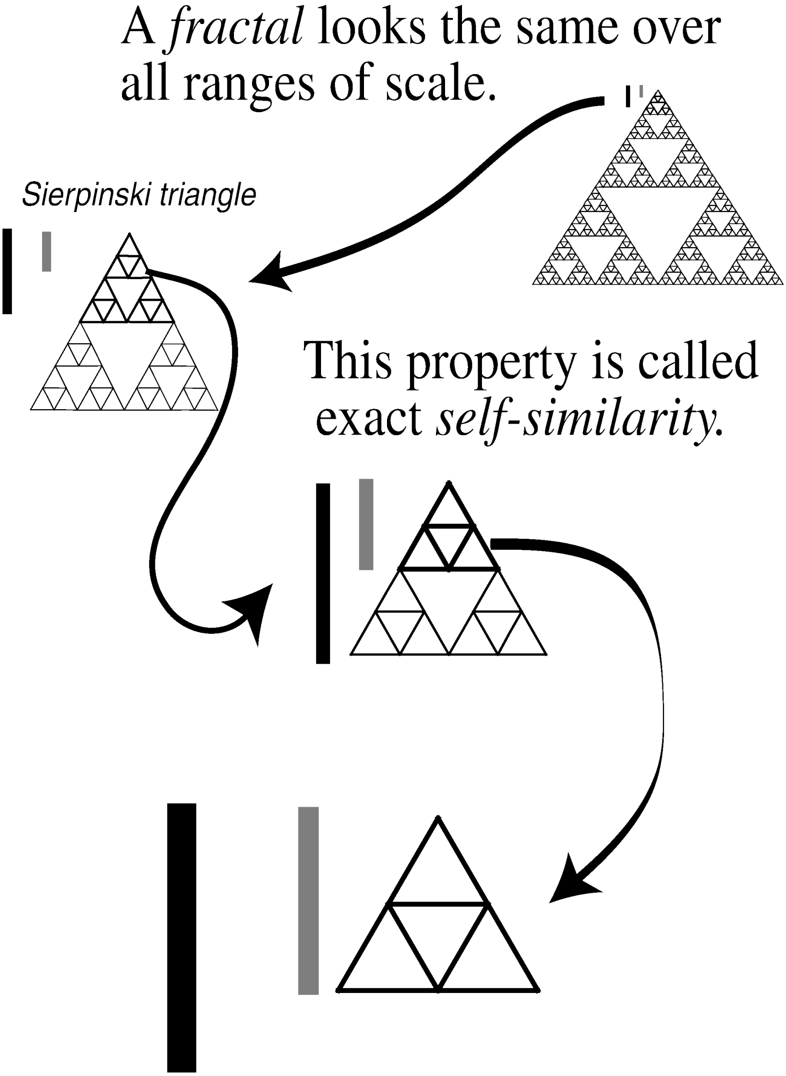
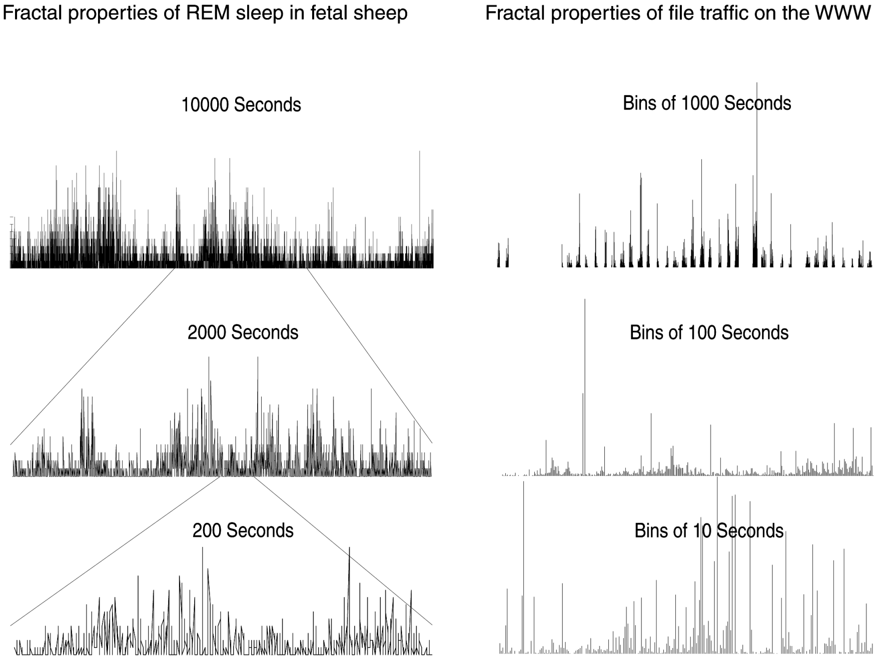


Figure 1. A depiction of geometric exactly self-similar fractal objects. The Sierpinski triangle contains smaller triangles of all sizes (in the infinite limit). The self-similar nesting of infinitely repeated subunits are indicated by the arrows and bars.

The term fractal applies to objects in space or sequences of events in time that possess a form of self-similarity: fragments of the object or sequence can be made to fit to the whole object or sequence by shifting and stretching. Fragments of fractal objects can be exact or statistical copies of the whole. Mathematical fractal objects visually convey the concept of self-similarity (see Figure 1). However, only fragments of mathematical fractal objects can be exact copies, and exactly represent the concept of self-similarity, whereas the fragments of natural fractals are only statistically related to the whole.


Fractal properties of REM sleep in fetal sheep

Fractal properties of file traffic on the WWW

Figure 2. Nuchal EMG activity sampled at 10 Hz and plotted over 1000 seconds on the horizontal axis (top left trace) represents a time series displaying statistical self-similarity. Rescaling time, the horizontal axis, over a 2000 and 200 second subsets of the original series (middle and bottom traces) reveals smaller bursts within larger bursts of muscle discharges. Fractal bursting in internet file traffic (top right trace). Bursts are statistically self-similar over different sampling times (middle and bottom traces) with similar Hurst and Lévy exponents (Crovella and Bestavros, 1996, pp. 161–162) to those observed for nuchal atonia (Anderson et al., 1998, pp. 355).

Another way to think of fractals is in terms of clusters of points or events in space or time. Self-similar clusters have smaller clusters within larger clusters of clusters. Clouds, broccoli, or the surface of the brain can all be visualized as clusters of clusters in space[5]. Phenomena with self-similar clusters in time, such as electronic traffic on the internet, spontaneous activity associated with REM sleep or neural spike trains appear very similar when displayed side-by-side; (compare self-similar clustering in nuchal atonia (Figure 2, left) with postsynaptic miniature endplate currents (see Figure 1; Lowen et al., 1997, pp. 5666)[6] and self-similar clustering in file traffic on the WWW, Figure 2, right[7]).

The repetition of "self-likeness" in recordings of physical or neurobiological phenomena is sometimes described in different ways depending on the degrees of freedom present. In geometric terms, if variation at different scales of measurement occurs along one dimension, such as time, the phenomenon would be called "self-similar." If fluctuations are present over two dimensions, such as time and amplitude, they are termed "self-affine[8]." In this circumstance, the time series is statistically invariant under a transformation that scales the time and amplitude dimensions by different amounts. The nervous system is an especially rich source of examples of fractal processes that can be described as self-affine.

Self-similar clusters in time have unusual statistical ramifications for data. For example, the mean and/or the variance may grow with the sample size, becoming for all practical purposes very large or infinite. Mandelbrot, who first observed these strange statistical properties in price changes, commented: "To anyone with the usual training in statistics, an infinite variance seems at best scary and at worst bizarre" (Mandelbrot, 1983, p. 338). These curious qualities are the result of large intervals or so-called "outliers" among the clusters, which give plots of the distribution of interval times long or heavy tails.

While not Normal or Gaussian, these distributions are related through the stable Lévy model (Shao and Nikias, 1993, pp. 986–1010), which represents a mathematical space of possible distributions mapped by the convergence of mean and variance, sometimes referred to as the "moments" of the distribution (Mantegna, 1991, pp. 232–242). For Gaussian distributions, as the sample size is increased, the mean and variance both converge. While in Lévy space, Gaussian distributions are mapped to an exponent $\alpha = 2$, which is determined by the rate of convergence of the tail of the distribution. Non-Gaussian distributions with a convergent mean, but non-convergent variance have exponents in the range $1 < \alpha < 2$. Distributions such as the Cauchy lack both a convergent mean and variance, and have $0 < \alpha < 1$.

