ADVANCES IN CONSCIOUSNESS RESEARCH



Fractals of brain, fractals of mind

Edited by Earl Mac Cormac

& Maxim I. Stamenov

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FRACTALS OF BRAIN, FRACTALS OF MIND

ADVANCES IN CONSCIOUSNESS RESEARCH

ADVANCES IN CONSCIOUSNESS RESEARCH provides a forum for scholars from different scientific disciplines and fields of knowledge who study consciousness in its multifaceted aspects. Thus the Series will include (but not be limited to) the various areas of cognitive science, including cognitive psychology, linguistics, brain science and philosophy. The orientation of the Series is toward developing new interdisciplinary and integrative approaches for the investigation, description and theory of consciousness, as well as the practical consequences of this research for the individual and society.

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Volume 7

Earl Mac Cormac and Maxim I. Stamenov (eds)

Fractals of Brain, Fractals of Mind
In search of a symmetry bond

FRACTALS OF BRAIN, FRACTALS OF MIND

IN SEARCH OF A SYMMETRY BOND

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Preface

Leibniz believed that most of the world's problems could be solved by mathematical calculations. We have captured and continued that intuition in our presumption that fractals can play a major role in explaining neuronal processes that generate mental activity: hence the title of this volume, *Fractals of Brain, Fractals of Mind*. The self-organizing activity of neurons reacting to the external world through perceptions and actions produces fractal and fractal-like patterns, many of which are symmetrical. Our investigations and those of the authors of the chapters in this volume have not progressed far enough to allow us either to claim necessity for symmetry in these relationships because we do not yet comprehend how symmetry operates in these fractal-like patterns. Again, our intuitions suggest that it probably occupies a necessary role in this self-organizing behavior. Only in the future will this and other questions be answered.

Conversations for this volume began when the editors first met in Berkeley after a year of correspondence. Since then, the discussions have continued and resulted in visits not only between the editors but also between their families. Having not only the editors but also the authors located in several different continents has given this project an extremely interesting and pleasant intercultural aspect. With one editor located in Bulgaria and the other in the United States, except for visits, most of the contact has been by electronic mail and we must express our gratitude to the electronic age which makes this possible. Similarly, we could have never operated as smoothly with our widespread authors without this technological advantage. Individuals, however, operate the machines whether they be e-mail, fax, or computer and we must express our appreciation to several without whom this volume might have never been published. In the United States, Bonita Kuki, secretary to the PET facility of the Duke University Medical Center provided the backbone of organization, typed sections and coordinated the dispatch and revision of chapters. Thomas Hawk, Associate in Research of the PET facility assisted in the production of a number of figures. In Bulgaria, Kiril Simov, a computer scientist at the Linguistic Modeling Laboratory (Bulgarian Academy of Sciences), helped with

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Finally, we express our appreciation to our families, especially our wives, Nancy H. Mac Cormac and Reneta Kileva-Stamenova, for their support and patience during the production of this book. It is to Nancy and Reneta that we dedicate this volume.

Introduction

1. Facing the problem

A leading exponent of nonlinear (chaotic) brain dynamics paradigm summarized recently the current research situation as follows:

> It is still unproven mathematically and experimentally whether chaos does or does not exist in the brain, and if does, whether it is merely an unavoidable side effect of complexity that brains have learned to live with, or is essential for the formation of new patterns of neural activity in learning by trial and error. Our present results suggest that indeed it is essential, but we are far from having proven that or made use of this insight. (Freeman 1992:480)

This is rather an unexpected move, especially for a tutorial, because the work of Walter Freeman and his associates from Berkeley (cf. e.g., Skarda & Freeman 1987) was and is cited as an experimental evidence for the existence and functionality of chaos in brain performance. King (this volume), Anderson & Mandell (this volume), Mac Cormac (this volume), and Alexander & Globus (this volume) cite and comment on the results of Freeman and his group as an evidence for the functionality of chaos in brain processing of information. In other words, we start to detect potential troubles for the possibility of realizing the program to prove mathematically and experimentally the functionality of nonlinearities and chaos in the brain operation. Perhaps those troubles are associated with different views of what it would mean 'to prove mathematically and experimentally' the functionality of some process in the brain?

We must be also aware of a further complication. Even if we prove the existence and the functionality of some chaotic regimes in brain performance, this means exactly what was said and nothing more. That there is some place for chaotic processing of information by the brain, does not automatically mean that chaos matters for the formation of mind. We can maintain that chaotic patterns can and do appear in the brain, but they remain 'brute neurophysiological facts' (*pace* Searle 1992). If we ascribe functional

significance to brain chaos in the emergence and performance of mind, the situation becomes further aggravated with all the vicissitudes of the mind/brain problem, because we must also show how chaos becomes accessible to experience in mind, i.e., where to look for the imprints of chaos in what we see, hear, and think about.

The requirement put by Searle, that a structure of process is mind if and only if it is in principle accessible to experience — the so called Connection Principle — is much more troublesome than it was acknowledged in the peer discussion of Searle (1990). This becomes more and more evident, when we make an attempt to discuss a topic like the one we are currently facing: What it would mean to prove experimentally the functionality of some brain process for some mind process. The mind process Freeman was interested in was learning, but not simply to display with experimental data that there are some nonlinear processes in the brain *per se*.[1]

Facing a situation like this, many, perhaps the great majority, of the scholars in cognitive sciences would prefer to shy away from nonlinear dynamics, chaos, and fractals leaving this *terra nova* to remain a battlefield for mathematicians and physicists. It is to the credit of the authors contributing to the present volume that they speak not simply about the implementation of chaotic dynamics and fractal geometry in the brain, but also about the possible functional place of the latter in what we experience as our mind processes and representations.

The editors feel it necessary to explain the rationale for a project like the one we present here, its place in the context of the development of cognitive sciences. We think that this project is a logical outcome of convergence of several different directions of research having as their aim:

(a) the development of formal models of brain and mind processes;
(b) of brain research; and
(c) the research in different branches of psychology.

Our point will be that a venture like ours was a necessity from at least three main perspectives in the studies of brain/mind. The views in this Introduction, however, are those of the editors and they are not necessarily shared by the other contributors to the project.

2. The trouble with computation

Concepts like 'computation' and 'information processing' are notoriously troublesome if at all possible to define and we will not make such an attempt (cf. e.g., Smith 1995 for up-to-the-date assessment). We will simply start with

the remark that the possibility of giving formal characterization to some mental and neural processes in 'implementation neutral terms' was one of the most fascinating ideas around in the cognitive sciences in the last 25 years. In simplistic terms, the idea was put forward that the characterization of the nature of *representation* is fundamental to answering how it is that we can see or solve the problem, whether the problem is considered in psychological or neurological terms. The same is true for *processes* operating on representations — the computations (cf. Churchland 1986:9).

A further belief was expressed that cognition is a species of computation. Any mental representation consists of a limited set of discrete atomic symbols with some semantic and syntactic relationships between them. According to Pylyshyn (1984:51), the notion of a discrete atomic symbol is the basis of all formal understanding and of all systems of thought and calculation, for which a notation is available. Computation is a rule-governed process; so is cognition, too (Pylyshyn 1984:57). The computation can be enacted both on the computer and in the brain, independently of the differences in the physical implementation in each particular case. We can give a computational characterization of mind independently of its implementation in the brain — this was one consequence of the acceptance of this idea. Another popular opinion, quite paradoxically, is that if both computers and brains can implement mind, they also are from some points of view comparable devices. And why? Because they both compute, or process information. (For a critique of this idea in relation to the brain, cf. Globus 1995.)

The idea of a computational (and implementation-neutral) interface between mind and brain was succinctly expressed by Jackendoff (1987) who put it further to use explicitly in the context of consciousness studies. It is curious to acknowledge that while the computational metaphor of mind found many followers in cognitive sciences, there was no significant application of the latter metaphor to the nature of consciousness itself. Jackendoff (1987:25-27) himself dismissed consciousness as epiphenomenal from a computational point of view.[2]

All the basic ideas associated with computer and computational metaphor in the case of brain/mind functioning were step by step questioned (after being initially proposed with aforementioned enthusiasm). The notion that cognition as a computation of symbol manipulation type was questioned, for example, in the neural nets paradigm: While the cognitive computation is symbolic (or conceptual), it was maintained, the neuronal computation is of different type. The individual neurons do not transmit large amounts of symbolic information. They compute instead by being appropriately connected

by large numbers of similar units (Feldman & Ballard 1982:208; cited from Churchland 1986:461).

A step forward in the development of the idea of the applicability to mind and brain of the idea of (symbolic vs. subsymbolic) computation was made by Smolensky (1988). He explicitly expressed the thought that the connectionist models (= the massively parallel numerical computational systems that are a kind of continuous dynamical system) promise to offer "the most significant progress of the past several millennia on the mind/body problem" (Smolensky 1988:3). He distinguished between symbolic vs. subsymbolic paradigms of cognitive description. Each paradigm has a preferred level of description — the conceptual vs. subconceptual processing with different information-processing capacities. Without going into the details of this proposal, one of the points he made is that the symbolic computations are accessible to consciousness and are executed serially; the subsymbolic ones are executed in massively parallel way and only the cumulated outcome of their functioning on a relatively large time-scale can have access to consciousness (i.e., the outcome starts somehow to 'symbolize' the lower-level collective functioning and interaction of many subsymbolic units of information processing) (cf. Smolensky 1988:13). A single discrete operation in symbolic paradigm is achieved in the subsymbolic paradigm as a result of a large number of much finer-grained (numerical) operations.

In the mind the top-level conscious processor is the one that runs the conceptual cultural knowledge. The mind processing achieved below this top level and without access to consciousness is called by Smolensky (1988:5) the intuitive processor. Conceptual-level description of the intuitive processor's performance, unlike the subconceptual one(s), will be:

(a) incomplete, i.e., describing only certain aspects of the processing; or
(b) informal, i.e., describing complex behaviors in, say, qualitative terms; or
(c) imprecise, i.e., describing the performance up to certain approximations or idealizations such as 'competence' idealizations away from actual performance (cf. Smolensky 1988:7).

The complete formal account of cognition does not lie at the conceptual, but at the subconceptual level. Here we will leave aside the problem, can we at all talk and if yes in what sense, about 'cognitive representations on subconceptual level' or about 'representations over neurons in the brain' (cf. Smolensky 1988:8). We will simply pay attention to the statement that a description of cognition as a quasilinear dynamical system will give complete, formal and precise description of cognitive processing of information, unlike the one describing the processing at the conceptual level. In the future, Smolensky

(1988:9) claims that the best models from the subsymbolic paradigm will offer a modeling on subconceptual level of information processing, a reasonable higher-level approximation to the neural system processing supporting them. In this way we will, hopefully, come closer and closer to the actual implementation of mind in the brain (although connectionist modeling was and is a higher-order modeling, compared to a modeling pretending to do that for a real neural system implementing a thought process). The scale from completeness, precision and formal rigor to higher and higher incompleteness, imprecision and informality is given, presumably, in the following hierarchy by Smolensky (1988:10):

(a) neural level →
(b) subconceptual level processing which runs at a connectionist computer →
(c) conceptual level of description of the way of functioning of a connectionist computer by using patterns (or conscious rules) of activity that have conceptual semantics →
(d) conceptual level of description as applied to an intuitive processing in connectionist machine, which can give us only an approximation to the actual subconceptual processes.

We are left with a complicated hierarchy of the ways by which we are supposed to *describe* cognition as implemented in conscious mind, unconscious mind and in the brain. The description becomes most formal, precise and complete, when we get to the *level* of the concrete brain implementation of the corresponding mental process or state. This would be the logical consequence of the position of Smolensky. Although he was critical of some aspects of the Marr's (1982) levels differentiation into computational/ algorithmic/ implementational analysis (Smolensky 1988:65), his own hierarchy of levels amounts to a similar ternary structure consisting of conceptual/ subconceptual/ neural levels. This continues to be the case even if we accept the possibility of many subconceptual sublevels between concepts and their brain implementation (*ibid.*). But let us not forget that there are currently seemingly insuperable difficulties in locating and discretizing the mind state and the mind's brain site in catching the 'real' dynamics (according to Smolensky himself; cf. above). So the latter possibility could be considered to be a part of the belief system of the corresponding scientist.

Smolensky (1988) was among the first scholars in cognitive sciences who seriously and in an systematic way considered the possibility for cognitive processes to be implemented by nonlinear dynamical systems. He explicitly pointed out that the most interesting connectionist systems are nonlinear. He also maintained that cognitive categories can be modeled as attractors in

connectionist dynamical systems (Smolensky 1988:20-21). Unlike Smolensky (1988), however, some of the contributors to this volume maintain that the outcome of the functioning of the massively parallel computations in brain/mind are at least sometimes directly accessible to consciousness.

Another troublesome aspect of the theory of Smolensky (1988) is his treatment of symbol/concept/subconcept and their mutual relationships. According to Smolensky, subsymbols (subconcepts) participate in numerical, but not symbolic computations:

> Operations that consist of a single discrete operation (e.g. a memory fetch) are often achieved in the subsymbolic paradigm as the result of a large number of much finer-grained (numerical) operations. (Smolensky 1988:3).

By 'symbolic' here, apparently he means the manipulations of formal logic. We believe that Smolensky's 'numerical' computations are inaccessible to consciousness, as we do not experience numerical values, but concepts and qualia (cf. Stubenberg 1996 for an extensive up-to-the-date treatment of the latter concept). Furthermore, that seems to be the case because Smolensky (1988:13) explicitly notes that the contents of consciousness reflect only large-scale structure of activity patterns, which are extended over spatially large regions of the 'network' and which are stable for relatively long periods of time. Actually, in our opinion, the outcome of the nonlinear performance of the brain with its 'numerical values' can yield effortless access to consciousness directly in the form of fractal-like patterns (if we take care to direct our attention to them; cf. below).

A next step (logically, not chronologically) in the reconsideration of the way the computations are implemented and function in the brain/mind was undertaken by Walter Freeman and his associates. The position of this group was most succinctly represented in their 1987 publication (cf. Skarda & Freeman 1987). There they identified some nonlinear patterns in the olfactory bulb in the brains of rabbits as the equivalents of the mind performance in recognizing different odors. New odors could be learned if and only if the latter could have *functional value* for the animal in coping with the requirements of the objective world. The basic functional value of deterministic chaos as a self-organizing feature of the brain dynamics is in the capacity to support learning to recognize new stimuli independently from the set of already available as recognizable smells (in other words, unlike the structuralist tenet about the dependence of the new differentiation from the set of previously made ones). The change in the set of recognizable odors is caused by the functional value of the new smell; the new stimulus is not dependent for its differentiation from the

set of the previously made differentiations. In this way Freeman and his associates evidently wanted to break the spell of the vicious circle that for mind to manage to differentiate something in the environment it must already be capable of differentiating it. From the latter circle a ready-made exit was to cling to 'universal ideas', 'universal grammar' and the like (in the case of the studies of the cognitive capacities of humans). Freeman showed a way out from this blind alley in the way the brain actually performs.

What remained unclear, though, was, how, if at all, brain chaos might emerge as accessible to experience. Otherwise the whole experimental proof might be dismissed due to the force of the logical argument of the Connection Principle of Searle (1992): That something is functional for the performance of the brain does not necessarily mean that it is also functional for mind formation. There are certainly a lot of things going on in the brain of which we cannot in principle become aware. If we cannot point out experiential correlates to those brain computations we posit as possibly mind-implementing, we will never be completely confident that those brain states are the causally efficient ones in implementing mind state. The problem is to close the gap between the correlated computational descriptions, as imputedly implementing brain vs. mind, up to the level of their interface, i.e., coincidence.

What is this type of formalism that can implement BOTH brain and mind? Our own opinion is that the nonlinear dynamic systems implementation of mind is a massively parallel brain-implemented computational system the numerical variables of which formally correspond to fine-grained fractal-like features directly accessible, for example, in consciously experienced perception (but not only in the latter). Stamenov (in this volume) point out, in this respect, that the outcome of the mental processing is accessible to experience in some aspects of the formal specification of the perceptual representation. It is represented 'directly', i.e., there are no differences, in this respect, between 'symbolic (or conceptual)' and 'subsymbolic (or subconceptual)' operations. The difference between them lies, first and foremost, in the incapacity to repeat within the 'time window' of conscious mental processing of the highly parallel and high-speed iterative computational processes leading in brain functioning to the experience of textured 'perceptually dense' mental images (for opposite opinion cf. Leyton 1992).

A computational description of some processes in both brain and mind is possible, in our judgment, where they perform as not-two, i.e., one and the same formal specification could be given for both the process in the brain and in the mind. The danger here would be to say that they are identical, but we will try to avoid such a strong commitment and would prefer to speak about the

'secret symmetry' between the patterns in brain and mind making the two indistinguishable from formal point of view. From this perspective, fractal or fractal-like patterns could function as a formal (computational) interface between brain and mind. They would be mind to the degree they are accessible to experience (they can be seen as projected onto the real objects as the fine texture of visual images, for example). They are brain to the degree it is possible to prove some fractal-like computations in its functioning with the assistance of contemporary technologies of brain research (this is a tenet explicitly maintained by several contributors to this volume, e.g., Alexander & Globus; Anderson & Mandell; Mac Cormac; Gregson).

The reader might accuse us, and rightly so, of using 'computational' in some very vague way. What a type of 'computation' might be at issue, when we have no symbols, no discrete logical operations with those symbols, and no idea how those operations might be implemented on a computer. On the other hand, however, one may hear on many occasions that before the advent of computers it was practically impossible to do research on fractal geometry (cf. Mandelbrot 1983). The way to come out of this paradox is to consider that the computer can help us to approximate many features of the nonlinearity in action which beforehand was impossible to model as it is impossible to imagine them in real time (as a process in action) by the human mind.

But even this didn't end the troubles of computationalism. With the advent of the research on the nonlinear dynamical systems it seems that we 'finally' have a formal key to the way the brain/mind performs. This was due to the application of the cognitive strategy 'explain obscure (= brain functioning) with even more obscure (nonlinear dynamic systems)'. As a matter of fact, today we witness the first stage of the development of the sciences of complexity, the studies in nonlinear dynamics included.

The expectation first was that brain/mind might, well, perform according to simple or even very simple formal rules iterated many times during the processing of the information. Here the plausibility of the concept of the deterministic chaos was introduced. In the most simplistic terms, the deterministic chaos is determined by the incapacity to predict the final outcome of the development of some dynamical pattern because of its 'sensitive dependence on the initial conditions' even if the computational procedure applied to the input is strictly deterministic and quite nonproblematic to formulate by formal means. In other words, the procedure is uniform, remains self-same throughout millions of iterations (for more detailed exposition and literature cf. Van Eenwyk, this volume; Vandervert, this volume).

Recently Penrose (1994a, 1994b) challenged this last refuge of computationalism — the possibility to formulate a set of uniform rules or procedures of evolution of the brain/mind system. He explicitly pointed out that by non-computability he does not glimpse at the processes and states of the so called deterministic chaos where a very tiny change in the initial stage can produce a large change in the final state. With an appropriate example (cf. Penrose 1994b:244-245), he displays the mathematical possibility of the existence of non-uniform computational procedures. The patterns of the evolution of the system are non-periodic, i.e., never repeat under certain conditions. For any procedure one lays down, e.g., for tiling the toy universe Penrose gives as an example of, there is always some other set which gets outside of that procedure. This is the meaning in which the system (or toy universe, or possible world) is not computable (cf. Penrose 1994b:244). The system in question can always get outside any previously given set of patterning, processing information, etc.

Penrose makes a further strong claim, that the capacity to get outside any previously achieved limit or set of rules is a feature not of brain, or of mind, but of conscious mind/brain. This aspect or feature of consciousness is due to some unknown yet principles of reality on the physical level. The explanation of the radical 'openness' of consciousness is due to some principles yet to be uncovered by a scientific revolution in physics. "Appropriate physical action of the brain evokes awareness, but this physical action cannot even be properly simulated computationally." (Penrose 1994b:241).

The outcome of our short excursion into the possibilities to give formal characterization of mind and brain turned out to put us into a quite uneasy position. The brain indeed computes. But its computations are not uniform; it performs in a very sensitive way due to even the tiniest changes in the conditions in the outside world as well as those due to tuning of different subsystems in it; the results of the brain 'computations' even if due to self-organizing (cf. Kelso 1995) processes, represent, and quite veridically so in the case of perception, the situation not of the brain, but of the outside world. Reasons along lines like these might have persuaded Gregson (this volume) to make the claim that even with heavy computer simulation only certain aspects of the brain functioning could be modeled with reasonable approximation.

Another point also deserves to be mentioned explicitly. If the reader remembers the presentation of Smolensky's belief in the 'iceberg' of computation from the shallow, informal, incomplete conceptual level of description to the rigorous, formal, complete description of brain computations

at the bottom of the seamless iceberg (cf. above), this does not seem to be *in principle* the way the mind/brain implement each other. The most formal, complete and precise description by definition would be not able to give account of the phenomena implemented by the not uniform computational procedures resulting in different aperiodic patterns and oscillations with which the brain/mind displays ultimate versatility. The openness and spontaneousness of eruption of the self-organizing processes by definition exclude the possibility of completeness. The 'iceberg of computation' is simply a wrong (even if implicit in the case of Smolensky) metaphoric image. The same holds for the 'iceberg' (as well as to the other attempts to build 'integrative') theories of consciousness (cf. the Global Workspace Theory of consciousness of Baars 1988). Something much more paradoxical is involved here.

One might criticize Penrose for different shortcomings in the presentation of the thesis he developed, as well as to praise the soberness of the accounts like that of Baars (1988), but we should be aware that consciousness cannot be equated with a serial mechanism with limited capacity for information processing. The conscious mind/brain can behave like that: It can ape (slowly) the computer, but the (symbol processing) computer cannot ape the mind/brain (neither slowly, nor on a fast pace). This asymmetry in computational capacities is strange, indeed.

Still, we will be speaking about the ways the brain, mind, and consciousness itself compute because we believe that different aspects of this 'nonuniform computing' can be detected and modeled.

3. The trouble with the brain: Single anatomy vs. multiple hierarchies of brain functioning

Some neuroscientists seem to suggest to us today that we are not far from understanding how brain 'creates' the mind. An authoritative introduction to neuroscience makes the following claim in the first sentence of its Preface: "The goal of neural science is to understand mind, how we perceive, move, think, and remember." (Kandel, Schwartz & Jessell 1991:XXXIX). To analyze how a specific mental activity is represented we have to discern which *aspects* of a mental activity are represented in which regions of the brain. This could be achieved only recently by combining the efforts of specialists in cognitive psychology with the brain imaging in order "to visualize the regional substrata of complex behaviors, and to see how these behaviors can be fractioned into

simpler mental operations and localized in specific interconnected brain regions." (Kandel, Schwartz & Jessell 1991:16).

We have to remember, however, that we need to comprehend, how we are supposed to deconstruct mental operations into simpler and simpler ones and to correlate this procedure with supposedly parallel analysis of the brain structures. And what is a '*simple* mental operation' continues to be one of the troublesome questions for contemporary cognitive psychology, to the best of our knowledge (if we discuss cognition). Only recently this question was faced more realistically, to our judgment, in the context of cognitive linguistics (cf. Lakoff 1987; Langacker 1987, 1991; Talmy 1988).

Churchland (1986) made an attempt to distinguish different possibilities in the mapping between different levels of brain/mind organization (while defending the possibility of reductionism). She came out with the following proposal for possible levels of mapping (with an orientation to the brain): the membrane, the cell, the synapse, the cell assembly, the circuit, the behavior (Churchland 1986:359). Churchland & Sejnowski (1992:2) repeated the same thesis in a more cautious form, and a belief was expressed not as much in the mind/brain identity, as in the possibilities of emergent properties due to the computational operations performed by neural nets (cf. Churchland & Sejnowski 1992:4).

Churchland (1986a:299-306; cf. also Churchland 1989:209) proposed in his model of brain/mind functioning as a basic abstract representational unit of the brain, with which perceptual and cognitive patterns 'identify' themselves, that of 'state space'. But he did not mention explicitly how those subsystems (capable of generating state spaces) map onto different cognitive and perceptual states and how the interactions between them influence processing (e.g., the interaction between the state space of color and the state space of visual shape; cf. Gouras 1991:476 on the problem of the parallelism of their implementation in the brain).

Pulvermueller *et al.* (1994, 3) expressed the view that the hierarchy of linguistic structures (phoneme, morpheme, word, sentence) has its biological equivalents in a hierarchy of cell assemblies corresponding to these cognitive entities. As reasonable as this might seem, it is appropriate to point out that in mind we have only utterances. Phoneme and the others listed above are linguistic abstractions, part of the conceptual apparatus of linguistic theory, but not of language in use. The primary unit of speech (i.e., of language in use) is the utterance and it remains to be proven how the latter is distributed into a brain-specific 'representation', both 'vertically' and 'horizontally'.