A unique property of distributions that fit the Lévy model[9] is vertical convergence (Mandell, 1980, pp. 175–197; Mandell, 1986, pp. 809–888) or "convolutional stability." Intervals from separate stable distributions like the

Gaussian can be summed into larger stable distributions. Stable distributions are therefore self-similar over different sample sizes. Lévy exponents provide one way to categorize self-similar clusters or bursts that have non-convergent moments. They have also proven useful in understanding the possible origins and roles of spontaneous fluctuations in developmental systems, as well as providing a measure of their pathology.

In the following section, a "cross fertilization" between the concept of vertical convergence from the Lévy model and many observations of self-similar spontaneous fluctuations at different levels of the nervous system provides a "conceptual bridge" linking cellular and behavioral processes.

Multiple levels of spontaneous self-similar patterns in the nervous system: a bridge from molecules to minds

During the last decade, fractal patterns in time have been recurrently observed in spontaneous behavior throughout organisms, including bursting or clustering patterns in ion channel currents, neurotransmitter release, firing patterns in nerves and the cortex, search behaviors in animals and reaction time fluctuations generated by subjects in cognitive science experiments. Fractal behavior in time has the property that behavior observed at one sampling rate, say one millisecond, is statistically self-similar to the fluctuations sampled at a slower sampling rate, say one second. These clustering patterns, described as bursts within bursts, are, as Roder described in 1955, practically universally present in all levels of the nervous systems of insects and animals, as well as in the spontaneous behavior of many organisms.

Fractal ion channel currents

In Roder's time, however, the subcellular domain of ion channels, which Hodgkin and Huxley theoretically connected with nerve excitation in 1952, was largely unexplored. With the development by Erwin Neher and Bert Sakmann of the patch clamp technique in 1976, the behavior of a single ion channel, a cell membrane protein that governs the firing patterns of neurons by regulating the membrane potential, could be studied by observing the fluctuations of ion flow or current which occurs when the channel opens. The Hodgkin and Huxley model, based on what was known about proteins at the time, proposed that fluctuating currents were due to the random assembly and disassembly of rigid channel protein subunits that could only exist in a few states. One implication of the model was that the opening and closing events were not correlated in any way and a sequence of these events would lack any "memory" of or influence from past events. However, this fundamental assumption was questioned due to new and faster recordings of ion channel currents. Channel currents observed at different sampling rates displayed statistically self-similar patterns in time. One of the first researchers to consider and pursue this possibility was Larry Liebovitch[10], who describes his first consideration of the idea:

> At one session of the Biophysical Society meeting in San Francisco in 1989, each speaker reported that the rate of activity of channel openings and closings fluctuates in time, changing suddenly from periods of great activity to periods of little activity. Each speaker interpreted these changes as due to physical changes in the channel protein. However, one of us suddenly realized that this pattern can also be produced by [a] fractal process…That is, if there were bursts within bursts, of openings and closings, then data collected within the upper hierchies of bursts would show very high activity, data collected between the bursts would show very low activity, and data collected at the borders of these hierchies would show sudden changes in the level of activity, even though there was no physical change in the ion channel protein. This fractal description was supported by the qualitative self-similar appearance of the current records… (Bassingthwaighte et al., 1994, pp. 184).

Although the fractal model is still in dispute and awaits the development of new experimental techniques to support or refute its claims, a large body of experimental data and simulations support the model, as well as new findings that the conformational states of proteins exist over a wide range of time scales (Takeda et al., 1999, pp. 1157–1169). A large number of equal energy conformational states provide flexibility, allowing local fluctuations in membrane fluidity, ion species, and influences from the cell's protein skeleton to self-organize the channel structure into open and closed states (Liebovitch & Todorov, 1996, pp. 169–187; Liebovitch & Czegledy, 1991, pp. 145–153). Liebovitch's work promises to provide new insights into elements of the cell that are critical in neurotransmisson.

Fractal neurotransmitter release

The next level of the CNS where self-similar bursting patterns have been observed is at the primary event of neurotransmisson or communcation among neurons or between neurons and other tissues: the synaptic release of neurotransmitters. Steve Lowen[11], of Harvard University, has recently published a major paper (Lowen et al., 1997, pp. 5666–5677) describing the fractal properties of the spontaneous release of "packets" of acetylcholine, a neurotransmitter involved in movement, in a single cultured neuromuscular junction between an embryonic muscle cell and a motor neuron. Fat and Katz in the early 1950's proposed, based on analysis of short recordings, that the release of acetylcholine packets was a memoryless random process, akin to random processes like the radioactive decay of atoms. Because their work is considered one of the cornerstones of modern electrophysiology, and was in accord with views that are commonplace to this day concering the role of random process in biological systems, longer sequences had never been examined. Lowen was able to show that, although the frequency of packet release varied constantly, the variation exhibited memory. If, as in the Hodgkin and Huxley model of ion channels, there was a complete lack of any "memory", fluctuations would average out over long time periods. In fact, Lowen found that release fluctuates in the same way over many time scales, as do fractal bursting patterns in ion channels or the firing patterns of neurons. He has also proposed models based on fractal processes or fractal firing patterns, that can describe how ion channel fluctuations are reflected in the clustering patterns of acetylcholine packets or neuronal firing patterns (Lowen & Teich, 1993, pp. 745–748; Lowen et al., 1999, pp. 5970–5980).

Fractal firing patterns in the spontaneous activity of nerves and cortex

In 1964, Gerstein and Mandelbrot, recording from cortical neurons, found that in some cells the distribution of spike trains (a spike is associated with a neural firing event) were self-similar. As stated by Gerstein and Mandelbrot:

> Thus, incontradiction to our intuitive feelings, increasing the length of available data for such processes does not reduce the irregularity and does not make sample mean or sample variance converge
> (Gerstein and Mandelbrot, 1964, p. 66).

Since this early report, a great wealth of information about the fractal firing patterns of many different types of neurons, particularly those of the auditory nerve and visual system, has been published over the last 15 years by Malvin Teich[12], of Boston University and a colleague of Lowen's.

Many early observations of firing patterns throughout the visual system suggested the presence of long-range correlations; however many of these recordings were brief, and the mean and variances were calculated over short observation windows. In many cases, under Gaussian assumptions, occurrences of high variability were excluded. Teich describes how, in a recent report by Softky and Koch about firing patterns in visual cortex neurons, the investigators state that data segments were selected for "constant firing rate" to suppress nature bursting and variability, which they considered noise (Teich et al., 1996, pp. 79–87).

Teich's work strongly supports the existence of spike train patterns in numerous regions of the CNS which show fractal characteristics over many orders of time just as in neurotransmitter release, or ion channel currents (Teich et al., 1994, pp. 197–202; Teich et al., 1997, pp. 529–546). If self-similar patterns of activity enable vertical convergence of fluctuations over diverse levels of neural organization, how is this adaptive for organisms?

Fractal search behaviors in animals

Spontaneous patterns of animal behavior frequently show the existence of long-range correlations and spatial and temporal clustering patterns. The fruit fly Drosophila exibits episodes of apparently continuous activity that have shorter episodes of inactivity embedded within them; as a consequence there is no natural time scale for the measurement of the level of activity and the level of measured activity depends on the length of time measured (Cole, 1995, pp. 1317–1324; Martin et al., 1999, pp. 73–84). Fractal time variation in activity leads to movement patterns best modeled as fractal random walks or Lévy walks (Montroll & Shlesinger, 1984, pp. 1–121) which are the spatial analog of Lévy distributions (Shlesinger, 1987, pp. 214–228).

For example, a recent analysis of the search patterns of albatrosses, recorded electronically while they foraged in the south Atlantic over a period of three months, demonstrated spatial and temporal fractal organization (Viswanathan et al., 1996, pp. 413–415). The complex patterns observed seemed to allow the birds to efficiently search a large region of open water and were modeled successfully as Lévy walks. In addition, many features of the earth's surface and environment are irregular fractals in space or time. If vertical convergence of self-similar spontaneous activity at cellular and neural levels is a normal functional aspect of the brain which results in efficient searching strategies, it would provide an adaptive advantage to organisms in a world filled with fractal characteristics.

Roder was aware of the connection between spontaneous activity in nerves and in behavior; however he lacked the concept of fractals and the tools to measure and compare fractal patterns:

> The circumstances of spontaneity in nerve elements are strikingly analogous to those of kinesis or appetitive [search] behavior. However, it is very difficult to determine whether or not a causal or homologous relationship exists between these two types of biological activity (Roeder, 1955, p. 368).

I am sensitive to Roder's predicament, having also observed visually the relationship between spontaneous patterns of twitching in baby rats and behavioral state development, yet finding myself unsure scientifically how to explore the connections between these phenomena. In the next section I will describe the methods I was able to apply in order to investigate the relationship between spontaneous activity and the structure of REM sleep in developing animals.

Broad-band-binding in cortex and fractal clustering in REM sleep

As a graduate student at the Center for Complex Systems at Florida Atlantic University, my emphasis was on understanding the dynamics of brain function and its developmental origins. With Steve Bressler and Arnold Mandell, I investigated the spectral characteristics of the cortical EEG during different attentional states in primates, finding fractal patterns of coherence, called 1/f or broadband coherence, during these state (Anderson et al., 1993, pp. 737–740). Inspired by these observations of fractal processes in neurobiology, as well as the sense that this important perspective was neglected, I felt it necessary to attempt an up-to-date overview of the fractal organization of temporal processes in the brain. This attempt resulted in my 1996 chapter with Arnold Mandell, entitled "Fractal Time and the Foundations of Consciousness: Vertical Convergence of 1/f Phenomena from Ion Channels to Behavioral States", which reviewed the widespread prevalence of fractal spontaneous processes in the brain which ultimately shape behavior (Anderson & Mandell, 1996, pp. 75– 126). We proposed, based on theoretical work and experimental data, that this property may enable interactions across levels of neural organization, a kind of broadband as opposed to the now popular "40 Hz" or narrow band binding during attentional tasks which will be discussed later in a section on wavelett fMRI.

In our 1996 chapter, we also proposed a developmental hypothesis concerning the fractal nature of rapid eye movement (REM) sleep over the life-span of a mammal, from fetal to adult life. In order to investigate further this developmental fractal hypothesis of REM sleep, I needed to study the occurrence of this state in fetal and newborn animals. I chose to study nuchal atonia or the loss of nuchal muscular tone in the primary anti-gravity muscles of the neck, which is a key indication of the onset of REM sleep in many animal species. Nuchal atonia becomes apparent when anyone tries to sleep in an airplane seat; as one goes into REM sleep, nuchal atonia occurs and one's head drops, usually waking him or her up. Nuchal atonia can be studied by recording the electromyographic (EMG) activity of the neck muscle, which is much lower during periods of REM sleep. I was able to obtain neck EMG recordings from fetal sheep recorded over the last 13 days of *in utero* life before birth. I also made recordings of neck EMG in baby rats, while they slept in a warm incubator.

This data required a method to detect and measure self-similar clustering patterns allowing comparisons between different data sets. One method, called Hurst analysis, appeared simple to program, robust for small sample sizes, and allowed comparisons across data sets.

Hurst Rescaled Range Analysis, or simply Hurst analysis (Bassingthwaighte et al., 1994, pp. 78–89) was developed by the British hydrologist Harold E. Hurst, during the engineering of the high Aswan dam in the 1950's, to determine from historical records if the yearly flows of the Nile were random or clustered from year to year. Hurst reasoned that if high and low Nile flows were random over successive years (i.e., did not cluster in sequences of high or low years), then the reservoir size estimate could be based on the average of the recorded flows. On the other hand, if years of large Nile flows were not independent, but clustered or demonstrated serial dependency over successive years, then the "memory", or carry over between a series of wet years, could create a situation where reservoir capacity would have to be larger than the estimate based on the mean. Hurst examined 800 years of Nile flows recorded at the Roda gauge and determined they were not random but tended to cluster in runs of high or low years, supporting the need for a larger reservoir. He also examined 837 records of other natural phenomena (for example, annual river levels, rainfall, temperature and pressure records, tree rings, varves, sunspot activity), finding non-random positive correlations in most of them.

Hurst's method provides information about correlations among each burst or cluster event in a time series (see Figure 3)[13]. For collections of events of different sizes, the difference between each event and the average of events is obtained and successively added to a cumulative sum. For example, for a total of 256 events, cumulative sums would be generated for subsets of size 4, 8, 16, 32, 64, 128, and 256 (see bottom of Figure 3). A normalized range is then obtained by taking the difference between the maximum and minimum values that the cumulative sum attains (for each subset), and dividing by the standard deviation of events for each subset. The average normalized range for each

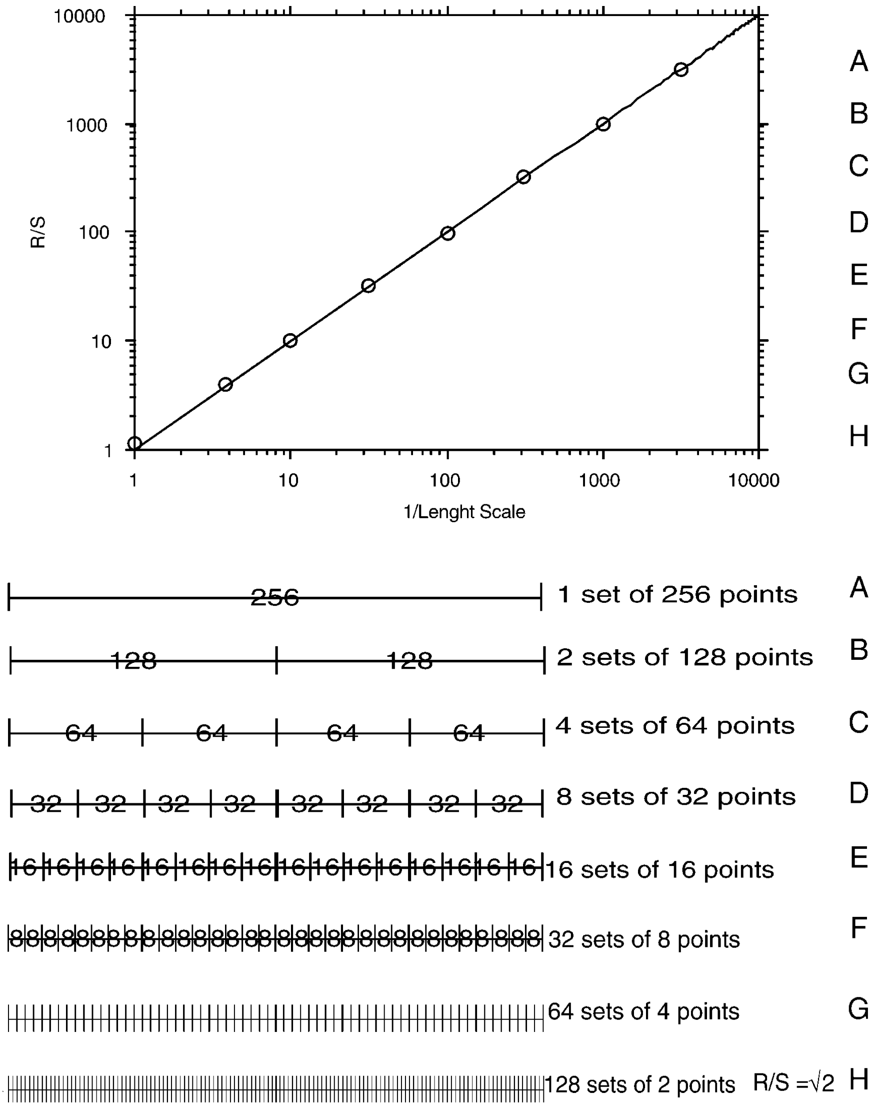


Figure 3. On the bottom, the segmentation of the time series as it occurs in Hurst analysis is represented. The time series is divided sequentially into$1/2^{n}$ blocks. The top figure plots the average Rescaled Range for a collection of blocks at each value of n versus the window size ($1/2^{n}$).

subset is then plotted against the size of the given subset on a log-log axis (seed top of Figure 3), and the slope of the relationship is calculated, yielding the Hurst exponent. When this exponent, called simply "H", is >0.5, positive correlations exist among all events, and self-similar burst within burst patterns abound. The "memory" in the clustering over time is termed "persistence", as in the reoccurrence of high river levels seen in the Mississippi river over the last decade. However, $H = 0.5$ indicates randomness and a lack of correlation between burst events, and no long correlations are seen. Many of the natural phenomena that Hurst examined had values of $H = 0.75$. My own investigations of spontaneous activity in fetal and neonatal animals found that H ranged from 0.70 to 0.80.