Singer (1994) found it appropriate to map to each other a class of perceptual features and the way the brain computes in the following way. The representation of the whole perceptual object consists of the distributed responses of a large assembly of neurons. The probability that individual neurons synchronize their responses both within a particular area and across areas should reflect some of the Gestalt criteria used in perceptual grouping (Singer 1994:55). Singer's hypothesis boils down to the idea that temporally coded assemblies require that probabilities with which distributed cells synchronize their responses should reflect some of the Gestalt criteria applied in perceptual grouping (Singer 1994:57). The global properties of visual stimuli can influence the magnitude of synchronization between widely separated cells located within and between different cortical areas. The high synchronization probability of nearby cells corresponds to the binding Gestalt criterion of 'vicinity', the dependence on receptive field similarities agrees with the criterion of 'similarity', the strong synchronization observed in response to continuous stimuli obeys the criterion of 'continuity' and the lack of synchrony in responses to stimuli moving in opposite directions relates to the criterion of 'common fate' (Singer 1994:59).

As attractive as this sounds and potentially plausible, let us not forget, that this means a direct projection of the way perceptual representations were formed onto the way the brain structures perform. Let us also remember that the Gestalt laws, as famous as they were, never were completely formalized (recently Leyton 1992 claimed success for that goal, at least to some degree). So, the 'direct reading' of some aspects of mental representation and its projection onto supposedly corresponding aspects of neural 'representation' might raise objections.

Singer (1994), however, made an attempt to map quite low level features of mental representations onto the way the brain performs, unlike other theoreticians and experimenters from this field of study. It might well turn out that he is on the right track, how the 'higher levels' of perceptual representation are built above the interface of fractal-like texture (discussed in this Introduction and in Stamenov in this volume).

Other professionals are not so optimistic for the prospects of finding the footprints of 'the mind in the brain'. More than a decade ago Ulric Neisser in an interview evaluated the stand of neuropsychology as follows:

> There is no doubt that neuropsychology is making great strides. We know much more now about how the brain works and about what happens in the brain while cognitive processes are taking place. Unfortunately nothing that has been learned so far seems to help very

> much with the problems of cognition. Maybe it will in the future; we will see. My guess is, though, that neuropsychology won't help very much until we have a better idea of what it can be expected to explain. We need a clear conception of how language is acquired, of what goes on in problem solving and how it depends on experience and culture, if we are to set the right problems for the brain sciences. Of course, there may be an interactive gain; their discoveries may help to sharpen our concepts, and vice versa. [...] [T]he brain is no less complicated than the world. There is an immensely complex system of millions of neurons, of chemical transmitters and electrical activity. We need a conceptualization of it. It's not enough to divide the brain into areas, with this area more important for *X* and that for *Y*; we need to know how it works. There is not much chance of that in neuropsychology until we have a conception of language and thought that will suggest what kind of structure we should look for. Without that, there will be as many alternative models of the complexities of the brain as we already have of the complexities of the world around us. (Neisser 1983:138)

The lesson Neisser teaches us seems straightforward: Without an orientation into the structure of the psychological *process* (not some static structure) it is useless to look into the brain, hoping to trace some self-evident patterns to give us a clue in the opposite direction — toward finding the 'objective' structure of mind implementation. Up to now it is very unclear how many levels of structure there are in the brain and what are their constituents. The way we represent the architecture of anatomical brain structure and the hierarchies of activity patterns in it make sense if and only if they are associated with some purposeful orientation. And the purpose of the brain is possible to explain up to the level we manage to associate it with some mind patterns. In this sense, Kandel, Schwartz & Jessell (1991) were right that one cannot escape the problem of mind in studying the brain, but in order to ascribe structure to brain we must know what types of mind structure we are looking for the sake of associating them with their neural correlates. The brain structure ascription is dependent on mind structure ascription but not *vice versa*. We can study mind without any knowledge from the field of neuroscience. The opposite is true to a much lesser degree. From this point of view, the neuroscientists who claim that they are neutral in relation to one or another theory of mind, in the majority of cases simply happen to share some basic metaphors about the way of mapping of brain/mind without explicitly discussing them. For example the areas V1, V2, V3 and V4 in the brain, responsible for some stages and aspects of visual

processing are listed in this order due to some (implicit) model of the stages of visual perception (cf. Graham 1992), not because they self-evidently process information one after another (as that is possible to prove in neurobiology).

Today some experimental neurobiologists happen to be critical of the outcome of the efforts of both psychologists and computational neurobiologists. They believe that the study of the brain can give us clues about the way the mind performs (and less so in the opposite direction). They also believe that the formal characterization of the processes in the brain/mind must also be ascribed a 'servant maid' position in relation to the investigation of the living brain as a physically available object. For example, Semir Zeki (1993) who achieved remarkable success in localizing more precisely multiple areas in the brain, which in a distributed way implement what is experienced as visual perception, seemed not to be very fascinated with the prospect of formal modeling of brain functions.

Zeki (1993:118) defined the position of computational neurobiology in the following way: The brain is much too complicated an organ to be studied without some guiding theory. Because computers can undertake complex ('intelligent') tasks, they are the natural source for such guiding theories, which can then be tested by direct experimentation. In fact, however, as Zeki pointed out, the relationships between the theory, model, simulation and experimentation turn out to be quite problematic. This is the case because

> [...] to become meaningful to the experimental neurobiologist, the computational neurobiologist needs the facts of the nervous system even more than the experimental neurobiologist needs the theory generated by computational neurobiologists. [...] Indeed, one might well use the language of the computational neurobiologist and ask, 'Within what anatomical constrains must the addressing procedure [for specialized visual areas to interact with each other in order to construct the integrated visual image; E.M.C & M.S.] operate?' The answer to that derives from anatomy alone, not from mathematical models of the brain. A neurobiologist pondering these problems might well put his time to better use by studying the connections of the visual cortex — which also has a theory behind it — and thus help define the addressing problem in neurological terms far more sharply than any computational neurobiologist ever did. (Zeki 1993:120-121)

If the achievements in the computational approach to the brain depend on the developments in experimental neuroscience at least as far as the working of the real brain are the concern, the requirements for the development of the theory

behind the studies of the connections in the brain in general remains to be seen, and in the visual cortex in particular. To the best of our knowledge, it could depend only on the way we conceptualize the mental processes (the features of visual perception), whose neural implementation we try to identify (cf. Neisser 1983). For Zeki, what can make 'meaningful' some results achieved in neuroscience depends upon the theory of the brain he has, and the latter on his implicit theory how the brain implements mind. There is no alternative to that. The important thing, in any case, is that the three components — formal, neural and mental characterizations — are logically dependent on each other and one or two of them cannot be 'bracketed out', but only can be left unspecified (this today happens in the majority of cases).

In the case of vision in the brain, its conceptualization will depend what we consider 'simple' and what 'complex' in the way visual perception handles information (computes) (for exposition on different measures of complexity cf. e.g., Atmanspacher *et al.* 1992). What are the basic 'elements' (constituents), the basic building blocks of perceptual experience? If there are multi-stage integrative processes in the brain (cf. Zeki 1993:295-308, 321-336), they must follow some hierarchy. If the latter is the case, one must consider the possibility of the parallel if not identical complexity of neural and mental 'representations' and processes. We must, correspondingly, identify how the basic 'irreducible givens' (qualia) of perceptual experience are implemented in the brain, and how the information processing we posited as necessary for perception to take place is implemented in the hierarchy of brain computations. All these postulations are model- and theory-dependent, because 'integration' is not a model-neutral term (as we will shortly see).

At this stage we would like to remind the reader that up to the present time practically all models of neural computation are neuron-dependent. They take the neuron as a basic constituent element of brain functioning. The complexity of neural computation depends on the massive performance of millions of single neurons, which synchronize their performance into different rates and rhythms of oscillations on different scales (cf. Singer 1994 for an up-to-the-date presentation of this thesis; cf. also the discussion of the topic of hierarchies in brain functioning in Alexander & Globus in this volume) forming a cascade of neural networks. The following correspondence rule is implicitly accepted in this type of neural modeling: More complex mental computations must be implemented in more complex cascades of synchronized oscillations of some activated neural fields (or assemblies).

That the hierarchy of brain processing may be, however, of a quite different type is glimpsed at in a recent book. The aim of Jibu & Yasue (1995)

is to show that the architecture of the actual brain processes 'producing' mind and consciousness might be quite unlike the mainstream models of brain functioning currently discussed in the neurosciences — almost all of the latter taking as their elementary units the neurons manifesting continual appearance. Today, however, only some of the mechanisms that control the distribution of the receptor-sensitive ion channels on the cell membrane, which determine the plasticity of each chemical synapse, have been identified. Indeed, the discoveries of how the neural networks perform, might remain far beyond the scope of contemporary neuroscience (Jibu & Yasue (1995), because the detailed quantum physical phenomena taking place in the cell membrane have hardly been taken into account. Mainstream brain science has been established by efforts at the interface between medicine, biology, and chemistry. None of these sciences is precisely oriented toward an exploration into imperceptible quantum physical phenomena taking place in the cell membrane.

The 'straight (or parallel) complexity' upward possibility is associated with the upward spiral of biological complexity: Physical processes in the brain, for example, would support (if at all) in a very indirect way the lowest structures of mind; chemical ones — the higher; and biological ones (e.g., those of molecular biology) will implement the highest aspects of mind like thinking and consciousness. In other words, the growth of brain structure complexity would presuppose a growth in computational power to implement mind.

Jibu & Yasue (1995) give us a model with an 'inverted architecture' of brain functioning according to which the more fundamental (i.e., microphysical-cum-macrophysical) aspects of brain processing are supposed to implement the highest mental activities — those of consciousness and the subtle aspects of memory:

(1) The level of quantum brain dynamics (QBD). The quantum field theoretical dynamics of water rotational field and the electromagnetic field is what is called QBD. The latter system in the cerebral cortex produces memory and consciousness by playing the role of a self-reproducing automaton described by quantum field theory;

(2) The level of collective modes of the molecular vibrational field along the filamentous strings of protein molecules in the dense, three-dimensional network structure that spans the whole assembly of brain cells by patching together the cytoskeletons and the extracellular matrices;

(3) The dendritic network system which is formed by the dendrites of neurons with and without axons entangled with each other in a highly sophisticated manner;
(4) The neural network system which consists of the totality of neurons connected to each other by axons, forming a type of electrochemical circuit composed of a great number of circuit devices of multi-input and single-output type with threshold-majority-decision logic functioning (cf. Jibu & Yasue 1995).

The four types of networks-cum-fields mutually determine each others' functioning. The 'subtlest' (1) *controls* the functions of the other three, while the latter can disturb the vacuum (equilibrium) state of (1) by passing some energy quanta to it. In other words, the relationships between them are not symmetric. While the subtler 'control' the cruder, the cruder can *influence* (*disturb*) the way of work of the subtler. It is important to become aware that the field controlling all the others in this model is the lowest (physically the subtlest) one, unlike the models in line with the computer metaphor, where the higher level computations control the way of realization of the procedures in lower level computations. This feature of the model of Jibu & Yasue (1995) is the most intriguing one and the one with potentially most far-reaching consequences for our orientation about the ways the brain can implement mind.

The currently fashionable neural nets, connectionist and/or Parallel Distributed Processing (PDP) modeling of the brain and the 'neurocomputers' (computer modeling) which, purportedly, simulate the way of functioning of neural networks, are shown by Jibu & Yasue (1995) to be simulating only one aspect of brain functioning. In this sense, neural nets might be overestimated in their capacity to model higher cognitive functions, since essential aspects of the human brain performance potential might come from networks (and fields) of a different type (or types). In this respect, Jibu & Yasue (1995) challenges not only to the specialists in neural nets and AI community in general in their claims to model brain (and mind) functions, but also neuroscientists in relation to their theories and beliefs how the 'integration', for example, of mental image, is enacted in the brain (cf. e.g., Zeki 1993 for an up-to-the-date orientation into the problem).

Via neural modeling route we once again come to the necessity to posit an interface in neural computation, where what is happening in the brain coincides directly with what is happening in the mind according to its formal description. In the present volume this necessity is expressed in the papers of Alexander & Globus and of Gregson in discussing the specificity of the edge-of-chaos phenomena in brain dynamics. Furthermore, there seems to be an

inverse relationship between 'high-' and 'low-level' processes in brain vs. mind. This is suggested, for example, by the theory of brain implementation of mind of Jibu & Yasue (1995; cf. above). The two inversely related hierarchies should interpenetrate. This is a hypothesis — the hypothesis of an interface in brain/mind — of a secret symmetry plane, which should be possible to test and to refute or verify.

Once again the characterization of brain, mind and the formal description of the latter turn out to be inextricably interwoven. What happens in the brain is 'directly accessible' to the mind at least in some aspects of the form of the processes going on there. The necessity to posit *direct access* in some cases of mathematical modeling was also maintained by Mandelbrot (1983). The latter author was careful enough to distinguish 'concrete' from 'abstract' modeling spaces when it turned out necessary. He made, for example, the following distinction between fractal geometry and the 'theory of strange attractors and of chaotic (or stochastic) evolution':

> Indeed, my work is concerned primarily with shapes in the real space one can see, at least through the microscope, while the theory of attractors is ultimately concerned with the temporal evolution in time of points situated in an invisible, abstract, representative space. (Mandelbrot 1983:193)

Exactly from this point of view one can discover the last obstacle in the way of facing the problem how the brain produces mind on-line, because the deterministic chaos and strange attractor type of brain dynamics (cf. Freeman 1992; Skarda & Freeman 1987) is supposed to be situated in an invisible, abstract, representative space of a formal model, of a formal *description* of the brain processes, but not on the level of brain implementation itself.

When one says, however, that in the brain there are fractal patterns, this should literally mean that 'they can be seen, heard, or tasted', i.e., that they are, in principle, accessible to experience — they are as much brain as mind. Fractal modeling of the brain should mean modeling of those processes in the brain that produce even if 'subtle', difficult to get aware of but *in principle* (cf. Searle 1990, 1992) possible introspectively to access mind states. We cannot be sure that some brain process supports some mind process unless this process is accessible (under some conditions) to experience. In this sense, Searle (1992) is right in postulating the necessity of his Connection Principle, when he says that if we posit some neurophysiological state to 'generate' mind state, we must posit that it is accessible to experience and point out how it could be experienced. To say that there are neural states which are 'deeply unconscious',

i.e., that one cannot become aware of them 'in principle', is to posit two entities — a neural state as well as its deeply unconscious mental correlate we have no way to distinguish, also in principle. Maybe, there are some states which are mind-like, deeply and irremediably unconscious, and yet not identical to their supporting neurophysiological states, but if this is true, how to distinguish them from their neural supporting states? Correspondingly, the 'deeply unconscious mental states' fall pray to Ockham's razor.[3]

The reason for the application of Connection Principle in our context is that when we discuss, how the brain produces mind, we must point out at least three different aspects pertaining to that process:

(1) the formal specification of the neural and mind implementation of the process in question;
(2) its neural localization in a hierarchy of involved areas and networks-cum-fields; and
(3) the mental phenomenology we associate with it.

Are there any chances to find plausible candidates from the mental economy, for which we can cherish higher expectations to face the problems (1)-(3) listed above in a synchronized way? This now becomes a critical question.

4. The trouble with mind: The root metaphor of 'perceptual image' (= representation) and its vicissitudes

In cognitive sciences it is not appropriate to talk about 'images'. They are considered to be pretheoretical (or folk) concepts. In current terminology, what was named a 100 years ago an 'image' by William James or Wilhelm Wundt, is now called 'representation'. But with the advent of more and more sophisticated technical language the problems were also soon to proliferate. It turned out, as time went by, possible to talk about 'distributed subconceptual representations' (Dreyfus & Dreyfus 1988) or 'connectionist representation' or even about 'representations over neurons in the brain' (cf. Smolensky 1988:8). Evidently, these authors did not have in mind one and the same meaning of the term 'representation', because nobody nowadays believes that we can find mirrors somewhere in the brain.

As a 'starter' to the discussion of the problem, we prefer to share with the readers the famous classical anecdote from Pliny about the two painters, Zeuxis and Parrhasios (emphasized in its psychological and psychoanalytical significance by Lacan 1977:103, 111-112). The anecdote, in an abbreviated form, runs as follows:

> In a competition, who is a better painter, Zeuxis painted grapes which looked so life-like that the birds came to taste from them. Parrhasios, his friend, however, painted a veil such that Zeuxis, turning toward him said, *Well, and now show us what you have painted behind it.* (Lacan 1977:103; cf. also Gombrich 1960:173)

Perhaps, this is the most that one can say about the nature of the image (pictorial representation) — to narrate a story or myth? We personally do not believe in the last statement, but we think we can learn some things from it.

This parable addresses the question about the 'final' or 'true' nature of the image (representation):

(a) What is the image made from? What is the image referring to? What are the elemental qualities and quantities of visual experience? What is the 'medium' of the image — the 'canvas' onto which each potential image can be painted — and the 'pens' and 'brushes' for drawing or painting on the canvas?
(b) What is the 'beyond' of the image? The referent from the world? The grey matter of the brain? Or both? Perhaps neither (= a number, an immortal idea, a computational procedure)?
(c) What is 'behind' the image, behind the 'veil' — the objective reality? The hidden reality of the desired 'object'? Or both?[4]

We should also point out that even before approaching the image itself, we must become aware that all the theories about it are conceptualizations. In this sense, they are necessarily metaphoric in nature to the degree there are both commensurabilities and incommensurabilities between any perceptual image and its conceptual re-presentation. This point is not very popular among the professionals in the psychology of perception. This became even more so with the advent of cognitive sciences and the idea of the universality of computation, because everybody tried to minimize the possible incommensurabilities between perception and cognition and to maximize the points of their convergence, especially from computational point of view.

The 'standard' conceptualization of the architecture of the visual perceiving of an object was sketched in the following way by Gibson (1979):

(1) An object from the real world;
(2) A retinal image of this object;
(3) An image of the object from the real world projected from the retina to the visual areas in the brain;
(4) Various operations in the visual areas of the brain on the sensory image;
(5) Full consciousness of the object and its meaning (cf. Gibson 1979:252).

The functionality of the acceptance of those stages of visual perceiving were accentuated or questioned in different theories of visual perception at the expense of others. The basic 'logic' (or rationale), however, remained more or less along the following lines. The 'objective world' is a world of objects. This world is 'mirrored' in the 2D retinal representation. The latter image is analyzed into a distributed representation in different areas of the brain. The latter 'representation' is integrated into some higher-order mental image through some kind of computation, which is supposed to synchronize the responses of all the areas in the brain involved in visual information processing.

The position of Gibson (1979), whose opinion about the 'canonical' conceptual metaphors of perception we presented above, was that there are no 'objects' (= the 'discrete stimuli' of the psychological tradition based on behaviorism) to be considered as components or building blocks of perception. According to the latter author, in perception there are invariants extracted from the ongoing interaction with the ambient optic array and nothing else. For this same reason according to which there are no objects in perception, there are also no images of those objects. The problem of image is also dismissed as an artifact of the misleading conceptualization of perception as 'seeing in pictures (or images)'.

Gibson's position, however, is that of an insignificant minority (in quantitative terms) among the professionals in the psychology of perception. Otherwise, the status of images in the brain/mind was faced in two mutually contradictory ways in the eighties and early nineties. The first camp — of PDP and neural nets modelers — readily accepted the epiphenomenality of images and maintains that there are in reality no images whatsoever in the brain. The images are artifacts of the distributed computational exertion of a set of neural networks. Dennett (1991) made a philosophical claim from this idea in pointing out that there is no destination where all the integrative processes in the brain come to be displayed on some monitor to the homunculus-self for enjoyment.

The other camp continues to speak about the image and projects it also to the brain physiology when discussing the problem of the vicissitudes of the 'retinal image' and the ways of its coding and decoding into different areas of the brain (cf. e.g., Hubel 1988).

The situation becomes further aggravated when we face the necessity of integrating not what is supposed to form a single (and discrete) image but features of several neural and/or mental images into a higher order image, as in the latter case we need a buffer memory to collect the images of first order, to get them from that memory in order to compare them, and to extract the result

of comparison into another level of the image integration, etc. (cf. e.g., Julesz 1971).

Both camps introduce basic fallacies in their arguments: Either they dismiss on erroneous grounds the problem of the perceptual image, or they project the problem of image formation onto the way the retina and brain performs. In the former case we are informed that the 'mental images' are epiphenomena, a byproduct of the computational processes going on in the brain. They are 'epiphenomenal' in the sense that one should not care about them, if one wants to study the nature of the real (causally efficient) process involved. The 'real process' is the brain computation. The other stuff is a byproduct, a leftover. In the latter case we face the trouble that in the brain as anatomical organ we cannot find (literal) mirrors, images, screens or the like, but only grey matter.

Even if the belief about the image-driven nature of perception is shaken, the belief in the object-driven nature of perception continues to be dominating, in one or other way, in psychology of perception and in cognitive sciences, more generally. Recently Graham (1992) pointed out that at global level visual perception may be thought of as a two-fold process. First, the visual system breaks the information that is contained in the visual stimulus into parts; second, the visual system puts the information back together again. In other words, first we have an analysis, and next comes the integration or re-assembling of the image of the object. The reason why the image of the object in the retina should be taken apart at all is as follows. This is the case because the proximal stimulus — the light patterns falling on the retina — bears little *direct resemblance* to the important aspects of the world that must be perceived, the world of objects, the latter constituting the distal stimulus. The lack of resemblance between the proximal and distal stimuli makes the task of visual perception inherently difficult (Graham 1992:55).

Graham (1992), moving within the physiologically driven tradition of inquiry into the nature of mental image, starts with the analysis of the nature of the light stimuli and the way retina reacts to them. What remains inherently troublesome with this approach (as much as this orientation can give us in the investigation of the mechanisms of the physiology of vision proper) is, how from the analysis of the structure of 'proximal stimulus' the brain puts together not an 'image' of the work of the mechanisms in the retina, but supports the mind in 'putting back together' a perception that generally corresponds very well to the distal stimulus (cf. Graham 1992:61). But do we need the division into analysis-integration in perceiving the world and the division of stimuli into proximal and distal ones? What is the difference in the qualities of distal versus

proximal stimuli? How the complicated computation intervenes between the analyzers' outputs (of the eye retina) and observers' perceptions, if they are supposed to integrate the information from the proximal stimuli and in this way reconstitute the distal stimulus, remains rather problematic.

We do not pretend to give a systematic account of the different conceptualizations of the perceptual structure in the psychology of perception. A topic like that would require a book-length investigation. Even without special investigations, however, the incommensurabilitity between different approaches to the structure of perception seems to us self-evident. With this short sketch we would like simply to make the reader aware of the controversiality of the topic — that every theory of perception is based on a metaphor of perception. The latter is the case to the degree conceptual structure is incommensurable with some aspects of perceptual structure.

Trying to map mind (in our case we took as an example visual perception) to brain we face a fourfold problem:

(1) What is the status of patterns from objective reality as accessible to brain/mind?
(2) What is the way of coding of the structure of reality in the retina and in the brain?
(3) What is the structure of the mental image in perception we have conscious access to?
(4) What is the relationships between the structures (1)-(3) and their models made in the cognitions of scientists (i.e., the status of 'image of image' or of 'model of image', or of 'metaphor of image', or of a 'theory of image')?

In order to face this fourfold problem, we must find a *tertium comparationis* between each two of them, a single format for dealing with (1)-(3) and minimizing the metaphoricity aspect in the relationship between the modeled process and the modeling means used. This would be the ideal means for facing the problem of perceptual image and its functional equivalents in brain and in reality.

We consider as a possible computational interface between (1)-(3) the formalism of fractal geometry. The fractal-like patterns are available in the ambient optic array; the brain can attune to those patterns; the mind can perceive these patterns: They form the microstructure of the ambient optic array (cf. Gibson 1979), the structure of the brain's synchronized oscillatory activity (cf. Singer 1994), and the microstructure we experience as the incredible density of each perceptual image we effortlessly compute and innocently feel in each successive moment of our perceptual life.

The heart of the fascination with fractals seems very simple. Fractals opened the eyes of many laymen/laywomen to the inexhaustible denseness and beauty of each perceptual image we happen to perceive each successive 50 or so milliseconds of our experiential life. It returned to us the sense in which we are neither monitors of computers nor TV screens.

We maintain the opinion that perception is the aspect of mental life where we come as close as possible to the interface between brain, mind and the world without the service of any go-between of meaning, metaphorization or theory-dependence in their relationship. They simply should map, map formally, if we manage to find the appropriate formalism and format. Here there should be no meanings, metaphors, concepts, propositions, inferences, etc., whatsoever. Simply a running turbulent-cum-laminar flow of the primal phenomenal awareness (metaphorically this flow was conceptualized in the metaphor of 'the stream of consciousness').

The studies from three different perspectives — formal, neural and psychological — of different phenomena of brain/mind point in this direction — from more and more meticulous correlations between brain and mind processes and their formal models to the necessity to posit an interface between them. This volume should be considered as an attempt oriented, in one or other way by different contributors, in this direction.