Hurst analysis has, over the last six years, been applied more frequently in neuroscience (Bickel, 1999, pp. 251–256; Duarte & Zatsiorsky, 2000, pp. 173–176; Liebovitch et al., 1999, pp. 3312–3319; Liebovitch & Todorov, 1996, pp. 169–187; Selz et al., 1995, pp. 893–904; Treffner & Kelso, 1999, pp. 103–137). Applications of Hurst analysis to internet traffic have been particularly insightful, shedding light on how burst-within-burst patterns arise in complex networks, which may supply ideas for visualizing developmental and cognitive processes self-organized by spontaneous bursting (Crovella & Bestavros, 1996, pp. 160–169).

Fractal traffic clusters on highways and the WWW

At first glance, it might seem strange to be discussing fractal patterns of traffic in an essay on the nervous system. However, these complex meta-systems share some characteristics with the complex systems of brains that construct and constantly interact with them. Traffic systems are complex spatially distributed entities which function over many time scales. Heuristically, an overview of recent descriptions of self-similarity in internet traffic, and attendant models may give useful insights appliable toward understanding the origin and function of fractal bursting in developmental systems.

Would it be possible to use highways and freeways more efficiently by keeping traffic flow in a regime of maximum flow, for example? As it turns out the characteristics of this regime of traffic flow are complex and poorly understood[14]. In fact, work using simplified models of traffic flow indicates that, in situations where the highway is filled with cars, usually on holidays, fractal clusters of traffic jams of all sizes are more likely to occur. When one driver breaks too soon or too late, an avalanche of stops and starts is propagated for great distances over the highway, resulting in long-tailed distributions of and long-range correlations in inter-car-intervals. Traffic tends in general to self-organize into a critical state, where small fluctuations can lead to traffic jams of all sizes. Steps taken to reduce jams, for example mandating automatic car-following systems as in simulations, push traffic closer to the critical point where jams are more likely to occur. Traffic jams could be considered a one-dimensional model of vertical integration, in which all cars are effectively locked in one huge spontaneous fluctuation. Traffic jams in developing brains may lead to the enhancement of synaptic connections, sparing of axons, and synchronizing twitches that allow distant regions of the unconnected organism to link and coordinate gene expression and motor development.

Traffic jams on the internet are more complex, because of their multdimensional nature and rich connectedness, and therefore are more relevant to developing organisms and the brain. Information travels over the internet in the form of packets with a wide range of sizes. As a result the occurrence of bursts is more pronounced, because this form of traffic spans vastly different timescales, from microseconds to seconds and minutes. These bursting patterns show statistical self-similarity and are in some cases very similar to bursting patters from biological systems (see Fig.2, right). The fractal bursting patterns originate in the complex interactions between actions of file transmission, caching systems, user choice, file size distributions, and user “think times.” Recent fractal models of internet traffic have been successful in modeling many of its characteristics, including self-similarity, long-range correlations, and clustering that results in long-tails (Willinger et al., 1997, pp. 71–96). In these models, the superposition or cumulative counting of many packet trains with different short- and long-time characteristics generates self-similar traffic traces, with Lévy stable characteristics.

Recent findings by the cognitive psychologist D.Gilden assert that fractal time variation is a basic element of human judgment and decision making (Gilden et al., 1995, pp. 1837–1839; Gilden, 1997, pp. 296–301) suggesting that the user and his or her fractal processes may supply some of the fractal bursting present in the WWW. Further support for Gilden’s observations come from new models that propose that classical psychophysical laws such as Weber’s come from the accommodation of the perceptuo-motor system to the scale-invariant properties of the physical world (Chater & Brown, 1999, pp. B17–B24). I would propose that scale-invariant fractal bursting in the WWW is a reflection of the fundamental role of scale-invariant fractal bursting to the brain function of users.

Again applying these described conceptual models to developmental processes, we can see spontaneous activity at the cellular level as an avalanche within an ion channel causing it to shift into an open state, this in turn tips the fluctuating membrane potential into an avalanche of depolarization which then may trigger an avalanche of acetylcholine packet release that triggers a muscle contraction experienced as a spontaneous twitch. Like traffic on the WWW, this cascade of avalanches spans vastly different timescales, from microseconds to seconds and minutes.

Another aspect of this conceptual model involves the idea of horizontal integration. Horizontal integration is the coupling of scale-invariant fluctuations at one level of organization in a developing homogenous tissue. The heart may represent an example of horizontal integration, since it has recently been observed that intervals of spontaneous spiking events in the intact heart exhibit similar scale-invariant interspike interval fluctuations as those observed in isolated heart cells. Spiking activity is preserved when the cells are horizontally recouped into a tissue (Soen & Braun, 2000, pp. R2216–R2219).

During embrogenesis, horizontally coupled tissues and networks must reach a critical level of connectivity in order to vertically propagate fluctuations to the next level of developmental organization. An example may be the onset of spatial learning in young rats, which is individually variable, appearing when hippocampal and brainstem monoaminergic pathways have reached a critical density (Wilson et al., 1986, pp. 223–227). Another example that illustrates this important concept is the development of nuchal atonia (Clewlow et al., 1982, pp. 463–476), the marker of REMS. Developmentally, during the early third trimester in fetal sheep, eye movements, nuchal muscle activity, breathing movements, and desynchronized brain electrical activity (EEG) are almost continuous and uncorrelated. This may represent horizontal integration of cellular spontaneous activity without much vertical integration within the brainstem and motor systems of the animal. Nuchal atonia first appears with differentiation of EEG waves into synchronized high voltage slow waves and an increased amplitude of desynchronized waves beginning near the midpoint of the third trimester. At this time, continuous or "tonic" nuchal activity starts to break up into periods of atonia, signifying the emergence of vertical integration among reticulospinal, cerebellar and neural motor connections. This reorganization of continuous nuchal activity into alternating periods of atonia and activity appears analogous in a general way to the emergence of spontaneous electrophysiological responses in early chick muscle (Landmesser & Morris, 1975, pp. 310–326), or coordinated sequences of muscle contractions seen during later spontaneous motility in the maturing embryo (Bekoff & Lau, 1980, pp. 173–175). In addition, from about midpoint of the third trimester on, spontaneous changes in fetal movements (for example, rapid irregular fetal breathing, mouth and tongue, diaphragmatic, and isolated body twitches and generalized bursts of limb movements, changes in tracheal and arterial pressure) become correlated with most of the criteria of REMS in adult sheep. The modeling of systems with bursting patterns over many time scales, such as WWW traffic patterns, may provide general models for neurodevelop-mental processes as well as be helpful in understanding normal ontogeny and developmental disorders such as autism, or the presence of REMS disturbances in posttraumatic stress disorder (PTSD) (Ross et al., 1989, pp. 697–707).

The fractal structure of fetal and neonatal REM sleep

According to some estimates, the mammalian fetus spends as much as 50 to 70 percent of *in utero* life in the state of active sleep also known as REM or paradoxical sleep. Many have hypothesized that this state is fundamental in brain development and that it provides an internal source of stimulation during the self-organization of the developing brain (Blumberg & Lucas, 1996, pp. 1–22). Although the mechanisms by which REM sleep may accomplish this role are for the most part unknown, I have proposed that the correlated bursting nature of REM, or Active sleep as it is sometimes called in the fetus and newborn, provides an invariant stable Lévy temporal framework in which cortical and subcortical networks can organize and consolidate changes. In support of this contention, we have found that the structure of REM sleep is highly correlated and has recurrent fractal structure during the last trimester in fetal sheep, as indicated by Hurst analysis (Anderson, 1995a, pp. 1–217); Anderson, 1995b, pp. 179; Anderson et al., 1998, pp. 351–357)[15]. Also, analysis of the Lévy stable characteristics of nuchal atonia sequences demonstrate distributionally invariant activity. This finding is striking in that it demonstrates that some neural firing patterns associated with REM sleep are not random, as Allan Hobson implies (Hobson, 1988, p. 269). Ironically, my findings support the observations and interpretations of Edward Evarts, who observed almost 35 years ago that the enhanced spontaneous discharges of motor cortex neurons during REM sleep in adult monkeys were similar to stable Lévy distributions (and therefore not the independent random events of a Possion distribution) due to an excess of short and long interspike intervals (Evarts, 1967, pp. 545–556). Evarts, in fact, viewed REM sleep as a way for the brain to reorganize information (Hobson, 1988, p. 166). I propose that stable Lévy processes found during REM sleep may have great significance in understanding how the brain self-organizes, as well as elucidate relationships between REM sleep, neural plasticity, and cognitive-emotional function.