5. Further troubles and prospects in the search for an interface between brain and mind

How could we catch the brain in producing mind? Is this something reasonable to expect according to our current knowledge and available technology? Mac Cormac (this volume) comes closest to the realization of the idea for experimental verification of the existence and functionality of fractal-like patterns in creation of mind by the brain. This becomes possible, as Positron Emission Tomography (PET) and functional Magnetic Resonance Imaging (fMRI) offer noninvasive methods of imaging the physiology of the brain including metabolism and blood flow. During cognitive activations like the visual or auditory recognition of words (or, potentially, during perceptual tasks like form and texture discrimination) through the careful design of experiments those areas of the brain connected with these tasks can be identified. After statistical analysis including analysis of covariants, structural equation modeling yields a network analysis of the cognitive activity under study (cf. e.g., Gonzalez-Lima & McIntosh 1994). Thus far, a nonlinear analysis of brain

function during perceptual or cognitive activation has not been undertaken. Such an analysis, however, will further elucidate the role that fractals play in the chaotic activity of neuronal processes. This project is already underway at the Duke University Medical Center and Mac Cormac (this volume) describes both the program and its background.

This volume represents a group of explorers who stand on a mountain at the edge of an unexplored jungle who look ahead at the tangle of chaotically firing neurons and have glimpses of valleys through the jungle but do not know precisely how to get yet there. They know that they must have a map of this jungle and await both PET and MRI to provide such maps. They also know that mathematical modeling of nonlinear (chaotic) dynamical neuronal systems will necessarily uncover fractals (cf. Mandelbrot 1983:197 about the relationship between 'strange' attractors and fractal sets) and that when these fractals are revealed, an analysis of them will contribute to our fundamental understanding of both the brain and mind. Does each of the explorers in this volume agree exactly on how to find the way through the jungle? Not exactly, but they have had enough of a common vision to come together and share their insights and methods confident that either several of them or other explorers with similar insights will successfully explore one of the last unknown frontiers of humanity. We could prove the existence and functionality of chaos and fractal geometry for brain works *if and only if* we take them as patterns of mind, too, and in a *constitutive way* but not simply as a modeling formalism. With other words, the execution of some nonlinear patterns in the brain is formative for the emergence of mind structures.

Although Freeman (1992:480) concluded that "it is *unproven* mathematically and experimentally whether chaos does or does not exist in the brain [italics added; eds.]", he still believes that chaotic dynamics can at least serve a useful explanatory function as shown in the following:

> We will conclude that chaotic dynamics makes it possible for microscopic sensory input that is received by the cortex to control the macroscopic activity that constitutes cortical output, largely owing to the selective sensitivity of chaotic systems to small fluctuations, and their capacity for rapid transitions. (Freeman 1992:452)

While more experimental evidence is amassed to support the aim 'to prove' that chaos not only 'exists' in the brain, but is functional in the creation of mind, in the meantime nonlinear dynamical systems can usefully rationally reconstruct (i.e., can be used as models) brain activity. Some of authors in this volume presume that there exists a fundamental gap between brain activity and mental functioning even though each interacts with the other. One way of

handling this gap (potentially with many hidden sublevels) presupposes brain activity as the self-organization of a chaotic system arising from the interactions of millions of changing connections. Under certain conditions, these connections produce what seems to be background noise (chaos) and under other conditions meaningful activities like perception or thinking (= ordered patterns). The other possibility would be the one already mentioned above — of 'secret symmetry interface'. Currently it is difficult to judge which position will prevail.

Our claim with this volume amounts, *summa summarum*, to an approximate paradigm for future research, what are the conditions for 'catching' the brain in producing on-line mind (if that at all turns out possible in the foreseeable future). We called this level of mind/brain processing 'the level of secret (not yet uncovered and verified) symmetry'. At this level mind/brain performs as an indistinguishable one from formal, neurological and psychological point of view.

Notes

1. It is a different problem that will be not discussed here, can we maintain that there are processes in the brain, which are 'side effects of complexity the brain lives with', when the latter are not supposed causally to support the implementation of some process in mind. The formulation 'causally to support' is also theory-dependent and not without associated problems.

2. Only very recently the idea that consciousness might be a *reconstructive process* (on the level of conscious perception, but not, as suggested by the classical studies in the psychology of memory, a part of the process of recall; cf. Neisser 1967) was implicitly introduced by Leyton (1992). This author, however, projected the reconstructive process to the mechanisms of cognition and perception, but did not consider the possibility to understand it as a consciousness-specific operation. The idea about the necessarily reconstructive nature of explanation and modeling of brain and mind processes is further developed, in some aspects, by Mac Cormac (this volume). The ideas about the constructive nature of visual imagination and the reconstructive vs. attuning nature of conscious visual perception are also developed, from some points of view, by Stamenov (this volume).

3. In his critique of the concept of unconscious in psychoanalysis, however, Searle (1992) went too far. The accent in the latter discipline is made not on the discovery of the

unconscious *per se* (whatever the latter term might mean on different occasions; cf. the history of the concept of the 'romantic unconscious' in its relation to 'Freudian unconscious' as briefly and up to the point sketched by Lacan 1977:24), but on the discovery of the influence of unconscious on consciousness in the mental economy. The unconscious processes are uncovered and considered to be mind processes to the degree the effects and products of their work are traceable in and comparable to the mental products accessible to consciousness. Searle (1992:167-173) rightly observed that 'unconscious *per se*' or 'unconscious in principle inaccessible to consciousness' is by definition an empty category, but this was not the point of the insight of Sigmund Freud and the *Leitmotiv* of psychoanalysis.

4. As the reader may have noted, we made use here of two different prepositional 'spatializing' metaphors — of 'beyond the image' and 'behind the image'. They might look as if pointing to one and the same 'object', the object in the objective world, which is 'represented' in perception by its image. Whatever the outcome of the discussion about the functional place of objects and images in perception itself, we will preserve the 'behind' metaphor for the psychoanalytical aspect of visual image problematic, as discussed by Lacan (1977:67-119) under the rubric 'the eye and the gaze'. For more information, the interested reader should consult the cited source.

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Edge-of-Chaos Dynamics in Recursively Organized Neural Systems

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1. Recursively modular neural systems

The great organizational richness of the nonlinear dynamical brain provides a challenge to the application of chaotic dynamics. When inquiry proceeds at any one scale of organization — for example, do neurons fire chaotically? Does the EEG have fractal dimensions? — the attempted application seems straightforward enough, at least in principle. But when the various scales of complexity in the brain are considered, then the application becomes less clear. *Here the brain takes on a fractal-like structure in which neural structures at many different spatial scales are recursively embedded* (Alexander 1993). The brain is thus the quintessential example of what Bunge (1969) calls a 'level structure'. Perhaps the most widely known example of a neural model which encompasses multiple scales of supra-neural structure is the work of Edelman (1987). The properties at each level of the neural level structure are radically different, ranging from a complex self-modifying switch (neuron) to the global neural structures that enable conscious thought (Bunge 1969).

This meta-organizational principle — called 'neurophysiological stratification' by Weiss (1968) — is crucial to the understanding of the way neural entities function. The idea stems from an ontological principle that the natural world is stratified and that the divisions among the sciences reflect this stratification (Bhaskar 1975). Experimental evidence from neuroscience is consistent with this general approach (Rosen 1968). Attempts to model brain function may be enhanced by encompassing several scales of organization in

simulations (Alexander 1994). There are excellent examples of stratified models in the artificial neural network literature (Edelman 1987; Laskoski 1990; Walker & Alexander 1994). Ideas from dynamical systems theory may further refine understanding of the importance of stratified architectures.

The straw-person which will be attacked initially is the notion of the monolithic neural network. This straw-person is opposed to the stratified conception of neuroscience. Our discussion of current theoretical and experimental work attempts to provide a systematic account of the stratified conception of neural entities, to draw out many of the subtleties of this point of view and to push it to the limits of its usefulness. This, to our knowledge, has not been previously done. The argument about the nature of neurophysiological entities — monolithic or stratified — is also an argument about basic world views. Katchalsky (1974) traces this argument back to the pre-Socratic world views of Heraclitus and Democritus. To Democritus there was nothing but atoms and the void. This stark view corresponds precisely to the claim of 'neurons and the void' or 'connections and the void' put forward by our straw-person. To Heraclitus, on the other hand, the world was comprised of a complex hierarchy of large and small flow patterns and his catch-cry was *panta rhei*, "everything flows". The things we observe in the world are self-maintaining features in the flows which are relatively stable over time. This world view underpins the dynamic, multi-scale neurophysiological phenomena which are brought out here.

The term 'monolithic network' is used to describe the class of neural networks which are non-modular. As a class, it comprises most artificial neural networks constructed to date (Jacobs, Jordan & Barto 1990). Monolithic networks have but two scales of interest: the neurons and the global network. These two scales are linked by a repeated interconnection pattern between the neurons. This schematic monolithic network is illustrated in Diagram 1. In monolithic networks, transformations are carried out by individual neurons, usually by receiving weighted activations from other neurons, operating upon them in some way, and transmitting the resultant activations to the next neuron. Under the non-reductive account, these individual neural processes form the basis of the emergent properties of the network. In Diagram 1, an initial layer of neurons responds to pixels on a retinoscopic array. These neurons feed into a second layer of neurons which process slightly more complex features. This procedure is repeated throughout the layers of the network until the letter 'D' is recognized at the bottom layer.

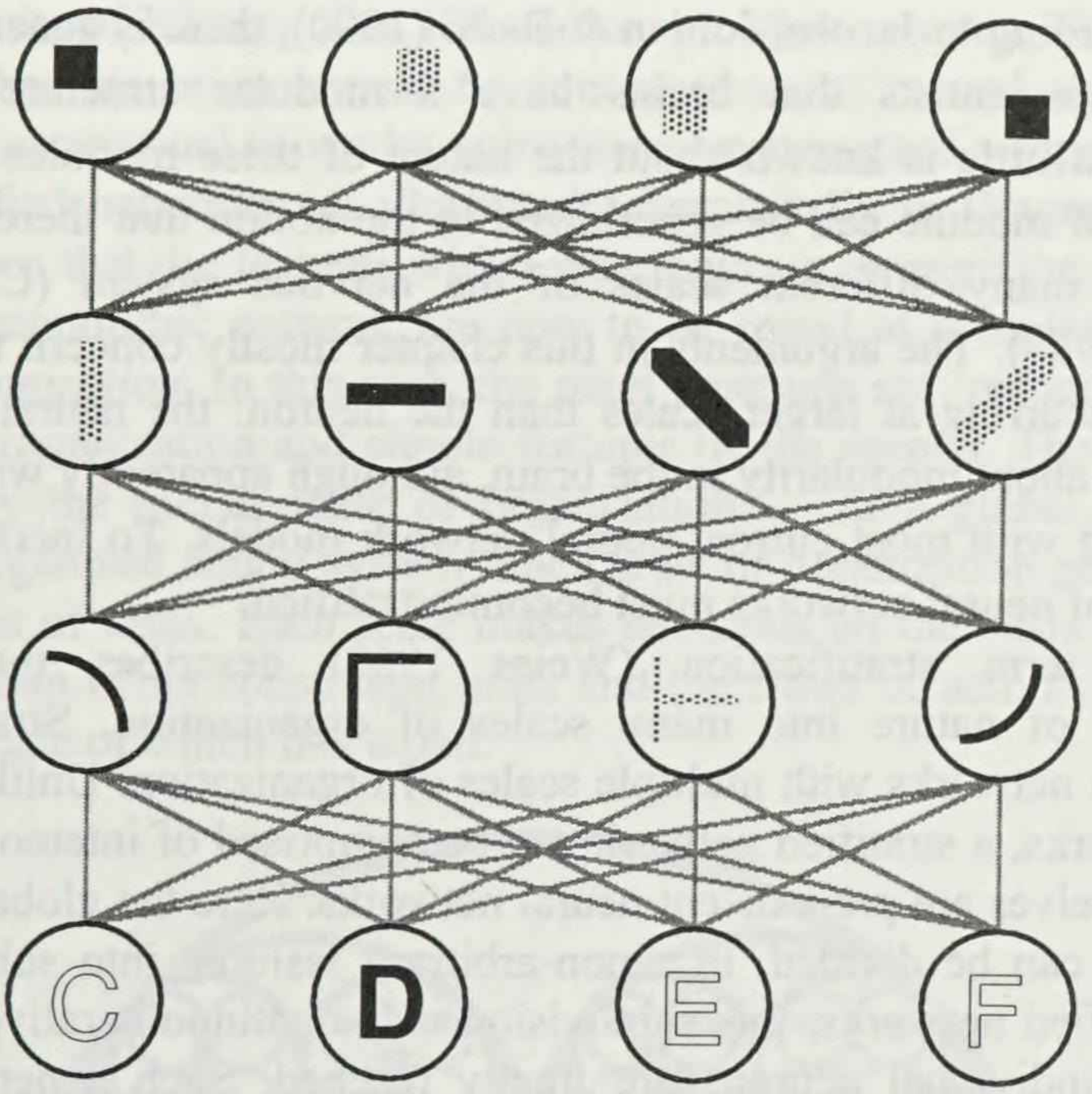


Diagram 1: *Monolithic neural networks. Schematic diagram of a monolithic network. The network consists of two scales: the neuron and the network. Each neuron is connected by repeating patterns of connections, feeding activation from layer to layer, top to bottom. Beginning with simple features in the initial layer, the network deals with more complex features in each subsequent layer, ending with the recognition of the letter 'D'. The network is monolithic precisely in the sense of having only one form of structure, the particular connection pattern linking the scale of the neurons to the global scale of the network.*

To define monolithic networks more strictly: a neural network will be said to be monolithic if the processes of the neuron are only one scale of organization below that of the global network. In other words, there is no non-arbitrary way to partition a monolithic network into smaller sub-networks. The details of the interconnection pattern are irrelevant to the definition of monolithic networks, provided they do not violate the chief requirement that the neural processors interconnect directly to form the global scale of the network. Thus, recurrent architectures in which there is a bidirectional flow of activations between layers of neurons are also monolithic networks. A network in which all neurons are fully interconnected to each other also counts as monolithic. There are many ways to connect a group of neurons into a non-divisible, monolithic network.

According to Jacobs, Jordan & Barto (1990), there is general agreement among neuroscientists that brains have a modular structure. They add, however, that little is known about the nature of these modules in the brain. The notion of module can be generalized to the notion that there is organized structure at many different scales of the nervous system (Churchland & Sejnowski 1988). The arguments in this chapter mostly concern the organized structures occurring at larger scales than the neuron: the neural architecture. These views about modularity in the brain, although apparently widespread, are not in accord with most current neural network models. To incorporate them, our notions of neural networks must become stratified.

The term stratification (Weiss 1968) describes the ubiquitous organization of nature into many scales of organization. Stratified neural networks are networks with multiple scales of organization. Unlike monolithic neural networks, a stratified network can be comprised of interconnected units which themselves are pre-existent neural networks. Here the global structure of the network can be divided, in a non-arbitrary fashion, into subnetworks. In highly stratified networks, this subdivision may continue iteratively to a great depth until individual neurons are finally reached. Such a network can be described as a *nested set* of neural networks (Freeman 1975). Describing these networks from the other direction, Globus (1992) finds neurons organized into hyperneurons, which themselves form nodes in a yet higher network, such that this organization upon organization ends with the highest scales being self-organizing modules of a supernet. While not yet fully elaborated, this radically stratified view of neurophysiological organization has had its proponents. Neural stratification was first suggested explicitly by Weiss (1941), who claimed this hierarchy of nested scales was a crucial property, or perhaps even a defining feature, of neurophysiological entities. Recursive modularity in neural systems is therefore not a new idea. Hebb (1949) described neural development in several stages, each developmental stage occurring at a different scale of organization. Neurons modify their interconnections to form *cell assemblies* which in turn form interconnections to create *complexes*. Rosen (1968) suggests that stratified organization is essential to understanding brain properties. He argues therefore, that any neurophysiological theory that does not include multiply nested neural scales is "seriously incomplete" (p. 22). Conrad & Hastings (1985) demonstrate mathematically that without such nested scales of structure, information processing could not have evolved in organisms. Freeman (1975) uses the notion of Katchalsky sets to describe a general organizing principle of the brain, namely: nested sets of interacting neural systems. Populations of neurons form K0 sets, which in turn are

constituent units of KI sets, then KII and so on. Most recently, Globus (1992) has argued that the brain should be conceived as a 'recursively organized' system of hyperneuronal networks, subsystems, systems and a supersystem.

Stratified networks are illustrated schematically in Diagram 2. In this diagram we see that the features which were built up *through* the layers of the single scale monolithic network are now to be found at completely different *scales of organization*. In this case, the pixel positions are 'recognized' by the first scale of organization and simple features by the second. The letter 'D' is recognized by the global scale of organization — as a global state of the recursively organized neural system. Each scale of organization performs quite different types of tasks. Each scale makes decisions on the basis of the states and organization of its constituent units and the flows of activity through the next largest scale of which it is a part.

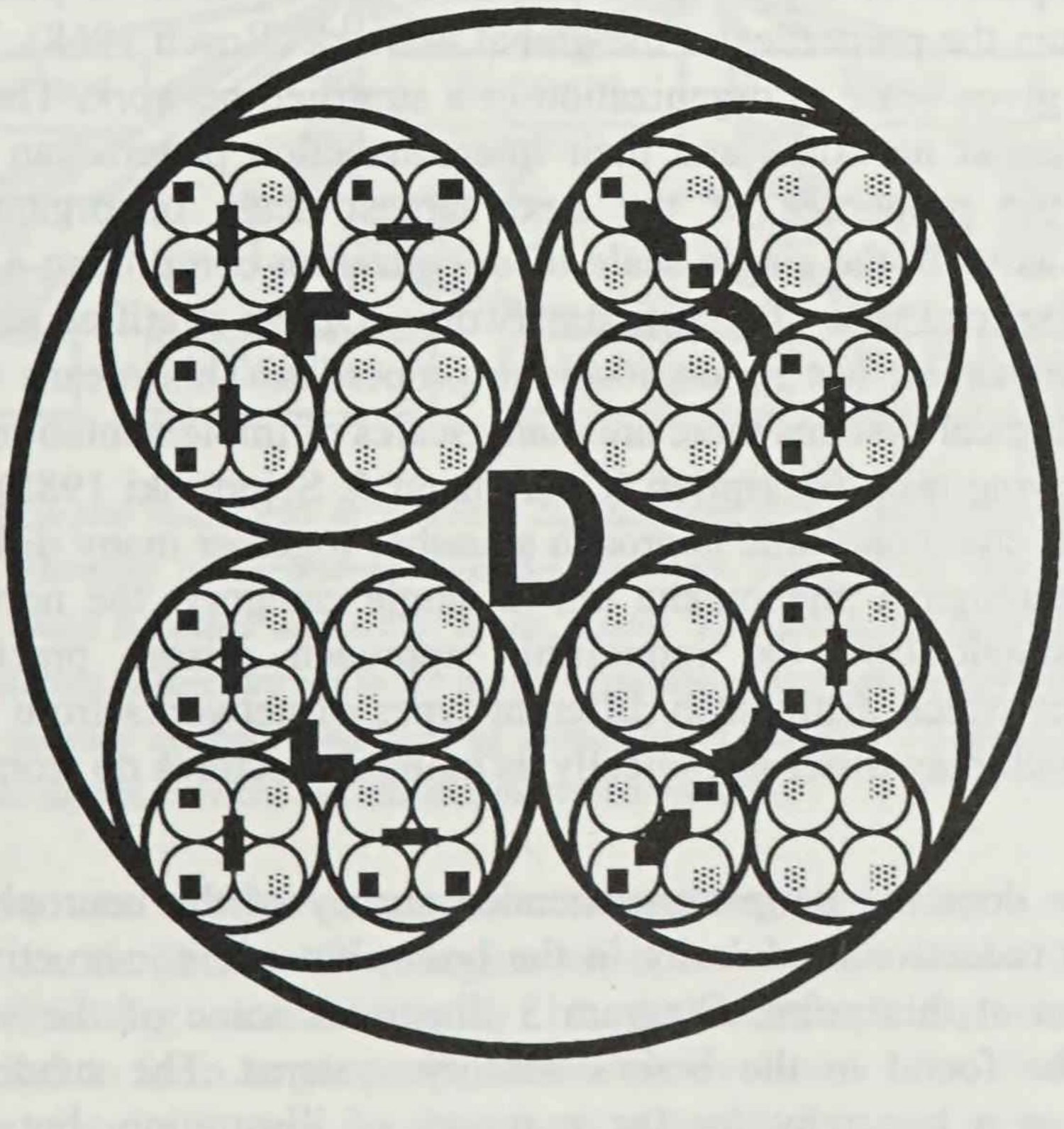


Diagram 2: *Stratified neural networks. Schematic representation of stratified networks. In this type of network, different feature types are 'recognized' at different scales of organization. A feature detector of a given complexity makes its 'decisions' on the basis of the states and organization of the lower scale units of which it is comprised, and on the basis of the activity of the higher order unit of which it is part. Each of the circles represents a process, utilizing the smaller circles contained within it as its constituent process.*

Monolithic and stratified networks are thus differentiated on the basis of their architecture, the difference being whether they can be non-arbitrarily decomposed into smaller constituent networks. In this architectural sense, the notion of neuro-stratification subsumes monolithic networks as a special category. There are many ways to construct new scales of organization from pre-existent neural networks, with construction from bare neurons being a special case of this. Ignoring the special case, a stratified network is one in which there is at least one scale of organization between the neuron and the global scale of the network. In this definition, the standard account of 'partially interconnected networks' being a special case of 'fully interconnected networks' (monolithic) is being modified.

In monolithic networks, neural processes modify and transmit activity within the network in order to achieve the desired global properties of the network. Properties of the neurons and their interconnection pattern can be used to explain the properties of the global network (Rosen 1968). This is also true for any given scale of organization in a stratified network. The properties of the constituent networks and their interconnection pattern can be used to explain to the properties of the next largest scale of organization. So functionally as well, the single scale of organization comprising a monolithic network is a special case of stratified networks. On the stratified account, each scale of organization has its own unique properties. This means that in real neurophysiological systems there are many scales of implementation, each with an accompanying task description (Churchland & Sejnowski 1988). From this point of view, the monolithic approach squashes together many different types of neurophysiological phenomena into a single category: the network. As a form of reductionism, the monolithic approach misses precisely those characteristics which distinguish different types of networks from each other, networks which may differ as radically as atomic structures do from biological ones.

Space does not permit an extended survey of the neurophysiological evidence for recursive modularity in the brain, but one constructive example will be given at this point. Diagram 3 illustrates some of the subdivisions which can be found in the brain's sensory systems. The subdivisions are represented as a hierarchy for the purposes of illustration, but it must be remembered that the relation between the 'levels' in the diagram is one of different scales of organization or complexity. Each 'level' is nested within more complex 'levels'. According to Kaas (1982), movement from the scale of the sensory system to the cortical column involves up to six iterative subdivisions of neural tissue. The subdivisions are based on anatomical and

functional evidence. The sensory system itself is part of the brain's global orgar.ization and the columns can be further divided into layers, local circuits and individual neurons.

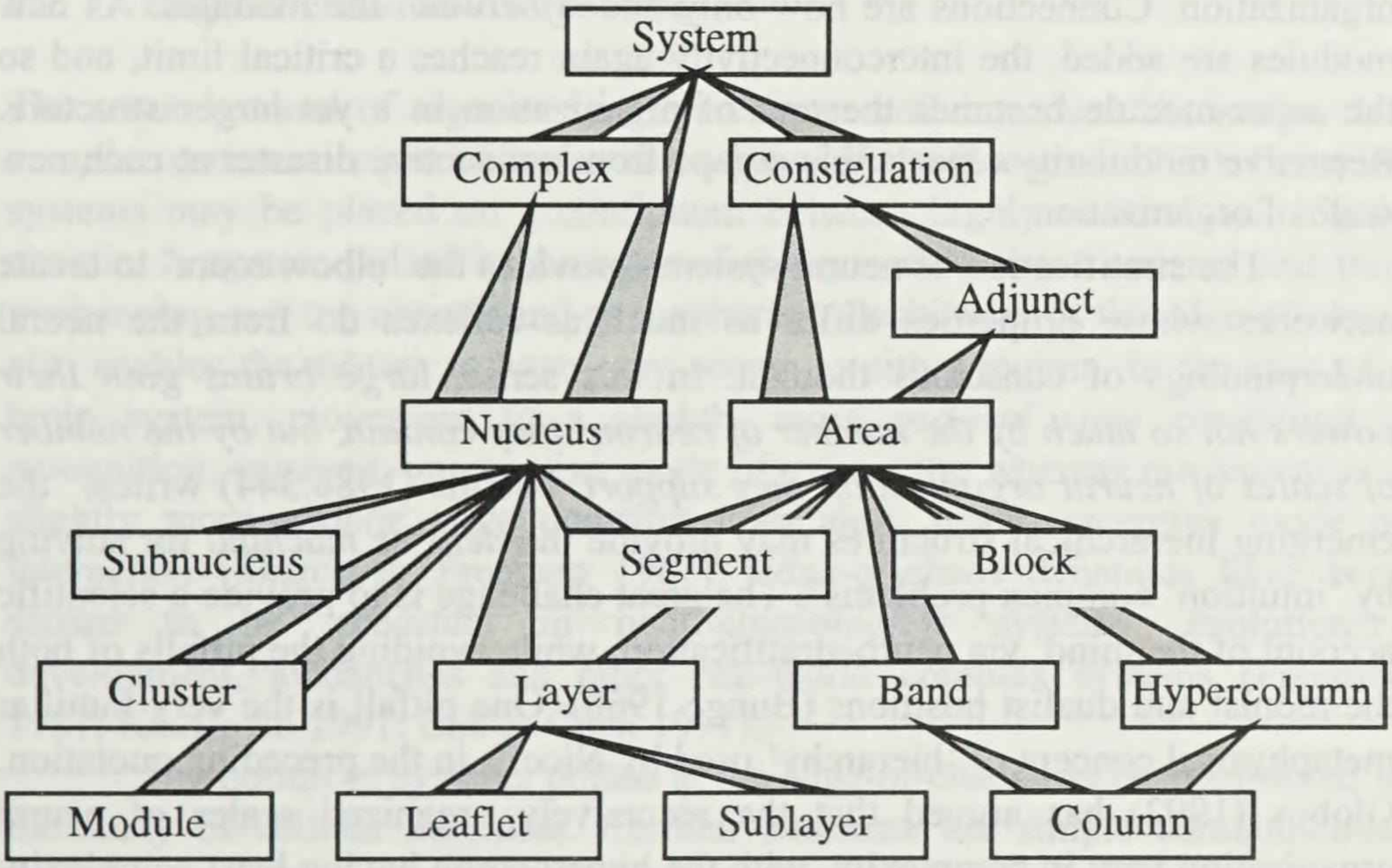


Diagram 3: *Recursive modularity in the brain. Subdivisions in the sensory system, according to Kaas (1982), showing its recursively modular structure. Each 'level' indicates a scale of organization which is nested within the 'levels' above. The connecting triangles indicate this 'is part of' relation. There are up to six iterative subdivisions from the sensory system to the column. The sensory system forms part of global brain function. Columns can be further subdivided into layers, cortical circuits and individual neurons.*

There are further arguments supporting the thesis of recursive modularity in the brain. One argument concerns the evolution of neural structures. Existing structures may be duplicated during evolution, and interconnected to form larger scale structures. Evolution often finds it easier to use existing circuits in new combinations rather that invent new structures *de novo* (Jacob 1977). In this sense, each existing neural structure is a potential *pre-adaptation* for a larger scale of neural organization (Walker & Alexander 1994). Another argument for the necessity of recursive modularity in the brain has been called the *connectivity problem* (Laskoski 1990). A human brain with all neurons fully interconnected would have a circumference of 10 km due to

the extra wiring required (Heemskerk & Murre 1991). The explosion of interconnectivity can be prevented by using a recursively modular architecture. As the interconnectivity *within* a particular scale of organization reaches a critical limit, that scale of organization becomes a module in a larger scale of organization. Connections are now only added *between* the modules. As new modules are added, the interconnectivity again reaches a critical limit, and so the super-module becomes the unit of organization in a yet larger structure. Recursive modularity repeats this escape from connective disaster at each new scale of organization.

The stratification of neural systems provides the 'elbow room' to create networks whose properties differ as much as reflexes do from the neural underpinnings of conscious thought. In this sense, *large brains gain their powers not so much by the number of neurons they contain, but by the number of scales of neural organization they support*. Nicolis (1986:344) writes, "the emerging hierarchical structures may provide the *deus ex machina* for solving by 'intuition' complex problems". The great challenge is to provide a scientific account of the mind, via neuro-stratification, while avoiding the pitfalls of both the monist and dualist positions (Bunge 1968). One pitfall is the very familiar metaphysical concept of 'hierarchy' used by Nicolis in the preceding quotation. Globus (1992) has argued that the recursively organized scales of neural organization vary in complexity, with the hyperneuron having least complexity and the supersystem most complexity. The 'hierarchical' organization of the brain — a core concept of modernity so familiar that it is transparent — needs to be 'deconstructed' in postmodern fashion (Globus 1995).

By encompassing several scales of neurophysiological organization, neuro-stratification forces a different conception of the essential functioning of neural networks. At the heart of the stratified conception of neuroscience lies the cross-influence of activity flows between multiple scales of organization in the supernetwork. According to Globus (1992), brain modules activate, inhibit, tune, participate in and departicipate from the flowing evolution of the supersystem. The supersystem arises out of the functioning of the interconnected parts. At the same time the large scales continuously transform the small on which they are based (Churchland & Sejnowski 1988). The stratified account reveals the possibility of *cascade effects whereby changes at one scale of organization can modify other scales in an exploding chain of reactions up and down the multi-scale structure*. It is such fluid up and down cascades that obviate the traditional 'hierarchical' structure in which the higher controls the lower. Before discussing these between-scale dynamics, it is

necessary to introduce a growing body of thought on the dynamics of complex systems.

2. Edge-of-chaos neurodynamics

The second strand of argument in this chapter will introduce the notion that *complex systems are positioned at the edge of-chaos* (Langton 1990). Complex systems may be placed on a continuum between highly ordered and highly chaotic. A system poised at the edge-of-chaos is neither too ordered and thus unchanging, nor too chaotic and so incoherent. Positioning at the edge-of-chaos also enables the system to have easy access to either regime. In the case of a brain system, movement to a slightly more *ordered state* constitutes a recognition, engaged, unreceptive mode of interaction whereas movement to a slightly more *chaotic state* constitutes an alert, ready, receptive mode of interaction (Skarda & Freeman 1987). Edge-of-chaos dynamics have been shown to be important in neurophysiological systems, evolutionary development, avalanches and other real-world complex systems (Freeman 1987; Kauffman 1991; Bak & Chen 1991).

The notion of systems poised at the edge-of-chaos has been explored in the study of cellular automata. Cellular automata are simple computational devices which switch from one discrete state to another depending only on the states of their neighbors at the previous discrete time step. Large systems of identical automata display properties which are very non-computational (Forrest 1990). The behavior of systems of cellular automata varies from highly ordered crystalline structures to extremely disordered and random boiling masses. These two types of extreme behaviors have been likened by Langton (1986) to the behavior of solids and gases, respectively. Langton reasoned that intermediate forms of behavior in these systems were equivalent to the sublimation of a solid to a gas and in which both types of behavior — chaotic and orderly — coexist in an uneasy balance. Cellular automata with these properties have been discussed by Wolfram (1984), and called *class four automata*.

Class four cellular automata display some unusual properties at the scale of the system. They display complex behaviors which are not seen in either highly ordered nor highly chaotic cellular automata. The complex behaviors seen in class four automata have been described as *extended transients*. These *metastable dynamics* are produced by the tension between order and chaos found in class four automata. Extended transients do not

become stuck in repetitive behavior, instead they propagate somewhat unpredictably. Yet they have clearly observable, coherent patterns in their evolution. Thus, their behavior is effervescent — both *transient* and continuous, extending through time. The structures produced by extended transients have an appearance similar to plant growth or tiny organisms. The most well known example of such a class four cellular automata is called the 'Game of Life' for this reason. An example of the type of complex propagating structures seen in the 'Game of Life' is shown in Diagram 4. It is important to remember that each cell in the 'Game of Life' only takes into account the behavior of its neighbors to decide its future states. The complex dynamics emerge out of these simple properties at a larger scale of organization.

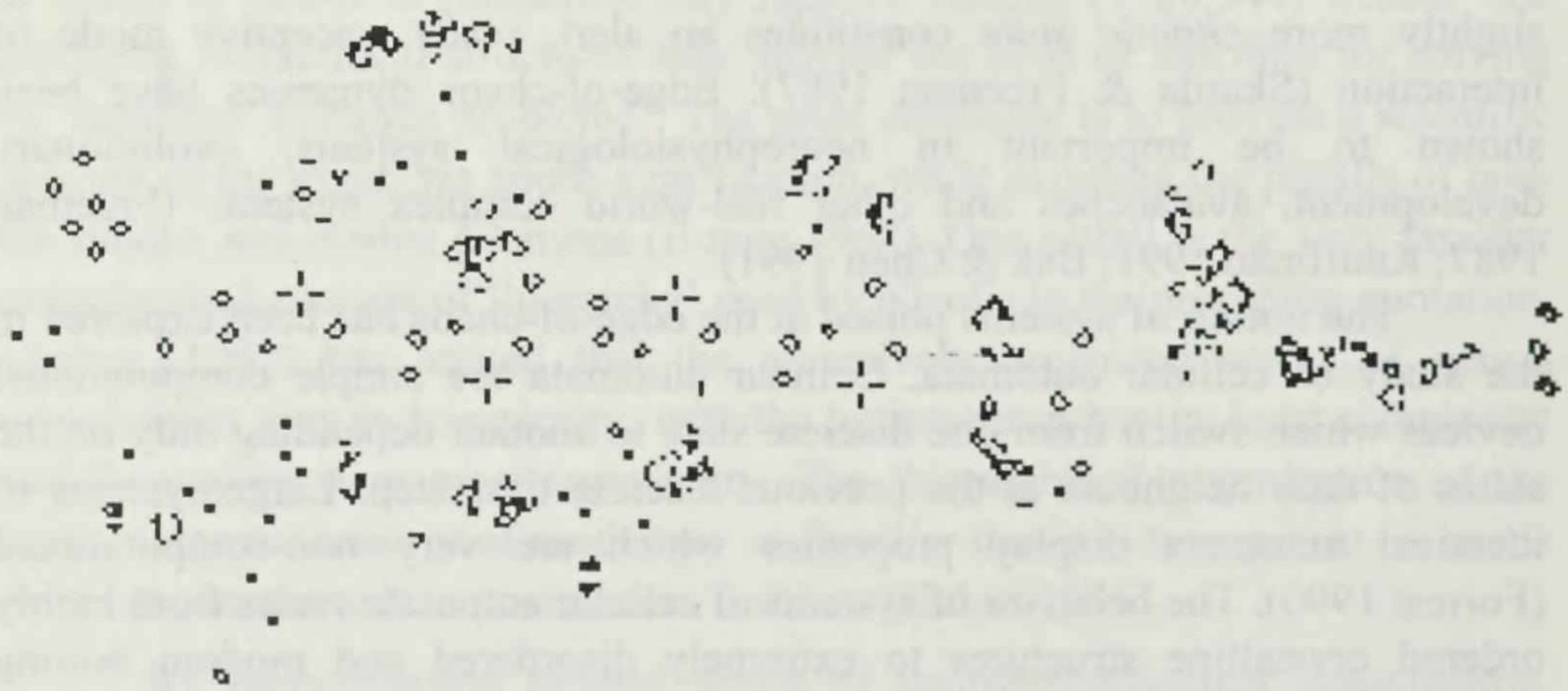


Diagram 4: *Edge-of-chaos dynamics. A structure from the 'Game of Life' — called a Puffer — propagates from left to right leaving a trail of complex interactions. The 'Game of Life' is a two dimensional cellular automata whose dynamics are located at the transition region between order and chaos.*

Extended transients enable the possibility of long range interactions at the global scale. Langton (1990) hypothesizes that, at the edge-of-chaos, a balance is struck between the preservation of local states and the transmission of influence of those states to other cellular automata. In this sense, total order is just as simple as total disorder. In cellular automata, total order does not allow the propagation of influence, locking the system into a rigid pattern.

Total disorder propagates influence too well, destroying any meaningful relation between the states. At the edge-of-chaos, cellular automata are able to influence each other according to a power law distribution (Kauffman 1991). Nearby sites communicate with each other frequently via small avalanches of changes. More distant sites communicate rarely via large avalanches of changes. Extended transients reveal the richest trajectories, optimally positioned between the simplicities of total order and total chaos.

The resultant behavior resembles the dynamics of real-world complex systems capable of producing *solitary waves* (Langton 1990). These particle-like waves preserve their shape and are capable of complex interactions at their own scale of organization. Langton (1990) emphasizes that these complex behaviors are found only within a small region of the order/chaos continuum. However, when the *transition region* at the edge-of-chaos has been located, automata can be devised whose global behaviors display dynamics of arbitrary complexity, for arbitrarily long periods of time (Langton 1990). Langton (1990) hypothesizes that extended transients are implicated the most functionally complex, and *apparently* mysterious, phenomena in nature. The study of edge-of-chaos dynamics in cellular automata is particularly applicable to neural systems (Victor 1990). In neural systems, concepts such as propagating waves, complex dynamics and transitions between order and chaos have become powerful explanatory tools. The edge-of-chaos dynamics found in cellular automata demonstrate that these properties can be produced from systems of relatively simple subprocesses (Rosen 1969).

According to Pellionisz (1989), future neuroscientific research will center on the relationship between ordered and chaotic geometries. There is already growing evidence of the importance of chaotic mechanisms in neural dynamics (Basti & Perrone 1989). Of particular interest here is the evidence that neural systems incorporate edge-of-chaos dynamics in their functioning. Most of the discussion of these neural mechanisms has centered around perceptual tasks involving regions of the cortex. Cortical dynamics poised at the edge-of-chaos function to integrate incoming sensory stimuli into neural dynamics. The essential idea is this: *the cortical area begins in a slightly chaotic trajectory and then relaxes into a more ordered metrical space as the sensory input is successfully recognized* (Pellionisz 1989). This integration is also the basis of attentional mechanisms, enabling focusing and unfocussing on particular stimuli.

Skarda & Freeman (1987) have discussed this mechanism in detail, and hypothesize that it underlies the recognition of odors in the rabbit. The rabbit's olfactory system displays abrupt global jumps via bifurcations analogous to

phase transitions in physical systems, for example, ice to water to steam. The system begins in its basal state, which has the form of a chaotic attractor. Inhalation of an odor, and resultant stimulation of receptors, places the system into a basin of attraction. There are different basins of attraction, in the form of limit cycles, for different odors the rabbit can recognize. Upon exhalation, the system returns from these regular oscillations to its basal chaotic attractor. This process of shifting from chaotic attractor to limit cycle and back is illustrated schematically in Diagram 5. The various types of attractors in the olfactory bulb are emergent properties of the neural mass (Freeman 1987).

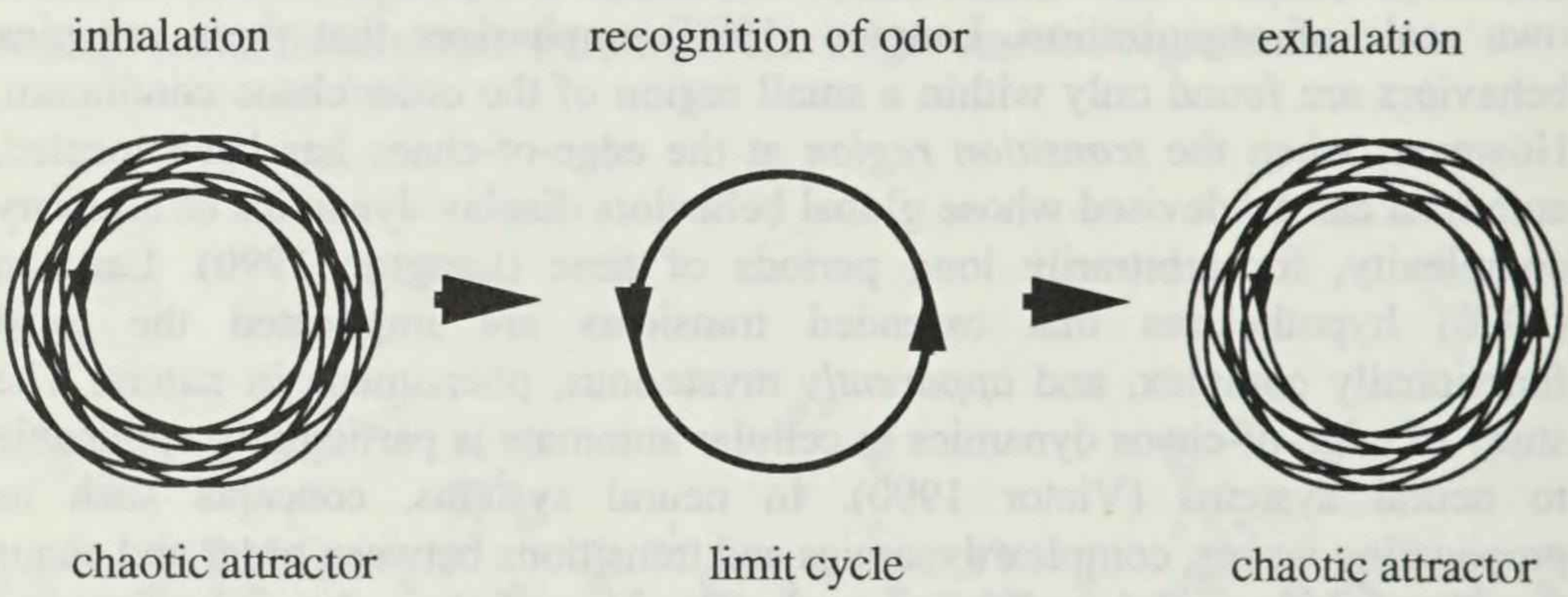


Diagram 5: *Edge-of-chaos neurodynamics. Schematic illustration of rabbit olfactory bulb dynamics described by Skarda & Freeman (1987). The dynamics of the bulb shift either side of the edge-of-chaos as inhalation, recognition and exhalation occur.*

Upon presentation of a *novel* odor, the olfactory bulb is pushed into chaotic activity. This enables the bulb to escape its established repertoire of responses and allows the formation of a new limit cycle attractor to suit the novel stimulus (Freeman 1987). The chaotic attractor also provides a phase-space for the novel stimuli which can be maintained while the bulb builds a new cyclic attractor via *Hebbian learning*. Classification of novel odors is therefore just as quick as classifications of those known. The advantage of neural mechanisms poised at the edge-of-chaos is that the chaos can be turned on and off instantly through a bifurcation. Unlike noise due to heat, the chaotic attractor is a very cheap and simple source of noise and is just as deterministic as the oscillations of recognition (Skarda & Freeman 1987).

The chaotic activity also provides a way of keeping neurons active without getting stuck in a particular non-strange attractor. At the same time the system's trajectory stays in the vicinity of those non-strange attractors. The

random character of the chaotic attractor places the system into a nonbiased state ready for the next inhalation with instantaneous access to all possible non-strange attractors (Skarda & Freeman 1987). There is therefore no 'search' through a memory store, only a subtle shift in dynamics which settles the system into an appropriate recognition limit cycle. As the system makes such a shift from chaotic attractor to limit cycle, it accesses the critical transition region. The rich dynamics at the edge-of-chaos are crucial to the attainment of the final recognition attractor (Langton 1990).

It is worthwhile contrasting edge-of-chaos neurodynamics to those in connectionist systems where convergence to a *point attractor* is the goal (Smolensky 1988). Recognition consists of convergence of the connectionist network to a stable set of output values. However, in natural neural systems, a point attractor constitutes death (Skarda & Freeman 1987). This is resolved in connectionist models by resetting the system from the outside at each new trial. The edge-of-chaos neuro-dynamic posits, on the other hand, that the two main types of neural attractors require only marginal shifts in dynamics to move from a ready state to recognition and back again.

During training, connectionist systems use a *gradient decent* method of error correction, trying to avoid local minima and converge on the lowest energy well. The connectionist's notion of energy minimization through gradient descent can be compared with an idea from the study of protein folding dynamics. The final tertiary structure of a protein is achieved, in part, through the minimization of potential energy in electrostatic and hydrophobic interactions. But the folded state has only *marginally less potential energy* than the unfolded state, making the packing and unpacking of proteins an energy efficient task (Richards 1991). A similar relation applies to learning in edge-of-chaos neural systems. The construction of new attractors involves only subtle shifts in dynamics to the other side of the edge-of-chaos. This means network relaxation is quick and efficient rather than labored and problematic (Skarda & Freeman 1987).

Singer (1988) has described similar shifts between chaotic and ordered regimes in observations of the cat striate cortex. Here large numbers of neurons engage in oscillatory activity between 40 and 50 Hz when the cat's retina is stimulated appropriate to the neurons' receptive fields. These oscillations synchronize across spatially separate columns as far apart as 7 mm (Singer 1988). The basis of these oscillations is a highly non-linear interaction within the cortical columns. Prior to the presentation of the stimulus, the resting state of the columns takes the form of a chaotic attractor of dimensionality 7 to 9. This chaotic attractor is hypothesized to enable quick transitions from a bias-

free state to a recognition limit cycle (Singer 1988). Basti & Perrone (1989) suggest that these properties apply generally to the visual cortex and note the similarity of this perceptual integration mechanism to that proposed by Freeman (1987) for the olfactory bulb of the rabbit.

Soong & Stuart (1989) have used Freeman's (1987) theory to describe patterns found in the human alpha rhythm. The alpha rhythm appears as oscillation within the range of 8-13 Hz. This rhythm corresponds to an attractor state associated with maintained, alert, relaxation. The alpha rhythm displays deterministic chaos; it is globally stable, but there is an exponentially fast loss of predictability in the detail of the alpha rhythm's trajectory. The human brain returns to the alpha rhythm after transitory perturbations caused by external stimulation or purposive mental activity. The alpha rhythm is hypothesized, by Soong & Stuart (1989), to be a global state of great sensitivity to incoming sensory stimuli, enabling the system to easily flip into a new regime.

Ordered and chaotic behavior has also been found at the scale of the neural membrane (Rapp *et al.* 1985). Mpitsos *et al.* (1988) have demonstrated chaotic patterns in the spike trains of individual neurons. We propose that *edge-of-chaos dynamics are utilized at all scales of organization in the nervous system*. At any given scale of neural organization, *S*, the neural system is poised at the edge-of-chaos. The system at scale *S* shifts subtly either side of the edge-of-chaos to utilize more ordered or more chaotic regimes and to take advantage of the rich dynamics to be found in the narrow transition region between the two regimes. At each scale of organization, *S*, chaotic attractors correspond to an alert, ready, receptive mode of interaction. For each *S*, the non-strange attractors correspond to a recognizing, participatory, unreceptive mode of interaction. These concepts apply to motor systems as well as sensory ones. Skarda & Freeman (1987) refer to processes of destabilization and reconfiguration of motor processes by sensory systems.

3. Influence between scales of organization

So far this chapter has described two related ideas. First, that brains have a recursively modular structure. Second, that any given scale of organization utilizes edge-of-chaos dynamics. These two ideas may be brought together when we ask what happens *between* scales of complexity as the shifts from either side of the edge of chaos are being made. Freeman (1988) has begun such an endeavor with his notion of conversion between pulse mode (action potentials) and wave mode (local cortical EEG) and then back again. Harth

(1983) has likened the shift between ordered and chaotic states in brain tissue to laminar and turbulent flow in fluids. In turbulent mode the macro-scale turbulence is an expression of microscopic variations in the structure of the flow. In the stable flow, this between-scale communication is reversed. Such flows may alternate swiftly, under certain conditions, between stability and turbulence, revealing edge-of-chaos dynamics (Shaw 1980).

The term 'laminar flow' refers to fluid moving in an ordered fashion. For example, water traveling slowly down a pipe exhibits a laminar flow. The trajectory of a laminar flow can, in principle, be completely described by an observer in terms of macroscopic observations about the velocity field (Shaw 1980). A laminar flow is completely predictable from its previous macroscopic behavior. As the flow speed increases past a critical point, the flow suddenly breaks into turbulence. A turbulent flow is not predictable from its previous observed macroscopic behavior. It is chaotic, revealing an exponential loss of predictability from the time of a first observation (Nicolis 1986). Given this sensitive dependence on initial conditions, the flow is a continuous source of unpredictable behavior. Shaw (1980) suggests that the novelty in the turbulent flow is produced from the configurations of particles interacting at the microscopic (i.e., molecular) scale. The particular quality of the turbulent flow is to magnify microscopic interactions up to the macroscopic scale.

Shaw (1980) describes the chief difference between laminar flows and turbulent ones. This difference is the direction of influence between scales (flow of Shannon-Weaver information, in Shaw's terms). In a laminar flow, macroscopic novelty is not generated by the flow. The motion of the flow is bounded by its initial macroscopic conditions. The large scale motion of the laminar flow causally constrains the molecular scales, keeping interactions at this microscopic scale within the bounds set by the laminar flow. Microscopic perturbations are absorbed into the orderly macroscopic behavior of the non-strange attractor. In turbulent flows, however, macroscopic novelty is constantly generated within the flow itself. Influence is now being projected up from the microscopic scales to macroscopic expression. The strange attractor allows the microscopic interactions of the system to initiate macroscopic events. The direction of influence is now reversed (Shaw 1980). This is illustrated in Diagram 6. Using the flow metaphor, we have the beginnings of a formulation with which to understand edge-of-chaos dynamics as a phenomena of *between-scales* influence.

Shaw (1980) makes some interesting observations about fluids whose velocity is near the critical transition point between laminar and turbulent flows. At this point, water passing down a pipe can alternate swiftly between

laminar and turbulent flow. This means the direction of between-scales influence is also swinging up and down. The turbulent phases effect the velocity of the water locally, speeding it up beyond or slowing it down below the transition speed. At the critical transition speed, therefore, the water provides its own dynamics, switching itself between laminar and turbulent flows depending on the complex past history of its dynamic trajectories (Shaw 1980). There is a strong parallel between this conclusion and the finding in cellular automata theory that the most complex behaviors of a system are found at the edge-of-chaos.