Insights into autism provided by the fractal view of REM sleep

Tanguay, Ornitz, Forsythe and Ritvo at Stanford University in 1976 opened a new window on childhood autism by their observation of the highly variable bursting structure of eye movements (EM) during REM sleep (Tanguay et al., 1976, pp. 275–288). They found that eye movements in normal children on the whole did not become organized into bursts until 40 weeks gestational age; thereafter, changes in the clustering of the bursts of EM were correlated with developmental age. Also, from 2 to 24 weeks postnatal, as total REM decreases, the number of EMs remain constant, resulting in an increase in the mean number of EMs/sec of REM. This recurrent theme in many developmental processes, vertical integration or the coalescence of spontaneous clustering in this neural motor system, was observed in normal children between 3 months and 5 years of age. At this age, a major organizational change occurred in the patterns of EMs, marked by the increasing tendency of bursts of EMs to cluster, with more and shorter EMs packed into bursts within bursts. However, autistic children were found to have substantially less clustering of EMs. In fact, no significant differences between burst structure in 2–5 year old autistics and younger (< 18 month) normal children could be found. If the vertical integration of fractal patterns at different levels of the CNS is a valid concept, then the autistic children seem to display a failure to complete integration at this stage of development. It is as if they are stuck at one level of brain development. The regions of the cerebellar vermis involved in the coordination of eye movements may be poorly developed in autistic children (Schmahmann, 2000, pp. 189–214). Since development of the vermis is associated with the ontogeny of nuchal atonia in the sheep fetus, it may also play a role in the coordination of REM sleep structure in children. If vertical integration among reticulospinal, cerebellar and neural motor connections can be facilitated by external stimulation, then this may explain the usefulness of the intensive physical therapy procedures that have been developed to treat autism. By sustaining long-range correlations in the behavior of the autistic child, vertical fractal clustering may be facilitated. This fractal perspective on autism could provide, via behavioral diagnostic tests and appropriate analysis of correlated clustering, a valuable adjunct to other clinical assessments in this devastating illness.

Fractal insights into developmental stress, tramua and PTSD

In my dissertation work (Anderson, 1995b, pp. 1–217), I compared fractal patterns of nuchal atonia in two species, the sheep and the rat. I found that the properties of nuchal atonia episodes in both species were similar and inconsistent with random processes[16]. One experimental confound of measuring nuchal atonia in baby rats is the introduction of maternal deprivation as a variable into the observations (Anderson, 1991, pp. 1–74). Baby rats are entirely dependent on maternal care, as are human newborns, in contrast to baby sheep, for example, who are born more mature and are soon able to walk. Isolation of baby rats is a severe stressor an alters the development of many brain regions including the cerebellum (Pascual et al., 1999, pp. 171–174). The baby rats I tested were subjected to two hours of maternal deprivation over the course of the procedure, and I noticed visually that their movement patterns seemed changed at the end of recording. I found that when comparing nuchal atonia patterns (across all ages) during the first 5 minutes of testing with the last 5 minutes, maternal deprivation caused an increase in the Hurst exponent from 0.75 to 0.86 and a decrease in the Lévy exponent indicating that their behavior became more clustered in time (Anderson et al., 1996a, pp. 5). This represents a major finding of my work: maternal deprivation, a model of early abuse, results in alterations of the Hurst exponent and the Lévy exponents, shifting distributions from their normal species invariant values. I was able to confirm that these shifts persisted into adulthood when I began my post-doctoral fellowship at McLean Hospital (Anderson et al., 1996b, pp. 687). Mandell and Selz (1997, pp. 67–81) have proposed that neurobiolgical systems conserve a quantity know as dynamical complexity, much as matter and energy are conserved, by altering a relationship between the Hurst exponent and the tail exponent of Lévy distributions. Thus, dynamical complexity may provide a way to measure changes in the convergence of fractal time fluctuations during normal development and in psychopathology (Smotherman et al., 1996, pp. 173–187).

Taken together, the above findings suggest that early stress results in disruptions of vertical integration of fractal patterns. What are the implications of these findings for child abuse drug abuse and PTSD? Recent findings by many researchers, including the author (Anderson, 1998, pp. 5–14[17]), support the contention that stress or abuse in early life induces functional hemispheric asymmetries and disrupts the structure of REM sleep resulting in PTSD, predisposing one to addictive and self-defeating behaviors resulting from the lifelong effects of impaired interhemispheric integration (Schiffer et al., 1995, pp. 169–175; Schiffer et al., 1999, pp. 221–225; Teicher et al., 1997, pp. 160–175). The application of fractal concepts and developmental perspectives will increase our understanding of the specific cognitive and functional nature of these disorders. In the following sections, I will explore recent findings with wavelet based functional MRI techniques that support the behavioral-state-dependence of fractal fluctuations in humans.

Wavelet fMRI: New perspectives on functional networks encompassing the temporal lobes, brainstem and cerebellum during dynamic brain self-organization

As stated in the introduction, it is widely known that much of the variance in fMRI signals is due to background subject-specific fluctuations. In addition, findings of Broad-Band-Binding among cortical regions during an attentional task in primates indicated that the common temporal variability among cortical electrodes had a 1/f power spectrum, indicative of self-similar patterns in time (Anderson et al., 1993, pp. 737–740). These observations suggest that the living brain exists in a state that may be analagous to what are termed critical states or second-order phase transitions in physical systems. The brain during these states could be said to contain coherent fluctuations of neuronal firing (or activated loops or pathways) at all scales woven together, emeshed in small groups of fluctuating neurons embedded in larger fluctuations between nuclei, in a self-similar fashion over the entire brain, and indeed coherent with all cortical and subcortical areas. This is analogous in many ways to dynamical turbulent flows in fluids, which also are self-similar. Could James's "stream" of consciousness be described as having "fractal" properties in time? If this is indeed the case, then the methods of fractal mathematics could be useful in the description of spontaneous fluctuations of the mind and body and how they vertically cohere during different states of consciousness.

Dr. Lowen and I (Anderson et al., 1999a)[18] have visualized spontaneous fractal fluctuations during three different states of consciousness in functional

MRI data by comparing the standard deviation (SD) of a Haar wavelet transform of a voxel time series vs. the wavelet scale (see Figure 4)[19]. A best fit on a log-log plot yields a fractal exponent W related to H obtained by Hurst's rescaled range analysis. W describes the tendency of the voxel time series to follow trends over various time scales. $W = 0.5$ indicates an uncorrelated sequence of signal intensity values; for $W > 0.5$ (persistence) signal trends tend to preserve direction. The SD of each voxel without wavelet transform was also calculated. Wavelet methods, similar to these, have also been used to characterize and model WWW traffic (Riedi et al., 1999, pp. 992–1018).

We observed local clustering of persistent W values ($W > 0.5$) bilaterally in all eye and brain regions under all conditions (see top part of Figure 4). As expected, W values $= 0.5$ dominate regions outside the head, and shuffling of the time series completely destroyed clustering. The emotionally intense condition resulted in more persistent W values for both subjects than did the emotionally neutral; in the second subject primary increases were in the right anterior temporal lobe, consistent with other work demonstrating emotional activation of the right hemisphere (Schiffer et al., 1998, pp. 47–73; Schiffer et al., 1999, pp. 221–225). Suprisingly, relaxation resulted in the most pervasive appearence of persistence in both subjects. Subject 1 reported that he had praticed a form of meditation termed "mindfulness" meditation, in which one attempts to concentrate one's attention on the sensation of the breath entering the nostrals. The movement of the chest or changes in the diaphram could work just as well. The object of this form of meditation is simply to focus one's awareness on sensations of the body.

Our imaging studies demonstrated that fractal fluctuations in brain, which appeared during recall of neutral and emotional memories, became more persistent during "mindfulness" meditation. Fractal fluctuations were also enhanced in the right hemisphere during recall of emotional vs. neutral memories. Therefore, it appears that meditation may promote vertical integration, by way of a self-created feedback loop between sensory flow, motor control and brainstem systems involved in attentional focus.

The process of meditation may enhance fractal-time coherence by bringing present self-awareness in contact with the internal milieu. During the practice of meditation, such as focusing attention and maintaining it on the physical sensation of air entering the nasal passages, many levels of coordination along brainstem and forebrain networks unite.

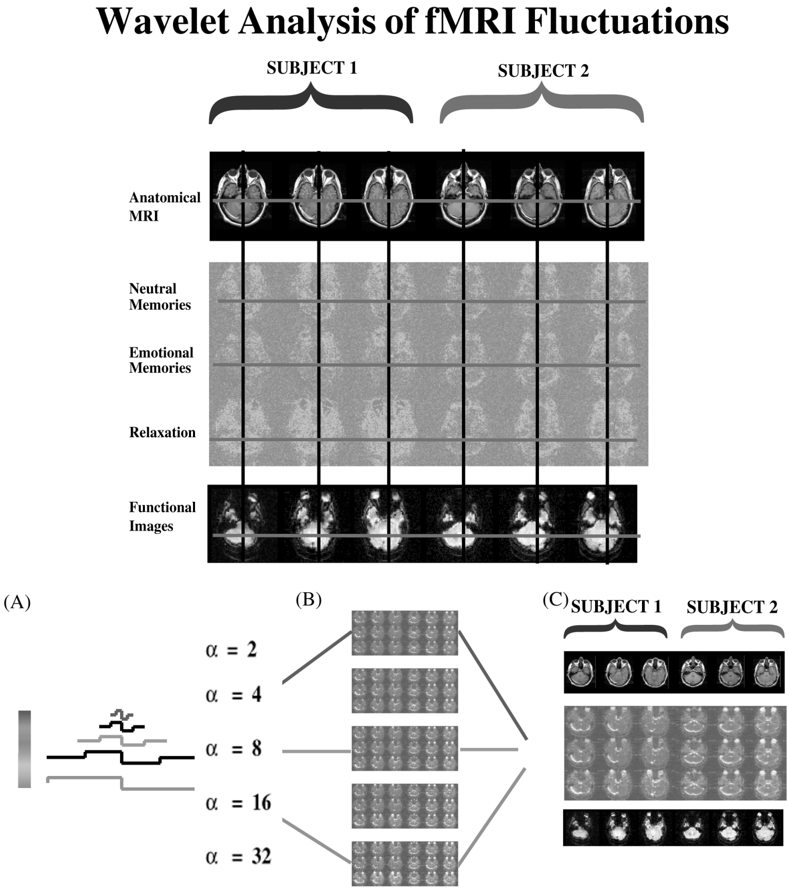


Figure 4. For each of the 3×64×64 voxels, the corresponding voxel time series was extracted from each fMRI data set. This time series was convolved with a Haar wavelet of scale 2, generating a wavelet transform at that scale. The standard deviation of the transform (in contrast to the standard deviation of the original voxel time series) was obtained. The process was repeated for each voxel and for each fMRI data set, resulting in the images A–C. The process was repeated for scales of 2, 4, 8, 16, and 32 (A), yielding five images (B). Images at scales 2, 4, 8, 16, and 32 were combined, to yield the image at far right (C). Finally, the five wavelet transform standard deviations for each voxel time series were fit to a straight line on a log-log plot, yielding a wavelet fractal exponent for each voxel (or each point in the image). The color green (W = 0.5) fills the air around the subjects head. The color red (W = 0.5) intensifies during the recall of emotional memory of during.

Summary

Both wavelet fMRI and EEG findings are concordant with the existence of dynamic spatio-temporal cortical patterns that are difficult to interpret within the current conceptual framework of neuroscience. As with the behavior of ion channels, neurotransmitter release, and neural firing patterns, these observations support the idea that neural function occurs at many time scales, which may provide great flexibility in terms of reorganization and plasticity. The developmental concepts of vertical and horizontal integration of spontaneous fluctuations across levels and time scales could provide new means of conceptualizing dynamic spatio-temporal neural patterns. We can now view the brain as a complex developmental system, much more richly interconnected than the WWW, constantly updating, losing neurons, strengthening synaptic connections under local and global changes in neurotransmitters and hormones, and undergoing behavioral state changes. Wavelet fMRI can provide a unique EEG-like approach to the help visulize this self-organization of functional connectivity associated with the development of cognition and emotional experience.

In this essay I have attempted to present in a diversity of levels of neural function and organization a unified theoretical and experimental fractal based approach to cognition and emotional integration. The larger perspective offered by fractal concepts to the sciences of the mind suggest that it is worth considering, and would, as James said, "renovate [our] science….and when [cognitve neuroscience] is renewed, its new formulas often have more of the voice of the [fractal] exception in them than of what were supposed to be the [absolute] rules."

Notes

* Carl Anderson was supported by special supplement to NIMH grant MH–53636 and a grant from The Center for Consciousness Studies, Univ. of Arizona and the Fetzer Institute.

1. William James from *The Will to Believe*, quoted by Benoit Mandelbrot, in *The Fractal Geometry of Nature*, p. 28.

2. For example see (http://www.math.umass.edu/~mconnors/fractal/fractal.html).

3. For example see (http://www.ccs.fau.edu/~liebovitch/f-1–1.html).

4. For example see (http://spanky.triumf.ca/), and (http://www.industrialstreet.com/chaos/metalink.htm).

5. For example see (http://www.math.umass.edu/~mconnors/fractal/brocco.html).

6. See (http://cordelia.mclean.org:8080/~lowen/jnsci/).

7. See (http://www.cs.bu.edu/~best/res/papers/sigmetrics96.ps).

8. In this essay I will use the terms "self-similar" and "self-affine" interchangeably, for descriptive reasons, although the reader should be aware that these terms are not always interchangeable in other contexts.

9. See (http://math.bu.edu/people/murad) for further information.

10. See (http://www.ccs.fau.edu/~liebovitch) for further information.

11. See (http://cordelia.mclean.org:8080/~lowen) for further information.

12. See (http://people.bu.edu/teich/)) for further information.

13. See (http://www.helbing.org/) for detailed information.

14. See (http://remfractal.mclean.org:8080/BR.article.pdf).

15. See (http://remfractal.mclean.org:8080/phd.html).

16. See (http://www.maps.org/news-letters/v08n1/08105and.html).

17. Behavior analogous to this, but in much more homogeneous substrates, can be found in second order phase transitions between magnetic and non-magnetic states in magnets and liquid or gas phases in water. For the less complicated case of magnets, an application of the concept of self-similarity called renormalization theory allows descriptions of self-similar states of matter. The relationship between different levels of observation in a homogeneous system can be described by a renormalization transformation equation (RTE). Simply, it means that because magnets look the same over different ranges of length, a model magnet can be simplified by reducing the degrees of freedom (number of atoms) by rescaling. A magnet at one scale of measurement can be compared to a magnet at a new scale of measurement, but the temperature (or fluctuations) at one scale may not be the same at the other scale. To have a valid model we must renormalize the temperature from the old scale to the new scale, and this is done with the RTE. A magnet is made up of many smaller atomic magnets that, when lined up in parallel, create a strong magnetic field. When a magnet is heated to a particular temperature, the Curie temperature, it starts to lose its magnetic properties and becomes non-magnetic. This is due to an increase in thermal fluctuations that disorder the parallel order, leading to a loss of long-range order, correlation or coherence over many spatial and temporal scales. At this special temperature the RTE is a constant. A unique situation exits with thermal fluctuations occuring over all ranges in a self-similar fashion creating the same temperature over all ranges. In the language of dynamical systems, when the RTE is a constant, it is a basin boundary or repellor between two states, in this case between low temperature magnetism and high temperature with a loss of magnetism (Peitgen and Richter, 1986, pp.129–146). Temperature is said to be a parameter that moves the system from magnetic before the Curie temperature or critical state, to non-magnetic when long-range interactions breakdown. As it happens, analogous critical states in dynamical turbulent fluid flows, where a continuum of states having multfractal behavior exits, may be even closer to the RF phenomenon (Kadanoff, 1990, pp. 1–14). Simulations of pattern formation during self-organization of ocular domance columns result in critical states displaying 1/f fluctuations (Usher, 1995, pp. 326–329).