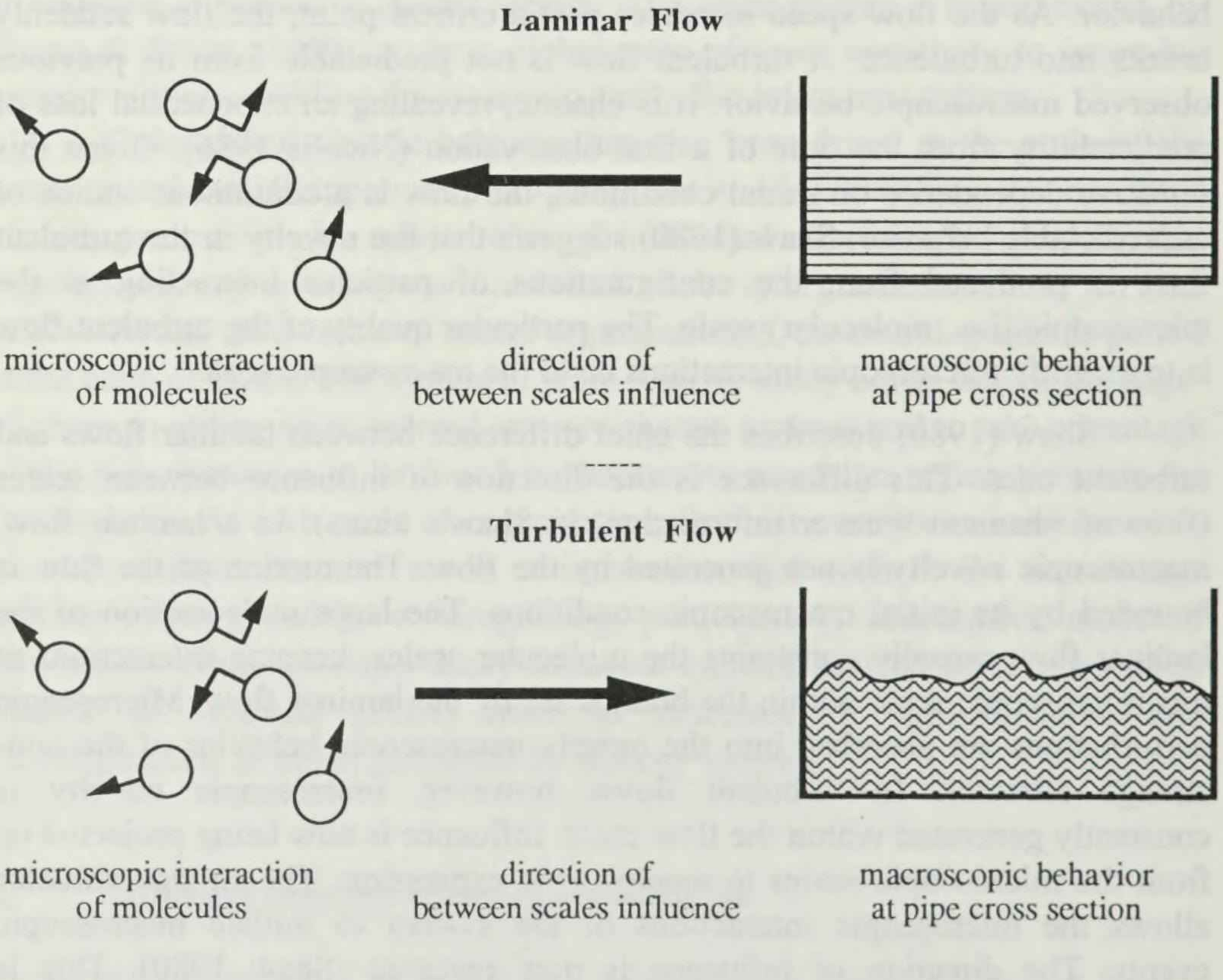


Diagram 6: *Between-scales influence. Schematic representation of laminar and turbulent flows, described by Shaw (1980). The ordered behavior of laminar flows is a product of the macroscopic behaviors constraining the interactions available to the microscopic molecules in the flow. The chaotic behavior of turbulent flow is a product of microscopic variations being magnified up to the macroscopic behavior of the flow. The microscopic interactions are the source of the novel behavior of the turbulent flow.*

Harth (1983) has related concepts about laminar and turbulent flows to brain dynamics. While agreeing on the utility of these concepts to neuroscience, he points out crucial differences between these dynamics and the properties of flows. In neural systems, the underlying fluctuations are not noise or *mere* perturbations, but contain meaningful information about the structure of an organism's environment. These structured perturbations do not cause *merely* turbulent and hence meaningless macroscopic behavior. The perturbations are filtered up through multiple scales of neural organization. At each scale of the neural structure, previous experience is embedded in the topology of various types of attractor spaces. The emerging behavior of the organism is the macroscopic counterpart of the laminar and turbulent behaviors in fluids (Harth 1983).

Similar concepts have been applied in detail to the behavior of the rabbit olfactory bulb by Freeman and others. There are two different physical scales at which observations are made. Individual neurons in the olfactory bulb are measured with a microelectrode. The behavior of the neural mass is measured by an array of micro-electrodes placed on the surface of the olfactory bulb. In a typical experiment, odors are presented to a rabbit. The presentation of each type of odor activates different constellations of neurons, indicating selective activation of the bulb by different odorants. The sensory input into the olfactory bulb takes the form of labeled line coding: each neuron typically responds reliably to particular odorants with the pulse rate or pulse probability as the state variable. Recognition of an odor is observed as simultaneous traces of a common waveform or carrier across the olfactory bulb. These waveforms vary in amplitude across the spatial extent of the bulb. Odor specific patterns in the waveform recur on presentation of odorants to the rabbit, but only if the subjects are trained to discriminate them and only if they are motivated to do so (e.g., by reward). Therefore, learning and arousal are essential to the formation of this global waveform in the olfactory bulb (Freeman 1988).

The dynamics of recognition cycle bear remarkable resemblance to the flow metaphor. This resemblance can be seen most clearly in Diagram 7. The state of the neural mass prior to recognition is a chaotic waveform with low amplitude and low gain (Freeman 1988). The neural mass is only loosely integrated and individual neurons are free to react to information coming up from the labeled lines. The activity of neurons so stimulated effects the wave-trajectory of the cortical mass. This results in the chaotic basal state described earlier. Described in terms of the dominance of individual neural processes, this is called *pulse mode* by Freeman (1988). Pulse mode is analogous to the turbulent phase in the flow metaphor. The direction of influence is from the

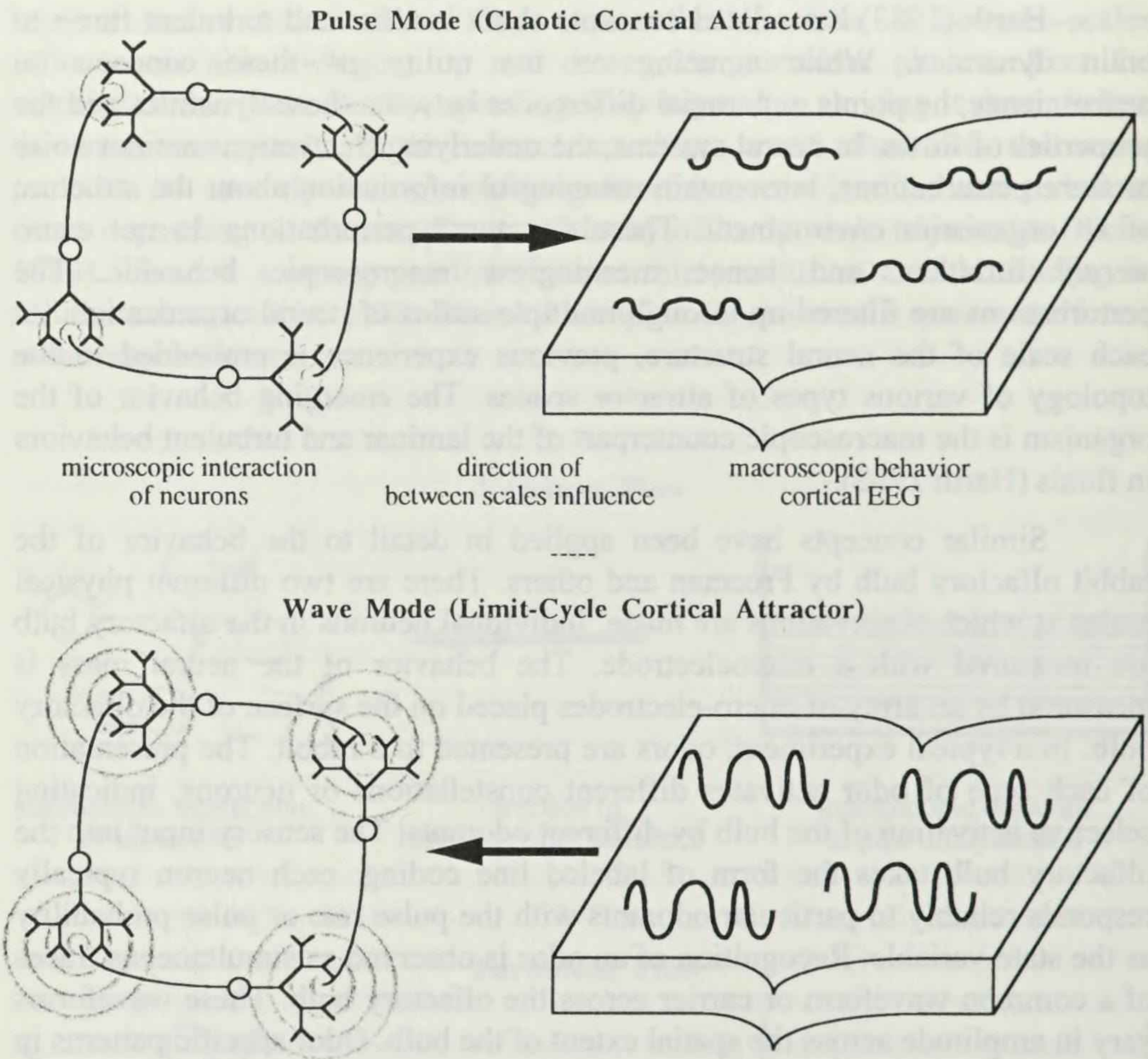


Diagram 7: *Influence between neural scales. Schematic illustration of the differences between pulse mode and wave mode in the odor recognition cycle of the rabbit's Olfactory Bulb. During pulse mode, labeled-line neurons respond to incoming stimulation. The neurons interact freely, and perturbations in their activity are magnified to the cortical scale in the form of a low amplitude chaotic attractor. The chaotic, low amplitude wave-form varies over the spatial extent of the olfactory bulb. The onset of wave mode is marked by a sudden increase in the density of neural interaction in the mass — indicated by the grey circles in the diagram. This increased density of interaction induces a high amplitude limit cycle in the wave-form which projects to all areas of the bulb, constraining the interaction of constituent neurons. During wave mode, the bulb is no longer sensitive to incoming stimulation.*

microscopic (individual) neural processes to the macroscopic (cortical mass) chaotic state. The dynamics of neural systems contrast with various physical systems and cellular automata in one respect. According to Freeman (1988) the chaotic basal state is a *low-energy* state. This contrasts with other systems in which the chaotic attractor is associated with a *high-energy* state. There is no necessary contradiction here, since qualitatively different systems are involved. The crucial parallel still holds: the relation between attractor type and direction of between-scales influence.

Each neuron in the mass receives input from up to 10^5 axon tips of other neurons. A small increase in synaptic efficacy (25-40%) increases the sensitivity of the bulb to a stimulus by 40,000 fold (Skarda & Freeman 1987). Sufficient input (of appropriate stimulatory configuration) leads the neurons in an assembly to interact strongly. The amplitude and gain of neural mass activity increases (Freeman 1988). When this occurs beyond a critical density of interaction, the interconnected ensemble undergoes a state transition to a highly stimulated state. Here, density of interaction is analogous to the velocity of water in the flow metaphor. This critical density of interaction is also analogous to the concept of critical transition regions discussed in relation to cellular automata. The role of density of interaction will be further defined in sections to follow.

Freeman (1988) calls the highly stimulated state *wave mode*, indicating the dominance of the global wave-form. The highly interactive state of the wave mode incorporates stimulatory influence received during the preceding phase and transmits it many square millimeters distant within a few milliseconds. The spatial density of this transmitted influence becomes uniform, in other words, the wave-form now causally constrains the activity of the individual neurons. The wave mode is analogous to the laminar phase in the flow metaphor. The direction of between-scales influence is from the global wave-form to the individual neurons. Cooperative activity shared by the whole is injected into the succeeding stage of pulse mode. This injection of influence into the new pulse modes helps clean incoming stimulation by attenuating any conflicting signals. Under wave mode, the original inputs are integrated spatially in a process which introduces past experience via the learned structures of the nerve cell assemblies. During wave mode, the bulb is *no longer sensitive* to further inputs (Skarda & Freeman 1987).

According to Freeman (1988), the key to understanding the state transitions occurring in the olfactory bulb is the flow of influence from the local to the global and then back again. The different attractors described in the activity of the bulb can now be understood in terms of alternation of direction

of between-scales influence. The chaotic basal state allows the injection of stimulation through labeled lines. The individual neural interactions are magnified upwards and influence the trajectory of the global wave-form in a chaotic fashion. The limit cycle attractors of recognition are the result of integration of this influence into a coherent and ordered wave mode. The ordered nature of the recognition limit cycle is maintained because the global wave-form constrains the interactions of individual neurons as that wave-form is transmitted throughout the bulb. The wave mode also integrates the present state of expectation (arousal) and the motives of future action (Freeman 1988). Wave mode can therefore be seen as incorporating some of the higher mental functions, apart from merely taking place at a large physical and temporal scale.

4. Neural systems as fractally embedded oscillators

Further neural realism may be injected into the flow metaphor by utilizing the recent work on coherent oscillations in the brain. The nervous system can be conceived as a series of embedded limit-cycle processes, from membrane oscillations and spike trains at one end to global EEG at the other. We note that a system of coupled oscillators has all the regimes of other complex systems, including chaotic, ordered and semi-chaotic — semi-chaotic regime corresponding to the extended transients found at the edge of chaos (Matthews & Strogatz 1990). Further, such a system displays the ordered, semi-chaotic and chaotic oscillations at the global scale. These global oscillations occur over larger spatial and temporal scales than the constituent oscillators; that is, the global oscillations are able to form the constituent units in the next scale of the hypothetical neural level structure.

Before extending our analysis of between-scales influence to multiple scales of neural organization, evidence for oscillatory processes — limit cycle attractors — at various scales of brain structure will be examined. According to Freeman (1988), the results found for the olfactory bulb are comparable to those found for other areas of the olfactory system and the primary visual cortex of the Rhesus monkey and the cat (Freeman, 1988). There are many known oscillatory patterns in the cortex, including the alpha-rhythm and the theta-rhythm which both involve the hippocampus (Crick & Koch 1990). The present hypothesis is that limit cycles are ubiquitous in nervous systems. *Coherent oscillations are hypothesized to be the ordered, non-strange attractor of the brain's edge-of-chaos dynamics*. It has already been noted that chaotic

and ordered oscillations have been found within the dynamics of neuron membrane potentials (Rapp *et al.* 1985). Empirical evidence shows that oscillatory processes span the brain's organizational depth, from the neuron to the supersystem. The ordered, limit cycle attractors are the focus of the following discussion, because neuroscientists have only recently begun to examine the role of strange attractors in neural dynamics.

New statistical and measurement techniques have revived the idea that the communication code of individual neurons lies in their spike trains (Frostig *at al.* 1990). This view contrasts with the idea of neurons as possessing an averaged firing rate which encodes the crucial information (Klemm & Sherry 1982). The new techniques in spike train analysis involve the use of multiple single neuron recordings and complex comparisons of spike trains. The essential finding is that patterns in spike trains are ubiquitous, and recur with precision within a single neuron's spike train and between different neurons (Frostig *et al.* 1990). The ability of neurons to utilize such fine grained oscillatory processes as spike trains has been questioned, involving arguments about synaptic precision and temporal dispersal of the spike's signal (Douglas & Martin 1991). Recent work by Gerstner *et al.* (1993) has shown that, provided the complex spatio-temporal structure of the neuron is taken into account, neurons are able to overcome the limitations of individual synaptic firing and reconstruct the crucial content of the spike train. Other evidence also points to the ability of individual neurons to process spike trains, for example, analyses showing that neurons are basically coincidence detectors rather than integrators of activity over time (Abeles 1982). It has been theorized that neurons further process the oscillatory patterns of spike trains by selective blocking of outbound spike trains in axonal arborizations (Chung, Raymond & Lettvin 1970; Luscher & Shiner 1990).

The bursting behavior of some cells is viewed as a higher order type of oscillation (Chung, Raymond & Lettvin 1970). Oscillatory dynamics have also been found to be ubiquitous in the study of insect motor patterns. According to Smith & Feldman (1990), rhythm generation can be a function of rhythmically bursting cells, a function of a neural circuit, or an interplay between both. This interplay occurs where the circuit alters the natural oscillation of the bursting cell. Alternatively, Selverston (1980) argues that endogenous bursters are mainly used as driving elements in larger rhythm generating circuits. The rhythms observed are interpreted as emergent properties of the network. Gallistel (1983), advocating a recursively modular approach to higher brain functions, lists the oscillatory circuit as one of the important base networks from which higher order circuits may be constructed. Chaotic-oscillatory

dynamics are hypothesized to be important to neural masses other than the cortex (Freeman 1988).

Oscillatory processes have been found in the larger neural masses which guide motor activity, such as the inferior olive (Pettigrew 1994). Perhaps the most exciting work in this area has been the rash of discoveries regarding the importance of oscillatory processes in the large scale sensory systems (Freeman 1988; Eckhorn *et al.* 1988; Singer 1988). Some of these findings have been discussed in previous sections. Eckhorn *et al.* (1988) utilized new, multiple electrode techniques to measure resonances in the cat visual cortex at 35-80 Hz. They hypothesize these oscillations to be a binding mechanism for different visual attributes and across different regions of the visual cortex. The oscillations are assumed to be a pre-attentive perceptual mechanism, linking features such as proximity in space, spatial frequency, movement direction and near simultaneity of events (Eckhorn *et al.* 1988). Visual features having a high degree of relatedness create coherent resonances which act as a temporal label linking the features together. The stimulus-evoked resonances recorded at various cortical positions showed almost zero phase-lag throughout vertical layers of a cortical column and across vertical columns. In different areas with common coding properties, synchronization was also observed. Eckhorn *et al.* (1988) suggest that the oscillatory correlation code is used within and between different cortical sensory systems and may be used throughout the entire brain. To rephrase this in terms of attractor dynamics: limit-cycle oscillations are implicated in the recognition phase at the scale of cortical sensory systems. These non-strange attractors may extend spatially across several cortical sensory systems, incorporating in their coherent dynamic various types of sensory modality.

Further evidence for multiply embedded limit-cycle brain dynamics comes from analyses of various organism's sensory fibres. Two examples will be given here. According to Tech (1989), the cat's primary auditory fibres show spike trains of a fractal nature. That is, the spike occurrences are correlated over multiple time scales. Tech (1989) used a measure of event clustering which is self-similar over different time scales. Subclusters form clusters at larger and larger time scales until the limit of the duration of the recording. The fractal dimension of the auditory neural spike train was found to be in the range $0.3 \leq D \leq 0.9$. The auditory spike train thus takes a form which can be likened to a temporal Cantor Dust. Tech (1989) argues that the fractal clustering is intimately related to the dynamics of the brain.

Chung, Raymond & Lettvin (1970) have demonstrated the presence of nested patterns of spike activity in the dimming fibres of the frog. They

describe three scales of oscillatory organization in the spike trains. The first scale comprises the individual spikes themselves. At the next temporal scale, the individual spikes tend to fall within specific bursts. At an even larger temporal scale, the bursts of spikes fall within definite patterns. The clarity of the three temporal scales of spike-patterns can be seen in Diagram 8. The spike-patterns are initiated by a flash of bright strobe light to a darkness accustomed frog. The patterns can only be seen in composite records after a hundred presentations of the stimulus. The considerable overlap in the records indicates that the patterns at the larger temporal scales are very reliable. In addition, the patterns found at the largest scales reliably predict the stimulus intensity (brightness of light) which invoked them. As the stimulus brightens, the frequency of bursts increases and the patterns within a burst also change. Chung, Raymond & Lettvin (1970) interpret their results as a multiple encoding of meaning at various scales of spike-train organization. The multiply-embedded oscillatory patterns enable the simultaneous transmission of multiple modes of influence; each mode is transmitted at an appropriate temporal scale. Such a method of communication would be ideally suited to recursively modular oscillatory neural networks.

In terms of the present discussion, fractal clustering of spike trains is precisely the sort of patterning one might expect in recursively organized neural processes with oscillatory dynamics. It is hypothesized that *sensory channels transmit multiple messages, each encoded as an oscillatory process at different temporal scales*. According to Harth (1983), qualitatively different types of neural processes can be distinguished by the time scales over which they occur. Higher brain functions occur over a time period of more than 300 ms, which is outside the range of the much faster reflexes. Conscious activity requires sustained dynamics, with a delay of at least half a second between presentation of a stimulus and its conscious realization. Harth (1983) explains these time differences in terms of different spatial scales of neural tissue which support the various processes. Harth's (1983) observations relate to the fractal clustering of spike trains: neurons and neural masses at various spatial scales are influenced by the oscillatory message appropriate to their own scale of organization.

Freeman (1988) captures a similar idea with the notion of the pulse probability wave. Here a bi-scale organization of the spike train simultaneously takes part in two scales of neural processes. The pulse aspect is generated by individual neural processes, while the probability-wave aspect is generated at the scale of the cortical mass. This larger scale oscillation appears as a rise and fall in the *probability* of the spiking action of any particular individual neuron.

Thus, small scale pulses are embedded within larger scale waves in a fractal-like manner. Another example, from Freeman (1987), is given in Diagram 9. The diagram shows two scales of oscillatory dynamics, the largest associated with integrated activity over the entire olfactory bulb. The smaller oscillations are also seen in unmotivated, awake animals in which the activity across the bulb is more diffuse. These smaller oscillations are therefore likely to be associated with the fluctuating action of subcortical neural circuits.