18. See (http://remfractal.mclean.org:8080/wave1999.pdf).

19. Methods: Two volunteers, a 37- and a 39-year old male, remained motionless while imaging was performed on a 1.5-T GE Signa system equipped with a whole-body echo planar gradient set and a quadrature head coil. Three sets of 640 images (specialized gradient echo) were collected in three axial planes through the eyes, anterior temporal lobes, and cerebellum (Lobules VI-VII). Images were corrected for frame-to-frame motion with the DART registration algorithm. Before entering the scanner subjects were instructed to 1) recall an emotionally neutral memory, 2) recall an emotionally intense memory, 3) relax (no memory). The second subject reported performing active "mindfulness" meditation during phase 3.

References

Anderson, C.M. (1991). *The development of habituation: noradrenergic modulation of olfactory orienting in infant rats.* Unpublished Masters Thesis, Duke University, Durham.

Anderson, C.M. (1995b). *The fractal time behavior of spontaneous perinatal behaviors associated with rem sleep: a possible ontogenetic adaptation and source of plasticity underlying the emergence of behavioral neophenotypes.* Unpublished Ph.D, Florida Atlantic University, Boca Raton.

Anderson, C.M. (1998). Ibogaine Therapy in Chemical Dependency and Posttraumatic Stress Disorder: A Hypothesis Involving the Fractal Nature of Fetal REM Sleep and Interhemispheric Reintegration. *Multidisciplinary Association For Psychedelic Studies, VIII*(1), 5–17.

Anderson, C.M., Holroyd, T., Bressler, S.L., Nakamura, R., Selz, K.A., & Mandell, A.J. (1993). 1/f-Like spectra in cortical and subcortical brain structures: a possible marker of behavioral state-dependent self-organization. In P.J. Handel & A.L. Chung (Eds.), *Noise in physical systems and 1/f fluctuations* (Vol. 285, pp. 737–740). St. Louis: AIP.

Anderson, C.M., Lowen, S.B., Teicher, M.H., Mass, L.C., & P.F., R. (1999). *State-of-mind-dependent fractal fluctuations in BOLD fMRI.* Paper presented at the Dynamical Neuroscience, Delray, Fl.

Anderson, C.M., & Mandell, A.J. (1996). Fractal time and the foundations of consciousness: vertical convergence of 1/f phenomena from ion channels to behavioral states. In E. Mac Cormac & M.I. Stamenov (Eds.), *Fractals of brain, fractals of mind* (Vol. 7, pp. 75–126). Amsterdam: John Benjamins.

Anderson, C.M., Mandell, A.J., Selz, K.A., & Terry, L.M. (1996a). The fractal time behavior of episodes of inactivity in the nuchal EMG of neonatal rats: Confirmation of the fractal time behavior of nuchal atonia in fetal sheep. *Developmental Psychobiology, 29*(3), 5–5.

Anderson, C.M., Mandell, A.J., Selz, K.A., Terry, L.M., Andersen, S.L., & Teicher, M.H. (1996b). Maternal deprivation alters a REM sleep associated behavior., *Neurosci. Abstr.* (Vol. 22, pp. 687).

Anderson, C.M., Mandell, A.J., Selz, K.A., Terry, L.M., Smotherman, W.P., Robinson, S.R., Wong, C.H., Robertson, S.S., & Nathanielsz, P.W. (1995a). The Fractal Time Behavior of Nuchal Atonia Episodes Associated With Rem-Sleep in Fetal Sheep. *Developmental Psychobiology, 28*(3), 179–179.

Anderson, C.M., Mandell, A.J., Selz, K.A., Terry, L.M., Wong, C.H., Robinson, S.R., Robertson, S.S., & Smotherman, W.P. (1998). The development of nuchal atonia associated with active (REM) sleep in fetal sheep: presence of recurrent fractal organization. *Brain Research, 787*(2), 351–357.

Bassingthwaighte, J.B., Liebovitch, L.S., & West, B.J. (1994). *Fractal physiology.* New York: Oxford University Press.

Bekoff, A., & Lau, B. (1980). Interlimb coordination in 20-day-old rat fetuses. *Journal of Experimental Zoology, 214*(2), 173–175.

Bickel, D.R. (1999). Simple estimation of intermittency in multifractal stochastic processes: biomedical applications. *Physics Letters a, 262*(2–3), 251–256.

Blumberg, M.S., & Lucas, D.E. (1996). A developmental and component analysis of active sleep. *Developmental Psychobiology, 29*(1), 1–22.

Bullock, H.T. (1977). *Introduction to nervous systems.* New York: W.H.Freeman.

Chater, N., & Brown, G.D.A. (1999). Scale-invariance as a unifying psychological principle. *Cognition, 69*(3), B17–B24.

Clewlow, F., Dawes, G.S., Johnston, B.M., & Walker, D.W. (1983). Changes in breathing, electrocortical and muscle activity in unanaesthetized fetal lambs with age. *Journal of Physiology, 341*, 463–476.

Cole, B.J. (1995). Fractal time in animal behaviour: the movement activity of Drosophila. *Animal Behaviour, 50*, 1317–1324.

Crovella, M.E., & Bestavros, A. (1996). *Self-similarity in world wide web traffic: evidence and possible causes.* Paper presented at the ACM SIGMETRICS. International conference on measurement and modeling of computer systems.

Duarte, M., & Zatsiorsky, V.M. (2000). On the fractal properties of natural human standing. *Neuroscience Letters, 283*(3), 173–176.

Evarts, E.V. (1967). Unit activity in sleep and wakefulness. In G.C. Gardner, T. Melnechuk, & F.O. Schmitt (Eds.), *The Neurosciences: A Study Program* (pp. 545–556). New York: Rockefeller University Press.

Gerstein, G.L., & Mandelbrot, B.B. (1964). Random walk models for the spike activity of a single neuron. *Biophysics Journal, 4*, 41–68.

Gilden, D.L. (1997). Fluctuations in the time required for elementary decisions. *Psychological Science, 8*(4), 296–301.

Gilden, D.L., Thornton, T., & Mallon, M.W. (1995). 1/f Noise in Human Cognition. *Science, 267*(5205), 1837–1839.

Heaton, P., Hermelin, B., & Pring, L. (1999). Can children with autistic spectrum disorders perceive affect in music? An experimental investigation. *Psychological Medicine, 29*(6), 1405–1410.

Hobson, J.A. (1988). *The dreaming brain.* New York: Basic Books.

Hsu, K.J., & Hsu, A. (1991). Self-Similarity of the 1/f Noise Called Music. *Proceedings of the National Academy of Sciences of the United States of America, 88*(8), 3507–3509.

Jeong, J.S., Joung, M.K., & Kim, S.Y. (1998). Quantification of emotion by nonlinear analysis of the chaotic dynamics of electroencephalograms during perception of 1/f music. *Biological Cybernetics, 78*(3), 217–225.

Kadanoff, L.P. (1990). Scaling and universality in statistical physics. *Physica A, 163*, 1–14.

Kavanau, J.L. (1999). Adaptations and pathologies linked to dynamic stabilization of neural circuitry. *Neuroscience and Biobehavioral Reviews, 23*(5), 635–648.

Landmesser, L., & Morris, D.G. (1975). The development of functional innervation in the hind limb of the chick embryo. *Journal of Physiology, 249*(2), 301–326.

Liebovitch, L.S., & Czegledy, F.P. (1991). Fractal, chaotic and self-organizing critical system: descriptions of the kinetics of cell membrane ion channels. In E. Mosekilde & L. Mosekilde (Eds.), *Complexity, chaos, and biological evolution* (pp. 145–153). New York: Plenum Press.

Liebovitch, L.S., & Todorov, A.T. (1996). Using fractals and nonlinear dynamics to determine the physical properties of ion channel proteins. *Critical Reviews in Neurobiology, 10*(2), 169–187.

Liebovitch, L.S., Todorov, A.T., Zochowski, M., Scheurle, D., Colgin, L., Wood, M.A., Ellenbogen, K.A., Herre, J.M., & Bernstein, R.C. (1999). Nonlinear properties of cardiac rhythm abnormalities. *Physical Review E, 59*(3), 3312–3319.

Lowen, S.B., Cash, S.S., Poo, M.M., & Teich, M.C. (1997). Quantal neurotransmitter secretion rate exhibits fractal behavior. *Journal of Neuroscience, 17*(15), 5666–5677.