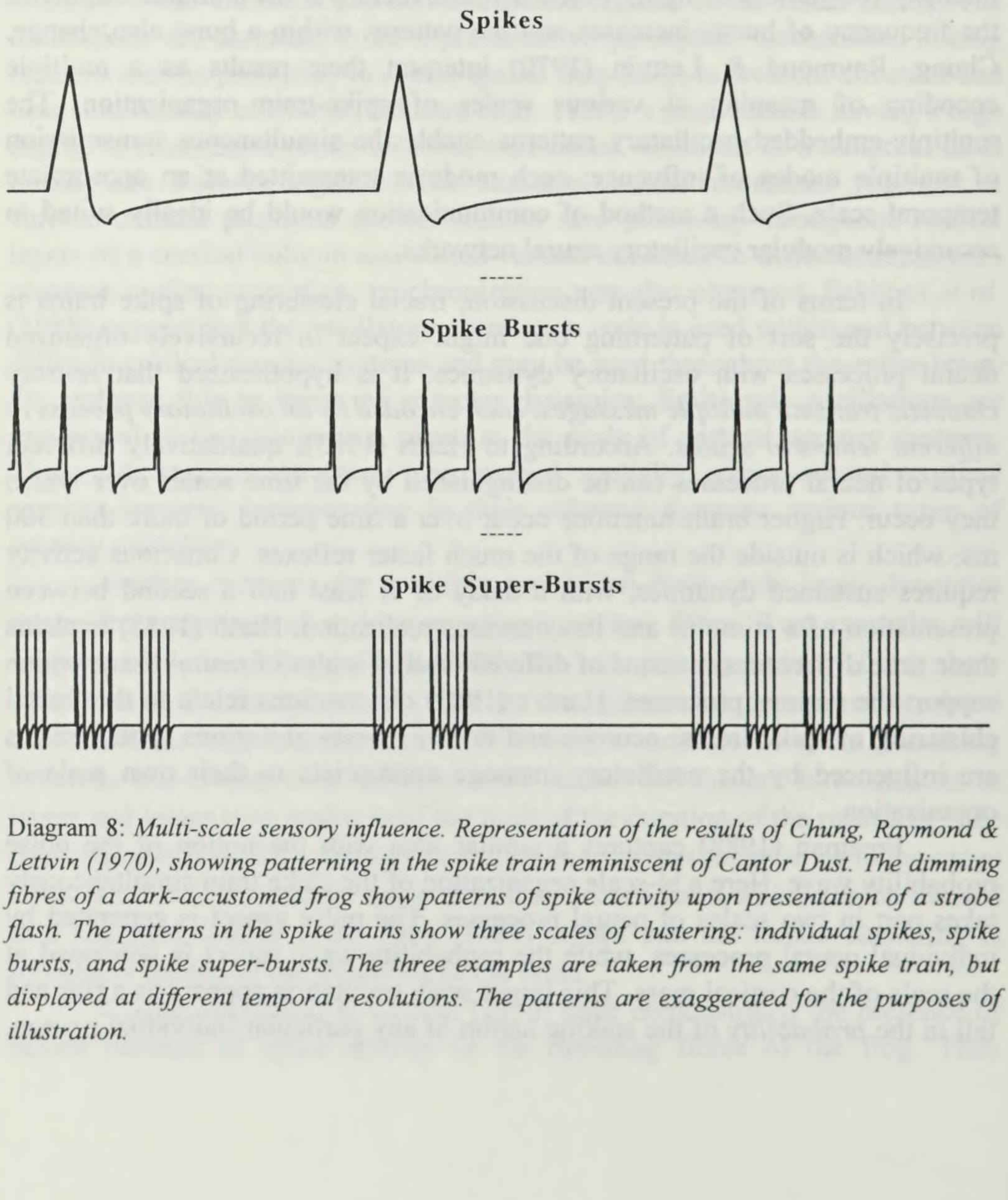


Diagram 8: *Multi-scale sensory influence. Representation of the results of Chung, Raymond & Lettvin (1970), showing patterning in the spike train reminiscent of Cantor Dust. The dimming fibres of a dark-accustomed frog show patterns of spike activity upon presentation of a strobe flash. The patterns in the spike trains show three scales of clustering: individual spikes, spike bursts, and spike super-bursts. The three examples are taken from the same spike train, but displayed at different temporal resolutions. The patterns are exaggerated for the purposes of illustration.*

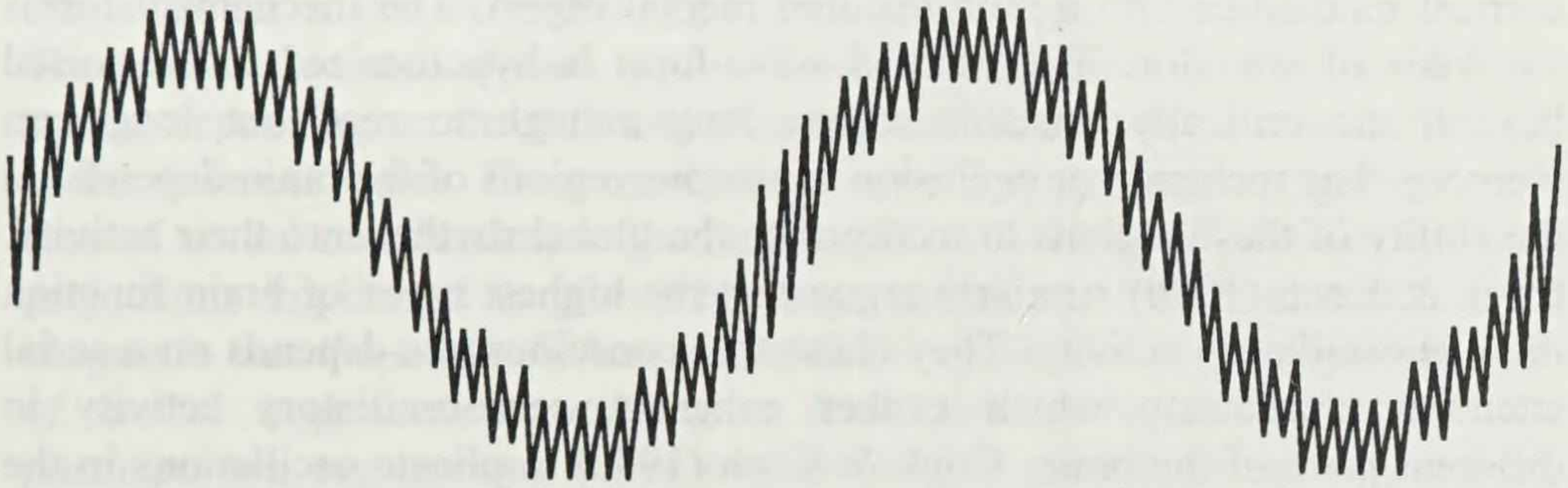


Diagram 9: *Fractally-embedded oscillatory dynamics. Schematic representation of activity in the olfactory bulb of a motivated rabbit. Oscillations are seen at two different time scales, revealing a fractal-like relation. The largest oscillations occur over a period of 0.5 seconds and coincide with the breathing cycle of the rabbit. Unmotivated, awake subjects do not show high-amplitude, ordered oscillations at the large scale (Freeman 1987).*

Freeman (1988) has reproduced some of the results from the rabbit olfactory bulb with the visual cortex of the Rhesus monkey. Here as well, the visual features are mapped spatially in the cortex as firing rates of labeled line neurons. Upon visual recognition, the Rhesus monkeys show specific identifiable patterns of amplitude modulation across the cortical mass. Also like the rabbits, these amplitude patterns only arise when the monkeys are motivated and trained to discriminate the cues. It is worth reiterating, therefore, that oscillatory processes are important to higher brain functions such as learning and motivation. Damasio (1989) has suggested that oscillatory processes are the brain's solution to the binding problem at the global cortical scale as well. Phase-locked loops in the forward integration areas of the cortex feed back to enhance or suppress the activity in sensory areas. The integration of sensory experience and past experience depends on phase-locked activations in these separate regions. Damasio (1989) stresses that the feedback connections between the 'higher' and 'lower' centers of the brain are reciprocal and that there are no specific integrative cortices. Coherent activity across multiple centers is necessary for global cortical binding to occur.

Similar ideas have been expressed by Kryukov & Kirillov (1989). According to these authors, the brain is capable of being excited globally at only one dominant frequency and phase. This global carrier combines different

cortical modalities into a multifeatured mental object. The mechanism forms the basis of attention. The ordered wave-form is hypothesized to be poised beyond the critically unstable region long enough to read out long-term memory. The inclusion or exclusion of various regions of the brain depends on the ability of these regions to incorporate the global rhythm into their activity. Crick & Koch (1990) similarly argue that the highest types of brain function involve oscillatory activity. They claim that consciousness depends on a serial attention mechanism which evokes coherent, semi-oscillatory activity in different parts of the brain. Crick & Koch (1990) implicate oscillations in the 40-70 Hz range; the activity of these oscillations is said to invoke short-term memory. Globus (1995) formulates coherent oscillations differently. He considers the 'binding problem' to be a false problem, typical of modernistic thought where parts (here features) are composited into a whole. Systems fluidly participate in and departicipate from the supersystem, subsystems fluidly participate in and departicipate from systems, and so on. Attention, on this formulation, is the facilitation of participation. Coherent oscillations, then, are the vehicles of participation.

There has, over the past five years been a steady increase in research devoted to the study of artificial limit-cycle neural networks. These studies include the use of neural spike trains (Alexander 1994; Dayhoff 1988), simulations of biological results in the cat visual cortex (Eckhorn *et al.* 1990), simulations of biological results in the olfactory bulb of the rabbit (Yao & Freeman 1990) and the use of oscillatory coordination in large-scale re-entrant maps (Sporns *et al.* 1989). There have been numerous explorations of the binding problem utilizing oscillatory networks (Kammen *et al.* 1990) and even hierarchically linked oscillatory networks (Lumer & Huberman 1992). Of particular interest has been Baird's (1990) construction of oscillatory networks which use biologically realistic connection fibres and Hebbian learning. Baird has shown that such networks are able to function as content addressable memories. The networks store amplitude patterns using the mechanisms thought to underlie sensory pattern recognition in the olfactory system. Most recently, Jennings (1994) has demonstrated the feasibility of Freeman-type networks for hand-written character recognition.

The multiply-embedded oscillatory processes found in brains may be summarized as follows. Each scale of brain organization supports non-strange attractors which take the form of limit cycles (an oscillation, spike, rhythm or wave). The wealth of neuroscientific evidence available illustrates the self-similarity of this ordered dynamic at all scales of brain organization. The wave-like processes occur within the neural membrane, in spike trains, spike bursts,

and at larger scales of neural organization including measurements of EEG. The exact state space of each type of limit cycle attractor may vary at different scales, depending on the different physical and biological mechanisms at each of the different scales. These mechanisms vary from molecular transport, in the case of neural membranes, to the large scale excitatory and inhibitory cortical projections implicated in global binding oscillations. The hypothesis of this chapter is that *the edge-of-chaos dynamic is self-similar across multiple scales of neural organization, utilizing a limit-cycle attractor for recognition, participation, engagement states and utilizing a chaotic attractor for ready, receptive, disengaged brain states*. It seems likely that the burgeoning literature on chaotic dynamics in the brain will reveal the ubiquitousness of the chaotic half of the brain's edge-of-chaos dynamics, as has been shown above for limit-cycle attractors.

Thus far in this chapter, the plausibility of the brain as a recursively nested set of limit-cycle/chaotic processes has been argued. A scheme for understanding influence between adjacent scales of this fractal-like structure has also been introduced. Next, evidence from non-linear systems theory will be discussed which will enable further clarification of dynamics between multiple scales of nested oscillatory processes. Matthews & Strogatz (1990) have simulated the collective synchronization of coupled limit cycle oscillators. The simulations involve a system of limit-cycle oscillators, each with its own natural frequency and each loosely influencing all other limit-cycle oscillators in the system. With low coupling strength, the individual oscillators maintain their 'natural' frequencies. As coupling strength increases, new synchronizations spontaneously emerge.

Matthews & Strogatz (1990) have described several types of global oscillatory behavior in the system, including periodic, semi-chaotic and chaotic. These global synchronizations are measured by a *complex order parameter* which reveals the average phase and frequency relationships of constituent oscillators over the entire system. The global synchronizations occur at the spatial scale of the entire system and at a much larger temporal scale than the cycle of individual oscillators. Nicolis (1986) has also described the same basic fates of a system of coupled oscillators. These three fates range from total entrainment, which is a form of self organization like crystallization, to part entrainment — extended transients in Langton's (1990) terms — and chaos. In the chaotic fate, trajectories of the system are attracted but do not cross; rather, they converge exponentially. The three basic fates of a system of coupled limit-cycle oscillators arise from deterministic interactions (Nicolis 1986).

The first point of interest is that such a system of coupled limit-cycle oscillators reveals all the regimes of behavior described for other complex systems: ordered, chaotic and semi-chaotic. Similarly, the most interesting behaviors (from the point of view of edge-of-chaos dynamics) all occur within a critical transition region of coupling strength. So, using limit-cycle oscillators as the constituent unit of a larger system produces the types of system behaviors of interest in this chapter, paralleling the same edge-of-chaos dynamics. The second point is that the new limit-cycle and chaotic attractors are global behaviors, occurring at the spatial scale of the system and at a larger temporal scale that the constituent oscillators. These new global oscillations are therefore suited to building yet larger scales of organization, that is; forming constituent processes of a supersystem. Consider the ordered side of the system's edge-of-chaos dynamics. The ability of limit-cycle constituent systems to form limit-cycle global behaviors provides a bridge to building larger and larger systems of limit-cycle processes, using a recursively modular strategy. Looking at this building process from the other end, our original constituent limit-cycle oscillators may themselves be constituted by a system of smaller scale limit-cycle oscillators and so on. Matthews & Strogatz's (1990) exploration of coupled limit-cycle oscillators provides an elegant proof that wave-like processes are capable of sustaining the recursively-embedded dynamics we have theorized to be the basis of brain function.

5. Fractal-dynamic multi-scale cascades

This section extends our analysis of self-similar edge-of-chaos dynamics to encompass multiple scales of neural organization. In order to make this extension, the concept of *density of interaction* needs to be clarified. This concept will enable the wave-processes of any composite system at *S(n+1)* to be linked to the wave-processes of its constituent systems at *S(n)*. Density of interaction is therefore critical to understanding between-multiple-scales interactions. The concept has its origins in the study of non-linear systems, in particular dissipative structures. Katchalsky (1974) lists, as one of the essential properties of a system exhibiting large scale dissipative processes, a sufficient density of interaction among constituent elements. An example of such a dissipative structure is the large-scale oscillatory patterns which form in liquids undergoing certain chemical reaction — for example, Zhabotinsky reactions. The use of catalysts results in a greater frequency of reactions among the molecules of the liquid. When this density of interaction reaches a critical

point, the large scale dissipative structures form. The critical reaction rate in this example plays an analogous role to the critical speed of water-flow in a pipe, discussed in previous sections. Freeman (1988) is drawing upon precisely the same metaphor when discussing density of interaction between neural processes. Beyond a critical density of interaction, neural processes undergo a state-transition to form large scale, coherent limit-cycle attractors in cortical masses.

The crucial insight which Langton (1990) brings from the study of cellular automata, is that for some complex systems at least, the critical density of interaction has an upper bound as well. Langton (1990) thus speaks of a transition region, discussed earlier in this chapter. This transition region occurs in a narrow range of the order-chaos continuum. Langton interprets this finding in terms of entropy management between constituent processes of the system. To sustain edge-of-chaos dynamics, each subsystem has to strike a balance between preserving its own local states and transmitting influence to other sub-systems, as outlined in the section on edge-of-chaos dynamics. Only at the transition region is Shannon-Weaver information both preserved and transmitted in sufficient degree to support the complex behaviors at the system scale. In other words, there is a critical density of interaction at the transition region.

Similar results are found for systems of coupled limit-cycle oscillators (Matthews & Strogatz 1990). Here, the density of interaction is explicitly manipulated in the form of the coupling strength between the constituent limit-cycle oscillators. At low coupling strengths, Matthews & Strogatz (1990) found the constituent oscillators acting freely and incoherence at the system scale. At high coupling strengths, the constituent oscillators became locked at a single frequency. Only at a thin intermediate range of coupling strengths did the large scale ordered and chaotic waves appear. An even narrower band of semi-chaotic behavior separated the ordered and chaotic regions — the extended transients at the edge of chaos (Langton 1990). The relation between density of interaction and attractor-type in systems of coupled oscillators is different from that found by Langton (1990) for cellular automata. This means the highly interactive (high-energy) states produce ordered behavior, as found in Freeman's olfactory bulb, and a lower density of interactions produces chaotic behavior, as per the bulb. The parallel of these latter relations adds impetus to the adequacy of a system of coupled limit-cycle oscillators as a model for certain types of neural dynamics.

Matthews & Strogatz (1990) also manipulated the *range* of frequencies of the constituent limit-cycle oscillators. Natural frequencies were assigned to

each constituent oscillator so that the frequencies were spread evenly along this range. A phase plot of the results is shown on Diagram 10. Increasing the range

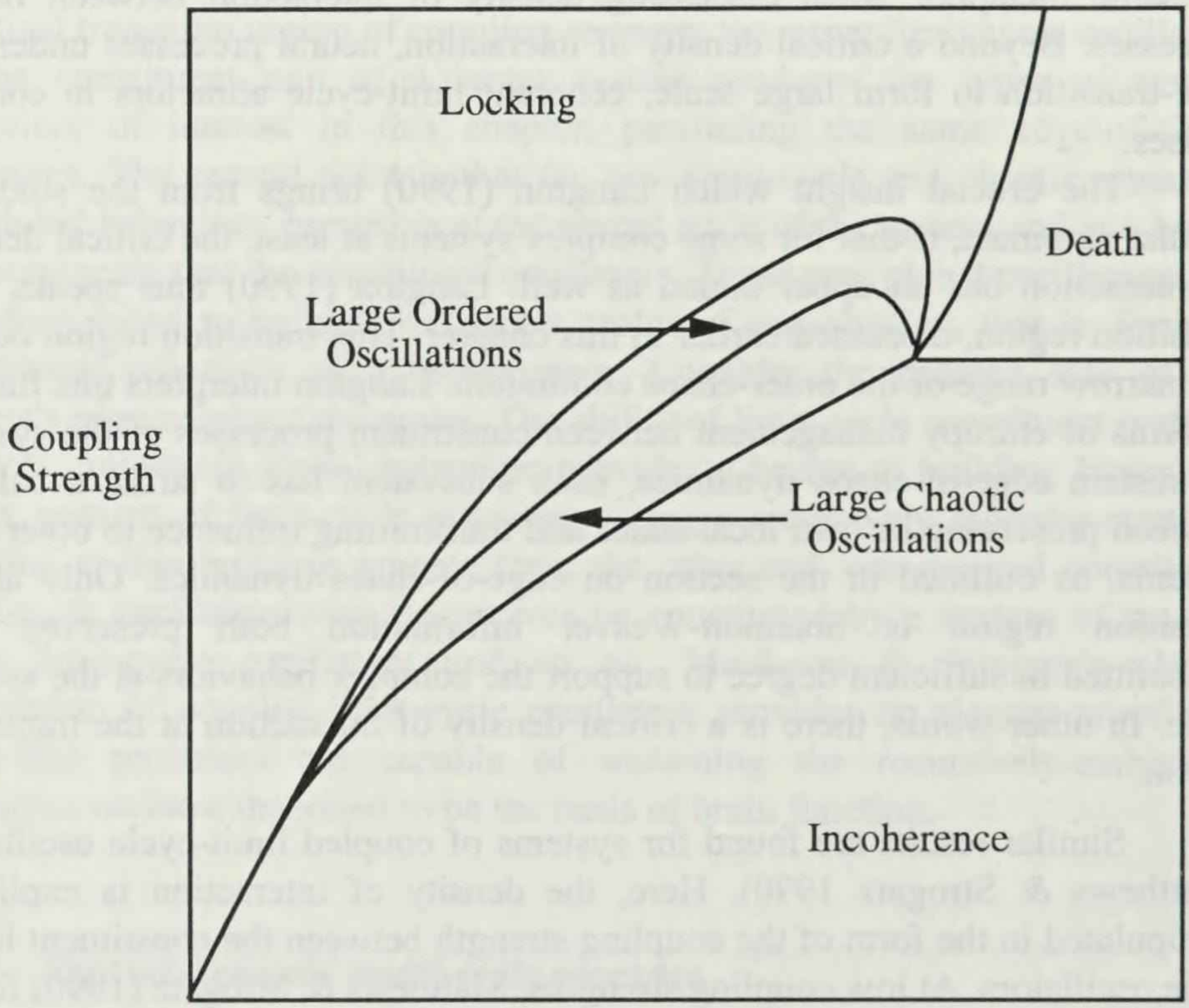


Diagram 10: *Global oscillations in a system of local oscillators. Phase plot of the behavior of a system of coupled limit-cycle oscillators, according to Matthews & Strogatz (1990). A system of coupled limit-cycle oscillators show various behaviors at the system level as the coupling strength and the range of oscillator frequencies are varied. 'Locking' refers to the locking of phase of individual oscillators to a common frequency. 'Death' refers to the amplitude death of constituent oscillators. 'Incoherence' refers to random, low amplitude behavior at the level of the system. The large-scale ordered and chaotic oscillations are found only within a thin linear region with a positive slope. These two latter behaviors are separated by an even thinner region within which large-scale semi-chaotic behavior is observed.*

of frequencies acts as a control parameter similar in effects to decreasing the coupling strength: the global system moves towards chaos then incoherence (extremely chaotic behavior). Decreasing the range of frequencies affected system behavior in the opposite direction: movement toward large-scale limit

cycles then frequency locking of the constituent oscillators. The edge of chaos is found in a near-linear region with a positive slope.

The arguments in this final section rest on a further assumption. The assumption is required because each of the constituent oscillators in Matthews & Strogatz's (1990) simulation take the form of an ordered limit cycle. The extension of our analysis of between-scales influence to multiple scales of organization requires and understanding of systems in which constituent oscillators can also engage in chaotic activity. The assumption is that varying the proportion of constituent systems engaged in chaotic mode has a similar effect to varying the range of natural frequencies of those constituent oscillators. Thus, increasing the proportion of constituent oscillators engaged in chaotic mode is hypothesized to have a similar effect to increasing the range of frequencies in Matthews & Strogatz's (1990) phase plot. Decreasing the proportion of constituent oscillators engaged in chaotic mode is hypothesized to have a similar effect to decreasing the range of natural frequencies of the constituent oscillators. This assumption is based on the common link that both *types* of change — greater frequency range or greater proportion engaged in chaotic dynamics — involve an increase in the degrees of freedom of the constituent oscillators. This association is plausible in that a system comprised of entirely highly chaotic constituent oscillators, with only a moderate density of interaction, results in incoherence at the system scale. Likewise, a system of constituent limit cycle oscillators (all things being equal, including no variation in natural frequencies), results in locking behavior.

This additional assumption delivers a phase plot, similar to Diagram 10, which relates the proportion of constituent oscillators in chaotic mode (horizontal axis) to the density of interaction between those oscillators (vertical axis). The phase plot describes the behavior of the global system. In previous sections of this chapter, the fate of an attractor has been described in terms of density of interaction of its constituent elements; that is, what is happening within the system. The extension of the analysis to cover the states of constituent systems allows the effects of edge-of-chaos transitions to be traced over multiple scales of neural organization. The two types of influences on a system's behavior are illustrated in Diagram 11. In Diagram 11A, a subsection of the hypothesized phase plot is magnified to reveal how changes of density of interaction within a system move its dynamic either side of the edge of chaos. In Diagram 11B, the same phase plot shows how changes in the proportion of constituent systems in chaotic mode move the system either side of the edge of chaos. In the discussion on turbulent flows, it was argued that water flowing near the critical speed creates its own dynamics, locally speeding up and slowing down through the critical transition region. To this within-system autodynamic can be added the autodynamics between multiple system-scales,

each poised at the edge-of- chaos. Since we can now relate changes in the attractor dynamics in systems at *S(n)* to changes in the attractor dynamics in the system at *S(n+1)*, the possibility of *multi-scale cascades of attractor changes* can now be elaborated.

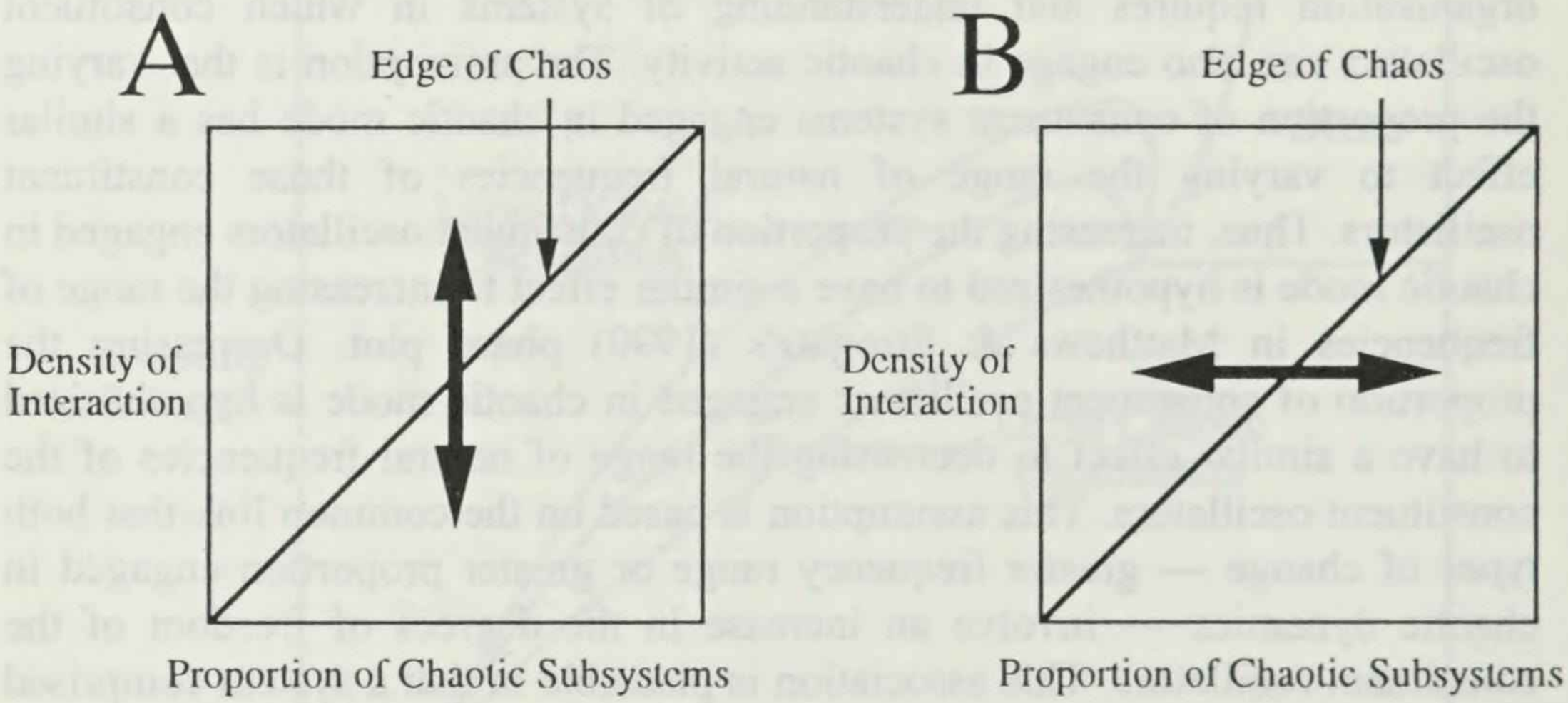


Diagram 11: *Edge-of-chaos dynamics across multiple scales. Hypothetical phase-plot relating density of interaction within a neural system to the proportion of subsystems engaged in chaotic activity. The phase plot describes the behavior of the global system in terms of shifts either side of the edge of chaos. The diagram magnifies the middle section of a phase-plot similar to that in Diagram 10. (A) The behavior of the global system shifts from limit cycle attractor (above diagonal) to chaotic attractor (below diagonal) as the density of interaction within the system is varied. (B) The behavior of the global system shifts from limit cycle attractor (left of diagonal) to chaotic attractor (right of diagonal) as the proportion of systems engages in chaotic activity is varied.*

Diagram 12 locates various within-system changes and changes across multiple systems on the hypothetical phase plot. The particular results of Matthews & Strogatz (1990) which are of most interest to this chapter are found at points a and b. These correspond to a system whose constituent oscillators are engaged in limit cycle behavior. The system can display either large scale ordered oscillations or large scale chaotic oscillations depending on a subtle shift in the density of interaction within the system — points a and b respectively. Points c and d illustrate two states of systems described by Rössler (1982). Chaotic subsystems can give rise to order, as has been described already for dissipative structures. The Hamiltonian chaos of

molecules in a chemical reaction can spontaneously give rise to large-scale limit cycles, provided a sufficient density of interaction is reached (Katchalsky 1974). Rössler (1982) also describes systems in which chaotic subsystems are coupled together to generate a higher order chaos — that is, chaos in the larger system. These two system fates correspond to positions c and d in Diagram 12, respectively. The positioning of the four types (a, b, c & d) of bi-scale-system descriptions within the phase plot lends credibility to the assumption on which it is based. The phase plot may not be valid for some physical systems which may show multiple phase transitions, for example, ice-water-steam. The phase plot is, however, based on Matthews & Strogatz's (1990) work on systems of coupled limit-cycle oscillators and seems a natural extension of Freeman's (1988) description of wave-neural dynamics to multiple scales of neural organization.