Lowen, S.B., Liebovitch, L.S., & White, J.A. (1999). Fractal ion-channel behavior generates fractal firing patterns in neuronal models. *Physical Review E, 59*(5), 5970–5980.

Lowen, S.B., & Teich, M.C. (1993). Fractal auditory-nerve firing patterns may derive from fractal switching in sensory hair-cell ion channels. In P.H. Handel & A.L. Chung (Eds.), *Noise in physical systems and 1/f fluctuations* (Vol. 285, pp. 745–748). St. Louis: AIP.

Mandelbrot, B.B. (1983). *The fractal geometry of nature.* New York: Freeman.

Mandelbrot, B.B. (1999). *Multifractals and 1/f noise: wild self-affinity in physics (1963–1970).* (Vol. N). New York: Springer-Verlag.

Mandell, A.J. (1980). Vertical integration of levels of brain function through parametric symmetries within self-similar stochastic fields: from brain enzyme polymers to delusion. In H.M. Pinker & W.D.J. Willis (Eds.), *Information processing in the nervous system* (pp. 175–197). New York: Raven Press.

Mandell, A.J. (1986). Toward a neuropsychopharmacology of habituation: a vertical integration. *Mathematical Modelling, 7*, 809–888.

Mandell, A.J., & Selz, K.A. (1993). Brain-Stem Neuronal Noise and Neocortical Resonance. *Journal of Statistical Physics, 70*(1–2), 355–373.

Mandell, A.J., & Selz, K.A. (1997). Entropy conservation as h(T-mu)approximate to(lambda)over- bar(mu)(+)d(mu) in neurobiological dynamical systems. *Chaos, 7*(1), 67–81.

Mantegna, R.N. (1991). Lévy walks and enhanced diffusion in Milan stock exchange. *Physica A, 179*, 232–242.

Martin, J.R., Ernst, R., & Heisenberg, M. (1999). Temporal pattern of locomotor activity in Drosophila melanogaster. *Journal of Comparative Physiology A Sensory Neural & Behavioral Physiology, 184*(1), 73–84.

Montroll, E.W., & Shlesinger, M.F. (1984). The wonderful world of random walks. In L.J.L. & E.W. Montroll (Eds.), *Nonequilibrium Phenomena: From Stochastics to Hydrodynamics* (pp. 1–121). Amsterdam: North-Holland.

Pascual, R., Verdu, E., Valero, A., & Navarro, X. (1999). Early social isolation decreases the expression of calbindin D-28k in rat cerebellar Purkinje cells. *Neuroscience Letters, 272*(3), 171–174.

Peitgen, H. O., & Richter, P. H. (1986). *The beauty of fractals.* Berlin: Springer-Verlag.

Posner, M. I., & Raichle, M. E. (1994). *Images of mind.* New York: W. H.Freeman.

Riedi, R. H., Crouse, M. S., Ribeiro, V. J., & Baraniuk, R. G. (1999). A multifractal wavelet model with application to network traffic. *IEEE Transactions On Information Theory, 45*(3), 992–1018.

Roeder, K. D. (1955). Spontaneous activity and behavior. *Scientific Monthly, 80*, 362–370.

Ross, R. J., Ball, W. A., Sullivan, K. A., & Caroff, S. N. (1989). Sleep disturbance as the hallmark of posttraumatic stress disorder [see comments]. *American Journal of Psychiatry, 146*(6), 697–707.

Schiffer, F. (1997). Affect changes observed with right versus left lateral visual field stimulation in psychotherapy patients: possible physiological, psychological and therapeutic implications. *Comp Psychiatry*, 1–8.

Schiffer, F. (1998). *Of two minds: The revolutionary science of dual-brain psychology.* New York: The Free Press.

Schiffer, F., Teicher, M. H., & Papanicolaou, A. C. (1995). Evoked potential evidence for right brain activity during the recall of traumatic memories. *Journal of Neuropsychiatry and Clinical Neurosciences, 7*, 169–175.

Schmahmann, J. D. (2000). The role of the cerebellum in affect and psychosis. *Journal of Neurolinguistics, 13*(2–3), 189–214.

Selz, K. A., Mandell, A. J., Anderson, C. M., Smotherman, W. P., & Teicher, M. H. (1995). Distributions of local Mandelbrot-Hurst exponents: Motor activity in fetal rats of cocainized mothers and manic-depressive patients. *Fractals-an Interdisciplinary Journal On the Complex Geometry of Nature, 3*(4), 893–904.

Shao, M., & Nikias, C. I. (1993). Signal processing with fractional lower order moments: stable processes and their applications. *Proc. IEEE, 81*, 986–1010.

Shearer, R. R. (1995). From Flatland To Fractaland — New Geometries In Relationship To Artistic And Scientific Revolution. *Fractals — An Interdisciplinary Journal on the Complex Geometry of Nature, 3*(3), 617–625.

Shlesinger, M. F. (1987). Fractal time and 1/f noise in complex systems. *Ann. N. Y. Acad. Sci., 504*, 214–228.

Smotherman, W. P., Selz, K. A., & Mandell, A. J. (1996). Dynamical entropy is conserved during cocaine-induced changes in fetal rat motor patterns. *Psychoneuroendocrinology, 21*(2), 173–187.

Soen, Y., & Braun, F. (2000). Scale-invariant fluctuations at different levels of organization in developing heart cell networks. *Physical Review E, 61*(3), R2216–R2219.

Takeda, T., Sakata, A., & Matsuoka, T. (1999). Fractal dimensions in the occurrence of miniature end-plate potential in a vertebrate neuromuscular junction. *Progress in Neuro-Psychopharmacology & Biological Psychiatry, 23*(6), 1157–1169.

Tanguay, P. E., Ornitz, E. M., Forsythe, A. B., & Ritvo, E. R. (1976). Rapid eye movement (REM) activity in normal and autistic children during REM sleep. *Journal of Autism & Childhood Schizophrenia, 6*(3), 275–288.

Teich, M. C., Heneghan, C., Lowen, S. B., Ozaki, T., & Kaplan, E. (1997). Fractal character of the neural spike train in the visual system of the cat. *Journal of the Optical Society of America a-Optics Image Science and Vision, 14*(3), 529–546.

Teich, M. C., & Lowen, S. B. (1994). Fractal Patterns in Auditory Nerve-Spike Trains. *IEEE Engineering in Medicine and Biology Magazine, 13*(2), 197–202.

Teich, M. C., Turcott, R. G., & Siegel, R. M. (1996). Temporal correlation in cat striate-cortex neural spike trains. *IEEE Engineering in Medicine and Biology Magazine, 15*(5), 79–87.

Teicher, M. H., Ito, Y., Glod, C. A., Andersen, S. L., & et-al. (1997). Preliminary evidence for abnormal cortical development in physically and sexually abused children using EEG coherence and MRI. In R. Yehuda, A. C. McFarlane, & et-al (Eds.), *Psychobiology of posttraumatic stress disorder* (Vol. 821, pp. 160–175). New York: New York academy of science.

Treffner, P. J., & Kelso, J. A. S. (1999). Dynamic encounters: Long memory during functional stabilization. *Ecological Psychology, 11*(2), 103–137.

Usher, M., Stemmler, M., & Olami, Z. (1995). Dynamic Pattern-Formation Leads to 1/f Noise in Neural Populations. *Physical Review Letters, 74*(2), 326–329.

Viswanathan, G. M., Afanasyev, V., Buldyrev, S. V., Murphy, E. J., Prince, P. A., & Stanley, H. E. (1996). Levy flight search patterns of wandering albatrosses. *Nature, 381*(6581), 413–415.

Willinger, W., Taqqu, M. S., Sherman, R., & Wilson, D. V. (1997). Self-similarity through high-variability: statistical analysis of Ethernet LAN traffic at the source level. *IEEE/ACM Transactions on Networking, 5*, 71–96.

Wilson, D. A., Willner, J., Kurz, E. M., & Nadel, L. (1986). Early handling increases hippocampal long-term potentiation in young rats. *Behavioural Brain Research, 21*(3), 223–227.

Author's address

Carl M. Anderson, Ph.D
Department of Psychiatry, Harvard Medical School, and the Developmental Biopsychiatry Research Program and Brain Imaging Center
McLean Hospital, Belmont, MA 02178