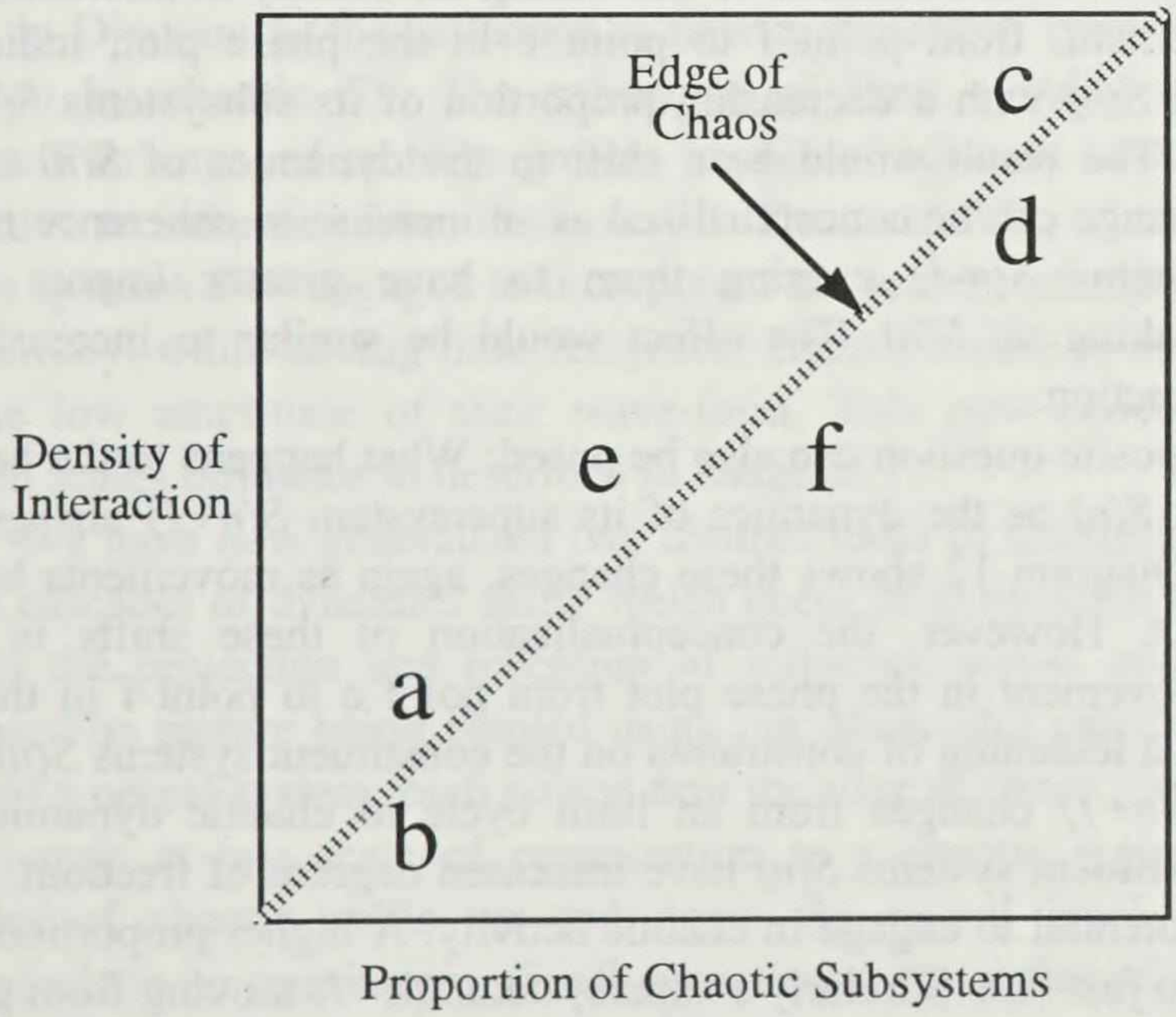


Diagram 12: *Examples of multi-scale dynamics. Hypothetical phase-plot relating density of interaction within a neural system to the proportion of subsystems engaged in chaotic activity. The phase plot describes the behavior of the global system in terms of shifts either side of the edge of chaos. The diagram magnifies the middle section of a phase-plot similar to that in Diagram 10. The various points (a to f) are referred to in the text).*

The analysis of between-multiple-scales influence can be made by considering horizontal shifts in the phase plot shown in Diagram 12. Such shifts either side of the edge of chaos are exemplified by movements between the points e and f. In this analysis we seek to hold the workings within a system *S(n)* constant, that is, maintain the same density of interaction *between* the *S(n-1)* constituent units of the *S(n)*. The question posed is this: What happens to the behavior of a system at *S(n)* as the dynamics within its subsystems *S(n-1)* change? This question can be answered by a perusal of the phase plot. Consider a system *S(n)* described by point e. It has a mixture of subsystems at *S(n-1)* in both ordered and chaotic regimes. The behavior of the system *S(n)* itself is that of a limit cycle. If the proportion of subsystems *S(n-1)* engaged in chaotic behavior increases, the system *S(n)* will itself shift in dynamic to a chaotic attractor. The system will move from point e to point f in the phase plot. This change can be conceptualized as a loss in the coherence of some subsystems *S(n-1)* causing them to have less impact in the interactions making up *S(n)*. That is, the effect would be similar to decreasing the density of interaction. The opposite movement, from point f to point e in the phase plot, indicates a chaotic system *S(n)* with a decreasing proportion of its subsystems *S(n-1)* in chaotic mode. The result would be a shift in the dynamics of *S(n)* to limit cycles. This change can be conceptualized as an increase in coherence in some of the subsystems *S(n-1)* causing them to have greater impact in the interactions making up *S(n)*. The effect would be similar to increasing the density of interaction.

The opposite question can also be posed: What happens to the behavior of a system at *S(n)* as the dynamics of its supersystem *S(n+1)* change? The phase plot in Diagram 12 shows these changes, again as movements between points e and f. However, the conceptualization of these shifts is subtly different. A movement in the phase plot from point e to point f in this case corresponds to a lessening of constraints on the constituent systems *S(n)* as the supersystem *S(n+1)* changes from an limit cycle to chaotic dynamic. This means the constituent systems *S(n)* have increased degrees of freedom, and so an increased potential to engage in chaotic activity. A higher proportion of the *S(n)* systems do just that. Similarly a supersystem *S(n+1)* moving from points f to e in the phase plot — moving from chaos to order — is conceptualized as increasing the constraints its constituent systems *S(n)*. That is, decreasing the degrees of freedom of each *S(n)*. A higher proportion of them will thus engage in limit-cycle dynamics. These conceptualizations for downward cascades of change can be seen as an extension of Freeman's (1988) notion that limit cycles in the cortical mass constrain the dynamics of constituent neural systems.

We now turn to Freeman's (1988) observation that cortical masses engaged in limit-cycle attractors are no longer sensitive to smaller scale inputs, and generalize it to multiple scales of neural organization. We hypothesized that the imperviousness to influence of an ordered system at *S(n)* is bidirectional. This means that an ordered system *S(n)* is no longer sensitive to the inputs from subsystems *S(n-1)*, but also displays an imperviousness to the greater dynamic context set by the supersystem at *S(n+1)*. Similarly, the ability of chaotic systems to be influenced by perturbations from their subsystems — and magnify the perturbations to the larger scale — is also assumed to be bi-directional. This means the chaotic trajectory of a system at *S(n)* is not only sensitive to perturbations projected up from subsystems *S(n-1)*. The chaotic trajectory is also molded by the dynamical path of the supersystem *S(n+1)*. The bi-scale account of between-scales influence, given in the discussion on turbulent and laminar flows, must now be replaced by an account of between-multiple-scales influence. Instead of a mere shift in direction of influence, as shown in Diagram 6, the influence is now a *projection* from ordered *S*'s and *reception* by chaotic *S*'s. The coherence of limit cycle dynamics enables systems *S* so engaged to have greater impact at adjacent scales, while being insensitive to influence from those scales. The sensitivity of chaotic attractors enables systems *S* so engaged to incorporate the activity of adjacent scales into their activity, while having little reciprocal effect because of their incoherence and the low amplitude of their wave-form. This new conceptualization of between scales influence in described in Diagram 13.

We have now generalized two distinct ideas to multiple-scale systems: (1) the cascades of dynamics shifts which occur in multi-scale neural systems, and (2) the projection and reception of influence across multi-scale neural systems. The picture being painted using our phase-plot palette is of multiple scales of a neural system, each poised near the edge of chaos. Destabilization of the dynamic at one scale of organization to a chaotic regime can lead to cascades of chaotic shifts up and down the neural level structure. This corresponds to an opening up of influence across the scales of neural systems, and a brain wide receptive mode. Coherence emerging at one scale of organization can result in cascades of ordered shifts up and down the neural level structure. This corresponds to shutting off influence between scales of the neural system, in a brain-wide decision mode.

Of course, this summary of our arguments is rather abstract. The realities of multi-scale neural processes are likely to be more subtle. Some

examples of multi-scale dynamics complementary to those hypothesized in this chapter are as follows:

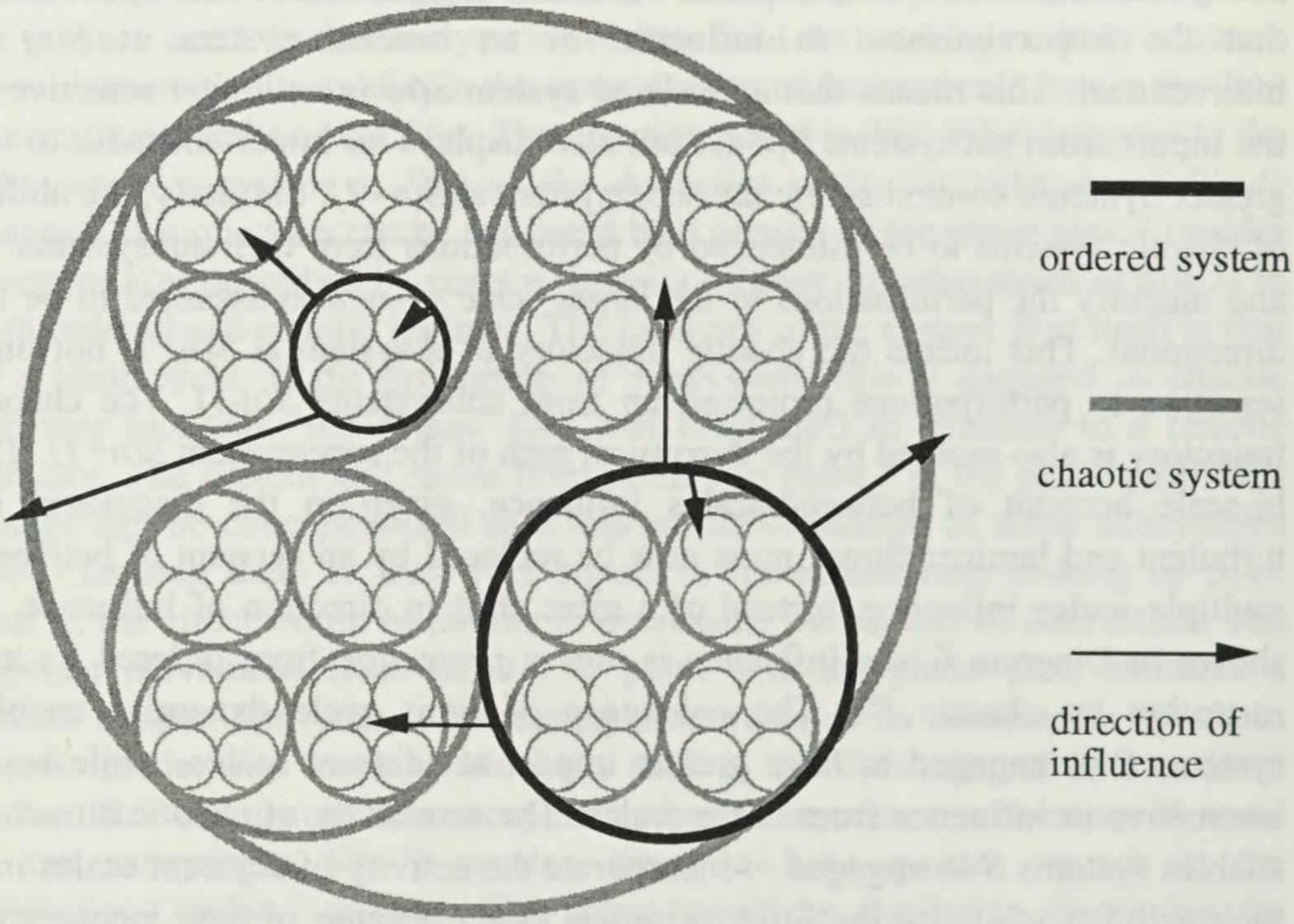


Diagram 13: *Multi-scale modes of influence. Schematic illustration of between-scales influence in a multi-scale neural system. Influence is projected outwards and inwards from ordered systems; chaotic systems are perturbed by this influence. The dark circles indicate the system at that scale of organization is in ordered mode. The light circles indicate the system at that scale is in chaotic mode. The ordered systems have a certain imperviousness to influence, while being able to influence the trajectory of chaotic systems. The chaotic systems show a receptiveness to influence, while having less impact on other scales of the neural system.*

(1) Movement to chaotic attractors in a subset of *S(n-1)* subsystems may move the ordered system at *S(n)* into the chaotic regime. This may enable a *different* subset of *S(n-1)* subsystems to engage in ordered activity by increasing their internal density of interaction. In turn, the system *S(n)* reconfigures itself to a limit cycle attractor *different* to its original state; or,

(2) A system *S(n)* may maintain itself in an ordered (active, participatory, decision) mode while keeping a small subset of the *S(n-1)* constituent systems in chaotic (receptive, nonparticipatory, passive) mode as a *pipeline of sensory influence*; or,

(3) As has been hypothesized for conscious dynamics (Globus 1995), subsystems, *S(n-1)* of *S(n)*, involved in conscious thought may drop in and out of the process, continuing on their own independent trajectory (ordered or chaotic) when not currently bound to *S(n)*; or,
(4) Attentional systems may recruit perceptual subprocesses by nudging them into an ordered trajectory.

These examples highlight Harth's (1983) warnings about the direct transfer of physical analogies to neuroscientific phenomena. The limit cycle attractors of neural systems are not *merely* attractors. They correspond to specific perceptual/ recognition/ motivational/ decision/ participation states. The chaotic attractors are not merely sources of noise. Their trajectories explore the known perceptual/ recognition/ motivational/ decision/ participation spaces. Many ordered systems at *S(n-1)* may not induce ordered behavior at *S(n)* because their specific content is *contradictory*. This can be interpreted as an inability to cooperate to achieve sufficient density of interaction. A system *S(n)* may maintain its ordered regime, despite most of its constituent *S(n-1)* subsystems maintaining a chaotic trajectory. If there are no contradictions in the subprocesses *S(n-1)* defining the system *S(n)*, the few *S(n-1)* subsystems engaged in limit cycles may achieve *sufficient* density of interaction.

The multi-scale attractor dynamics of neural systems can be conceptualized in terms of constraints. Systems at different scales in the neural level structure mutually influence each other in the manner described; these influences are felt as constraints on each process. The total neural system is constrained by the larger system of the environment and by the internal milieu of the body (Globus 1992). Within the brain, the specific functionality of each scale of organization forms a set of constraints on the state space of adjacent scales of organization, and; through cascade effects and projection of influence, indirectly induces constraints at all other scales in the brain total system. Weiss (1941) has described succinctly this conception of multiple, mutual constraints between dynamical attractors at different scales of organization:

> [...] the nervous system will have to be viewed [...] as a *system of systems, each of which consists of subsystems* and so on; [...] in which the competence, freedom of action, range of variability, etc., of each constituent member is strictly delimited by constitutional — and on higher levels, acquired, — properties. (Weiss 1941:91)

The between-scales cascades and flows of influence are always mediated by learned and innate neural structures at each scale of neural organization, *S*. The processes described in this chapter, in functioning neural

systems, always have specific content and properties. The various attractors correspond to different cognitive, attentive and motivational states at larger scales (Globus 1995) and different perceptual and fine grained motor mechanisms at smaller scales (Weiss 1941). The result is *a self-tuning entity which achieves this self-tuning by a multiply embedded set of processes which are continually dropping in and out of the whole and changing the way they influence the whole* (Globus 1992). As the system changes over longer time periods, interacting with the structures/patterns in the world, the various types of attractors (ordered and chaotic and at many different scales of organization) refine their tuning processes to become more adapted to the environment.

What has been proposed in this chapter is a universal mechanism of self-similar neural dynamics extending from individual neurons to the whole brain. The proposed mechanism links the different scales conceptually (since they use the same dynamics) and it links them literally, via the notion of between-scales influence. In this sense *the brain is doubly chaotic*. First, neural dynamics can move into the chaotic regime at any given scale *S* of organization. Second, even in the special case where all systems *S* are engaged in ordered limit cycles, the recursively modular structure of the brain means that global EEG will have a fractal dimension. This is due to the wheels within wheels nature of the brain's meta-organization. This may explain why fully engaged conscious activity, utilizing the full fractal depth of the brain, is only surpassed in its fractal dimension by the EEG of schizophrenics and REM sleep (Globus & Arpaia 1994). The latter two cases may also utilize the full fractal depth of the brain, but also have a much larger proportion of systems and subsystems in chaotic mode. Hence the term 'doubly chaotic'.

Despite the universality of dynamic proposed in this chapter, any reductionist (monist) interpretation is to be rejected. The properties of various systems *S* of the brain are related by a common (theorized) dynamic, but occur at radically different scales of organization in nature. It is as erroneous to confuse neural activity with conscious thought as it is to confuse hydro-carbons with eco-systems (Goldberg 1980). Neural systems are viewed as a family of related processes, but processes which differ qualitatively, depending on the scale of organization at which they occur. What is being proposed is a universality of dynamic which is also a structural and functional diversity.

6. The recursive vision

The vision of recursively organized neural systems developed above, with edge of chaos dynamics at each scale and with cascades of chaos and order passing variously between scales, is fundamentally at odds with the conventional view of neural processes. In the conventional view, there are levels rather than

scales, levels which are hierarchically organized with the higher controlling the lower. At each level of the hierarchy, informational representations are logically processed and the results passed to the next higher level for further computation, until reaching the top where the ongoing computation is tantamount to 'mind' (functionally speaking, where 'mind' is what the brain does). For the recursive vision, the higher doesn't control the lower. Instead, as already shown, the various scales are interactive, interanimating each other with chaos and order. (The present recursive vision is chaos-theoretical, unlike the usual view of recursion, e.g., as found in Hofstadter 1979.) It is precisely here that a symptom of a paradigm shift can be located. In the recursive vision, the scales are inseparable — part and whole indivisible — whereas in the conventional vision, scales are sharply separated levels of a hierarchy. The inseparability of part and whole, a peculiar feature of the recursive vision, has great affinity with quantum physics (Globus 1995); the recursive vision looks forward to the further development of quantum brain theories (Globus 1995; Jibu & Yasue 1995; Penrose 1989; Yasue, Jibu & Pribram 1991).

In any case, the brain envisaged is extraordinarily fluid and exquisitely sensitive in its own dynamics. All scales of a poised system variously participate in the whole (where 'participation' means both influencing and influenced), or departicipate, as the case may be. This fluid, recursively organized, nonlinear dynamical system evolves at the edge of chaos, moving variously between order and chaos at the multiple scales. It is crucial to appreciate here that the parts at a given scale are conceived of as oscillators; it is natural, then, to represent the system as an (immensely complicated) wave function. Metaphoric terms like 'flow' and 'cascade' become appropriate in describing such a system (whereas 'serial steps' is right for the conventional view). This gives the recursive vision an 'organic' feel, anything but mechanical; its progenitor is Heraclitus, anyone but Democritus; rather than abhorring chaos and valorizing order, its predilection is a reciprocating movement between chaos and order.

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Fractal Time and the Foundations of Consciousness: Vertical Convergence of 1/f Phenomena from Ion Channels to Behavioral States

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1. Introduction

From complex temporal patterns such as the bunching or clustering of spontaneous firing patterns of neurons, heart beats, and breaths in the fetus or of cars on an expressway, emerges fractal time. Only a decade ago these patterns were perceived as noise (West & Shlesinger 1990:40). Fractals in physical and biological phenomena provide a rich, aesthetic language for understanding complex, apparently 'noise-like' patterns in time and space. They also speak to a fundamentally new view of how living and nonliving matter is organized, with complex themes recursively nested in multiple sublevels of spatial or temporal organization (Mandell 1986; West 1991; Bassingthwaighte *et al.* 1994). The once purely mathematical concept of self-similarity combined with inexpensive computing power has now educated the contemporary eye to previously unseen worlds of stunning beauty in the forms of nature (Mandelbrot 1983; Peitgen 1986). During this 'decade of the brain' with great strides in molecular neurobiology, neurophysiology, and neurobiologically inspired computer modeling, we have yet to attempt to decipher the neurohieroglyphics of fractal dendritic arbors or diffuse collateralations of projecting neurons in the context of their connected self-organized spatial-temporal dynamics. Buoyed by the technical successes of molecular genetics, receptor cloning and the patch clamp technique,

neurobiology has become overly focused on the current 'molecular reductionism' approach at the expense of cross disciplinary integration. Conceptually, neuroscience has lacked a Rosetta Stone to trace parallel meaning across multiple levels of brain and behavioral organization enabling cross fertilization between static measures (e.g., *post mortem* distributions of receptors, messengers, neurotransmitters, etc.) with complex patterns of behavior in time (e.g., linking the fluctuations in ion channels to habituation of an orienting response). Additionally, this gap leads to a lack of conceptual cohesiveness in forming connections between the knowledge bases of molecular and behavioral neuroscience in developing and testing hypotheses, thus leading to a fragmented approach to mind, brain, behavior and even society as a whole (Bohm 1980:1, 1987:214). An attempt is made here to engage in a free play of ideas, with the central theme of fractal time (Shlesinger 1987:214; Shlesinger 1988:269) as observed in 1/f spectra of neurobiological phenomena, to provide one possible Rosetta Stone. This main theme, implied by the apparent occurrence of fractal time processes during developmental differentiation and organization of behavioral states (e.g., attentional orienting, rapid eye movement (REM) sleep), is the convergence of 1/f phenomena over all levels of neural organization in the organism. Variations on the main theme attempt to bridge the gulf between observations of 1/f spectra in current flows in potassium channels, coherent brain states of focal attention, and traffic patterns on highways.

What is the meaning of a '1/f spectrum'? The inverse relationship between frequency (f) and squared amplitude or power in the Fourier spectrum, '$1/f^{\alpha}$ power spectra' where the exponent 'α' is an value between 0.5 and 1.5, is one of the most common time fractals found in nature (Voss 1989:39). 1/f spectra have the largest values of dependency or correlation with the past of any of the random scaling noises (e.g., white, brown). The fractal scaling behavior in the power spectra of 1/f fluctuations abounds in astrophysical phenomena (Press 1978:103): the Gutenberg-Richter law of earthquakes (Scholz 1991:41), volcanic activity (Scholz 1991:41),the flow rate of the Nile (Mandelbrot & Wallis 1969:321), ocean currents (Taft & Hickery 1974:403) and daily average air humidity fluctuations (Vattay & Harnos 1993, unpublished). In the literature of physics and electronics, this intermittent bursting behavior in a time series is called variously 1/f noise, current noise, contact noise, excess noise, flicker noise or pink noise and has often been referred to as one of the most common forms of noise in natural phenomena and electronic systems.[1]

However, in neurobiology in general, and neurophysiology in particular, 1/f patterns in time are profound in their recurrent appearance across many levels of organization in the nervous system, from the underlying cellular dynamics of ion channels and intermittent firing patterns of neurons to developmental phenomena occurring during the organization of breathing to global dynamics in the nervous system such as subcortical, transcortical and scalp EEG defining behavioral states of consciousness. In essence, vertical integration of 1/f phenomena may allow fluctuations in molecular processes to be manifest in the macroscopic patterns of behavior of the entire organism. If we are organized around this recurrent motif we may be particularly sensitive to natural phenomena that mimic 1/f processes. The human perceptual system is particularly sensitive to the occurrence of pitch fluctuations that rise and fall in a 1/f fashion or visual images of nature with 1/f patterns such as turbulent water flows, movements of branches in the wind, wood grain patterns (Musha 1993, personal communication). All musical melodies mimic 1/f processes in time and mapping 1/f noise to sound generates reasonable 'fractal forgery' of music because the correlations inherent in the sound mimic the meaning found in natural sounds and music (Voss & Clark 1975:317, 1978:258). Richard Voss suggests a possible reason for our sensitivity:

> The 1/f-spectral density seems to occur for measured quantities that are more closely related to 'meaning' (musical melodies, spoken loudness) [...] Such a view of melody fluctuations emphasizes the common element in music and suggests an answer to a question that has long troubled philosophers (M. Gardner). In the words of Plato, "For when there are no words (accompanying music), it is very difficult to recognize the meaning of the harmony and rhythm, or to see that any worthy object is imitated by them." Greek philosophers generally agreed on the imitative nature of the arts. It seemed obvious that painting, sculpture or drama imitated nature. But what does music imitate? The measurements suggest that music is imitating the characteristic way our world changes in time. Both music and 1/f-noise are intermediate between randomness and predictability. Like fractal shapes there is something interesting on all (in this case, time) scales. Even the smallest phrase reflects the whole. (Voss 1989:42)

He reasons that we are susceptible to these fractal forgeries because we have evolved in a natural environment filled with temporal and spatial fractal patterns, and that it has only been in the last few thousand years that we have lived among artificial Euclidean shapes. In fact, stimulation of patients with 1/f

patterns in time visually, auditory or transcutaneously provide soothing relief from chronic pain or stress (Takakura *et al.* 1979:314). Although we may live in a self-made Euclidean world, we still seem to manifest fractal patterns in our behavior. At the level of human activities, fluctuations in the intervals between cars on Japanese highways exhibit bunching or clustering and 1/f power spectra (Musha & Higuchi 1976:1271) similar to the bunching seen in the density of action potentials in squid axons (Musha 1981:143; Musha *et al.* 1981:616). The same motif of clustering recurs in current flows in neural membranes, ion channels and cytoskeletal networks (see below). 1/f processes have underlying Lévy stable distributions which have the same additive properties as Gaussian distributions: the sum of two 1/f processes gives a 1/f process of a higher order (Takayasu 1990:123). In addition, the product of 1/f processes is again a 1/f process (Kawai *et al.* 1993:639). It is theoretically possible, therefore, that the sum of the products of 1/f fluctuations (or independent random variables with a 1/f distribution) in ion channel currents in the brains of drivers may be manifest in the mind wandering or 1/f fluctuations in their attention (Wegner 1993, in press) leading to the observed 1/f distributions in traffic patterns. In a profound way the fractal time process of 1/f fluctuations on all time scales has fundamental significance to biological systems. Richard Voss has suggested 1/f processes have the most dependency on, or correlation with, the past under the constraint of being random processes. Therefore, a $1/f^1$ spectrum density is "where you have the most information about the future from the past on all time scales" (Voss, personal communication).

2. 1/f processes and dependency on the past: Bunching in the past correlates with bunching in the future

Machlup (1981:157) described the sound of 1/f noise in a transistor as follows: "[...] the 1/f noise sounds like pshsh, ktshsh, pdk, kshsh [...]". You can hear the individual events in the time series x(t). Big events are less frequent than little events. "Twice as big occurs half as often." In general, 1/f noise is fractal with respect to time, because the same processes "[...] pshsh, ktshsh, pdk, kshsh [...]" occurring on one timescale, say microseconds, is identical to a "[...] pshsh, ktshsh, pdk, kshsh [...]" occurring on another timescale of say minutes. Press (1978) describes these bunched clustering, correlated patterns as manifesting a primitive form of memory:

> [there is] indirect evidence that the flicker noise in a carbon resistor, say, gives rise to fluctuations [in atomic clocks] coherent over times

> as long as 10^6 seconds. This is quite fantastic! How does the resistor remember over a period of weeks or months that it is in an 'up' fluctuation? (Press 1978:109)

One mathematical way of explaining why this memory or dependency structure of a 1/f spectrum implies correlations over all past times is based on the processes of fractional integration of x(t) (Barnes & Allen 1966:176; Press 1978:113). Fractional integrals are additive, so, for example, applying the 1/2 integral twice gives you a full integral. In terms of spectral analysis, quantifying the 1/2 integral involves adding up all components from the past. For example, one way to generate 1/f is based on the idea of half-order integration of Gaussian white noise.[2] The power spectrum of this noise is a constant and the 2-point autocorrelation function indicates there is no correlation between the fluctuations at two times separated by a correlation time τ, so the current value of a Gaussian white noise at one point in time is totally independent of a past value. Full-order integration of a Gaussian white noise x(t) (or the summation of random steps) gives a Brownian motion x(t), or $1/f^2$ noise in the power spectrum. Sounds generated from a Brownian motion sound slow, mundane, and monotonous (Voss 1989:43). There is a lack of correlation in the power spectrum of the Brownian motion x(t) and the power spectrum of Gaussian white noise x(t) because whether x(t) increases or decreases at some time in the future is not correlated with any time in the past. For the half-order integral of Gaussian white noise x(t), Press (1978:114) states: "[...] half-order integration consists of linear convolution with a kernel (or Green's function) $G(t-t_0)$". This kernel corresponds to the linear combination of two different impulse response functions, $G_+(t-t_0)$ and $G_-(t-t_0)$, the 'advanced' and 'retarded' respectively, responses of the half-integral to f(t) which are branch cuts in the complex plane. When a sample of white noise is filter by or 'convolved' with these impulse response functions, flicker noise is generated with the of $1/f^{\alpha}$ in the range between $0 \geq \alpha \leq 2$. Press (1978) concludes:

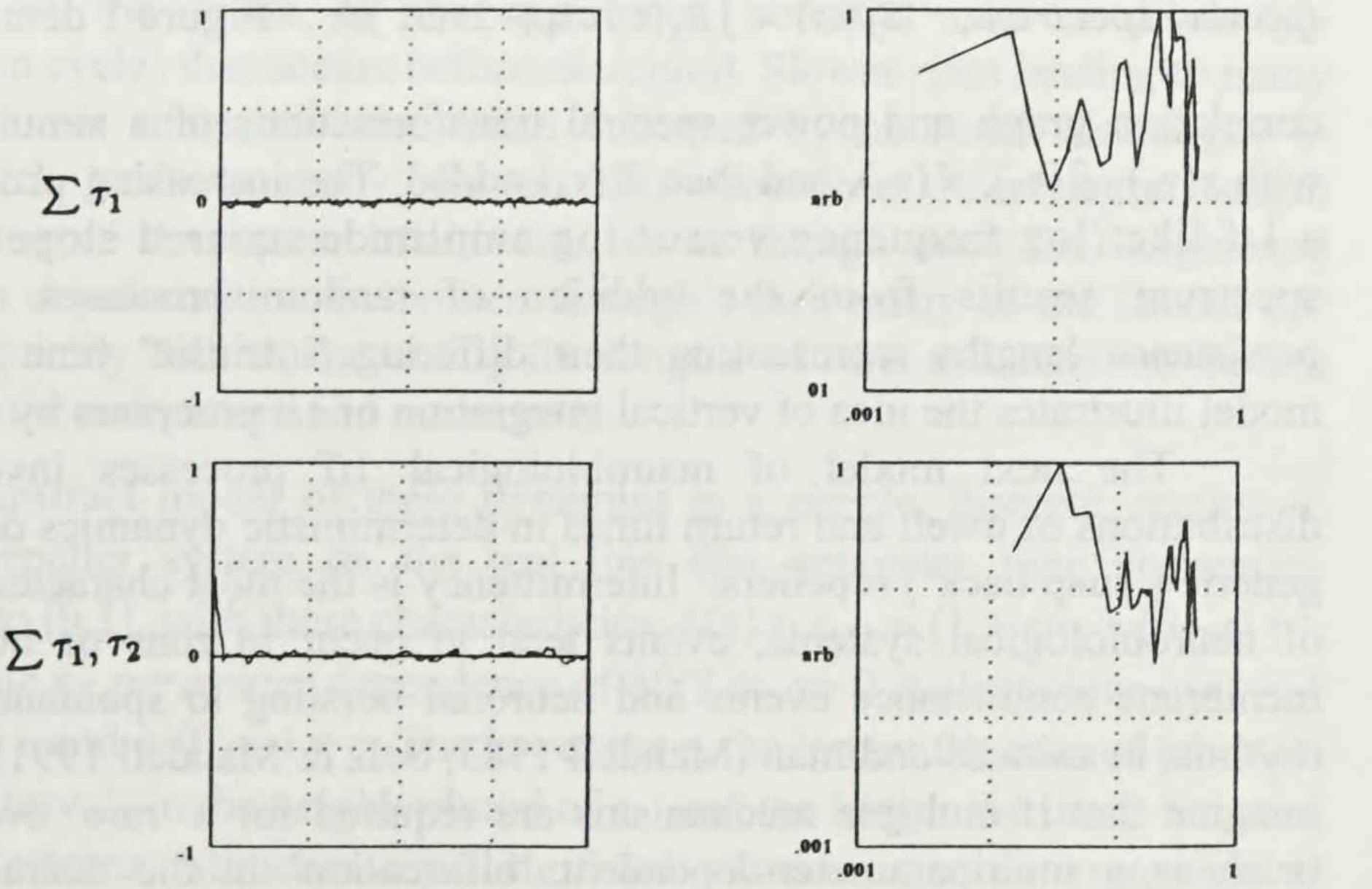
> It is evident that flicker noise generated in this way is not symmetric under time reversal (except in the special case of half-advanced plus half-retarded [α=1]) [...]. Gaussian white noise does not define an arrow of time; nor does its integral, [a] random walk; but its half-integral, flicker noise [$1/f^1$] does [...]. Now we can also see just how flicker noise can maintain a 'memory' of its fluctuation state over very long timescales: In the 'retarded' case, a delta-function impulse in f(t) produces a filter response which rises at once to a cusp, then decays away only as $t^{-1/2}$ [...]. The superpositions of these slowly

> dying tails from all previous impulses gives the very long time correlations in the noise. (Press 1978:114)

In general, there is no one generic explanation of 1/f noise in nature (Machlup 1981:157). There are however, many mathematical procedures for generating 1/f noise (Lowen & Teich 1993a:992). In the following, we will show that even with the lack of a universal model of 1/f processes, neurobiological systems provide a rich collection of mechanisms, that when modeled in a straightforward manor, can produce 1/f-like fluctuations. The following are examples of mathematical models of possible sources of neurobiological 1/f noise. The first example is a superimposition of random processes with differing characteristic times (or correlation times τ). Suppose we are using an electrochemical detector to monitor synaptic levels of a biogenic amine neurotransmitter as a function of time. The fluctuations around the mean value will reflect a mixed set of characteristic times τ with the assumption that slower and faster randomly varying processes contribute noninteractively to the electrochemically detected biogenic amine level (Mandell 1978:461, 1984:237). Representative sequences of contributing random observables, x_i, can be illustrated as follows:

(1) Ion-conductance-coupled neurotransmitter leaks in (as the fastest process) in milliseconds (τ_1): $x_1, x_2, \ldots$;
(2) Membrane vesicle attachment rate fluctuations in tens of milliseconds (τ_2): $\hat{x}_1, \hat{x}_1, \hat{x}_1, \hat{x}_1, \hat{x}_1, \hat{x}_1, \hat{x}_1, \hat{x}_1, \hat{x}_1, \hat{x}_2, \ldots$;
(3) Rate limiting enzyme conversion of substrate to product fluctuations in the low hundreds of milliseconds $\breve{x}(\tau_3)$;
(4) Rate limiting tetrahydrobiopterin cofactor regeneration fluctuations in the higher hundreds of milliseconds $\tilde{x}(\tau_4)$.

If we transform each series of observables, $x(\tau_1)$, $\hat{x}(\tau_2)$, $\breve{x}(\tau_3)$, $\tilde{x}(\tau_4)$ into a mean normalized set of deviations from the mean, $x = \dfrac{x_i - \langle x \rangle}{\langle x \rangle}$, we can then sum the four series, Σx, as indicated above to capture the scaling property of the frequency content of the resulting multidetermined and multitimescale aggregate fluctuations in biogenic amine level. Using the same size time step for each process, we represent the differing time scales by varying the persistence of redundant values in the sequences. We can compute and plot the *autocorrelation function* as $R_x(\tau) = E[x_i(t)x_i(t+\tau)]$ and then *Fourier transform* the *autocorrelation function* to obtain the *frequency*



$$R_x(\tau) = E[\ x_i(t)x_i(t+\tau)] \qquad S_x(\omega) = \int_0^\infty R_x(\tau)\exp(-2\pi\omega\tau)d\tau$$

Figure 1: *The autocorrelation function (left) and power spectral transformation (right) of the sequential superimposition of random processes with differing characteristic times,* $x(\tau_1)$, $\hat{x}(\tau_2)$, $\breve{x}(\tau_3)$, $\tilde{x}(\tau_4)$. *The addition of random processes with longer characteristic times (or persistence lengths) enhances the prominence of a 1/f power spectrum (bottom right).*

(power) spectrum, $S_x(\omega) = \int_0^\infty R_x(\tau)\exp(-2\pi\omega\tau)d\tau$. Figure 1 demonstrates the correlation graph and power spectral transformations of a simulation of Σx_i with $x(\tau_1)$, $\hat{x}(\tau_2)$, $\breve{x}(\tau_3)$, and then $\tilde{x}(\tau_4)$ added. The increasing prominence of a 1/f-like (log frequency versus log amplitude squared slope ≈ -1) power spectrum results from the addition of random processes with longer persistence lengths representing their differing 'intrinsic' time scales. This model illustrates the idea of vertical integration of 1/f processes by summation.

The next model of neurobiological 1/f processes involves broad distributions of dwell and return times in deterministic dynamics dominated by generic ('snap back') repellers. Intermittency is the most characteristic rhythm of neurobiological systems; events tend to occur in runs or bunches from membrane conductance events and neuronal bursting to spontaneous activity rhythms in animals and man (Mandell 1983; Selz & Mandell 1991). One might imagine that if multiple mechanisms are required for a 'rare' event to occur (such as a multiparameter-dependent 'bifurcation' in the neural membrane equations representing the neuronal discharge), then many of them will occur together. Statistical representations of these temporal patterns as interevent times, τ_i or as frequencies, $\tau_i^{-1} = \omega_i$ ($\equiv$ "*f*") using finite distributions and their moments is not possible since the integral $\int_0^1 p(\omega)d(\omega)$, where $p(\omega)$ represents the weightings over the values of ϖ_i, (statistically, the cumulative distribution), is logarithmically divergent. The relative weight of the mean decreases as the sample length increases, since more opportunities for longer interevent intervals arise. The probability density distribution as a transformation of the cumulative distribution $\approx \frac{d\log(\omega)}{d\omega} \approx \frac{1}{\omega}$ and this is reflected in the 'shape' of the power frequency spectral transformations as well.

Since characteristic times are expanding in a system that is bounded by physiological conditions, determined by system survival, the simplest system that qualitatively simulates this behavior is that of an unstable fixed point at τ_0, in a one dimensional, discrete dynamical system, $\phi(\tau)$: $R^1 \rightarrow R^1$, that expands along the one dimensional line and then is mapped back from its boundary. This dynamical system has been called a 'snap back' repeller. The dwell times in the neighborhood of the fixed point, τ_0, are governed by the value of its positive 'eigenvalue', $\phi(\tau)$' which is under parametric control in a codimension one (or two) groups of transformations of the real line, $\phi_{r,B}(\tau)$:$R^1 \rightarrow R^1$. In neuronal excitation, fixing ß, one might imagine the parameter r to control the slowness of the decrease in (negative) membrane potential, the 'steepness of

the ramp' (in the graph of the membrane potential over a discharge-repolarization cycle) that occurs before excitation. Slower rises leading to many longer interevent times are also often followed by neuronal discharges in clusters which leads to many shorter interevent times. Correlation length increases as $\phi(\tau)'$ decreases. Intuitively, it's as though once the heightened resistance to depolarization is 'broken through', then many of the 'saved up' discharges quickly follow, increasing the lengths of runs and intervals before escape from the run pattern and return to it.

An abstract model of these dynamics is a simple, discrete, recursive, snap-back repeller system on the real line that generates time sequences, normalized to [0,1], with these characteristics: $\phi(\tau) = \tau_{i+1} = (1 + r)\tau_i + (\beta - r)\,\tau_i^2$, *mod one*. The r - *parameter* dependence of $\phi(\tau)'$ at $\tau = 0$ is clear since $\phi(\tau)' = 1 + r + 2(b - r)\,\tau$ and $\phi(0)' = 1 + r$. The lower the r, the longer the runs of (shorter) interevent intervals in the neighborhood of τ_0 and the longer the times between escapes and returns. Attractive-repelling fixed points are generic organizers of the orbits of nonlinear dynamical systems and in the Cartwright-Littlewood-van der Pol reduction of the neural membrane equations, they are called 'saddle-sinks' (Mandell & Shlesinger 1990; Mandell *et al.* 1991; Mandell & Selz 1993). Figure 2 is from top to bottom a graph of the autocorrelation function and power spectra of $\phi(\tau)' = 1.99$, 1.2, 1.05, and 1.001, respectively. The 1/f like power spectrum becomes more evident as dwell times (cluster sizes of short interevent intervals) increase and escape and return times get longer.

The final example of 1/f processes in neurobiological systems involves correlations generated by neural activity: 'fractional Brownian motion' in sensitization and habituation processes in the brain. Mandelbrot & Van Ness (1968) developed a formalism to describe patterns of random motion with a parametrically controlled amount of autocorrelation among them as changes in the value of the observable *l* as a distance along some dimension, say excitability of a neural membrane. The range of deviation from Gaussian independence afforded by this approach is well suited to the representation of neurobiological processes. All kinds of brain activity, from enzyme and membrane protein function to higher perceptual-cognitive processes, are being modulated by the slow underlying processes of sensitization and desensitization which is a function of their ongoing activities (Mandell 1986). Highly active systems get progressively less active via 'desensitization' or 'habituation', whereas inactive systems become more active via 'sensitization'.

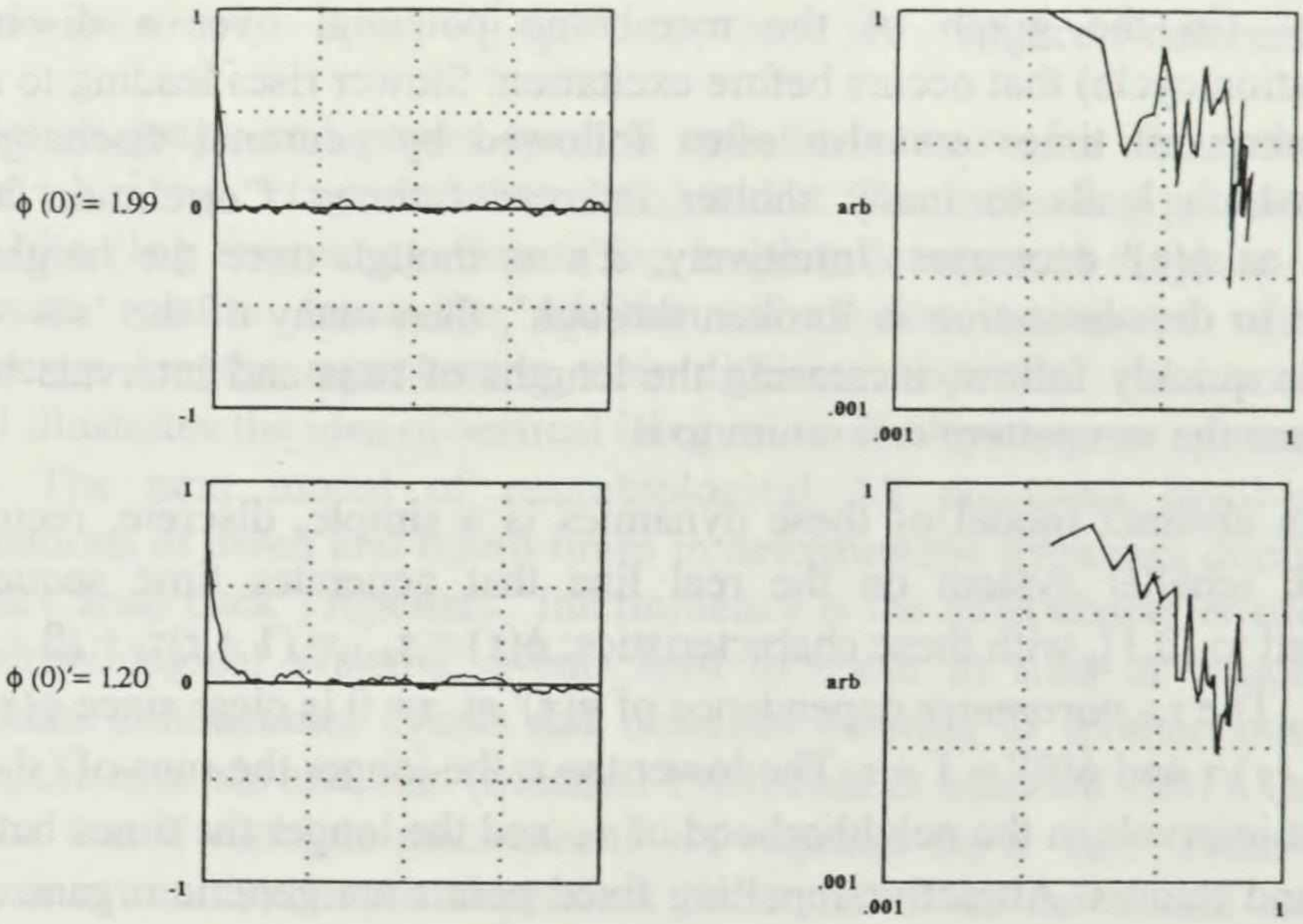


Figure 2: *The autocorrelation function (left) and power spectral transformation (right) of time sequences generated by shifting the r-parameter dependence of $\phi(\tau)'$, the positive eigenvalue of the dwell times in the neighborhood of an unstable fixed point. As dwell times (cluster sizes of short interevent intervals) increase, escaping the saddle-sinks, the return times get longer, and correlations in the system increase as $\phi(\tau)'$ decreases.*

These processes create and maintain autocorrelations among ongoing random events.

With δ representing a change in excitability, the initial minimal assumption would be of a random process as a function of time, $\delta l(\delta t) = l(t_2\text{-}t_1)$, generating a Gaussian distribution of l's with variance $\delta l^{2}(\delta t) \approx \delta t^{2h}$, $0 < h < 1$. The mean square change in distance, $\delta l^2(\delta t)$, goes like a power of the elapsed time, δt^{2h}. In the case of independent random l's, the value of $h = 1/2$ such that l going in two directions varies like t; the distance along l in one direction goes like $\sqrt{t}$, the solution to the almost hundred year old problem concerning the distance a drunk walker covers in time t. Nonzero autocorrelations arise during increased driving and inhibitory reduction in normal spontaneous neural activity and is reflected in $h \neq 1/2$ values for δt^{2h}.

As a random function of time, $l(t)$ can be characterized by its autocorrelation function, $R_l(t)$ or its conjugate power spectral density, $S_l(\omega)$. For example, with respect to the latter, if $l(t)$ is the input to a (narrow) bandpass filter at frequency ω and bandwidth Δω, $S_l(\omega)$ is the mean square output, $l(\omega)$, divided by $\Delta\omega: S_l(\omega) = \dfrac{|l(\omega)|^2}{\Delta\omega}$. Increasing correlation lengths, generated by the slow sensitization and desensitization processes underlying neural activity, leads to steeper ('power law') elevations of $S_l(\omega)$ at low ω, similar to that seen resulting from other mechanisms in Fig. 1 and Fig. 2 in $R_l(\tau)$ and (as the Fourier transformation), $S_l(\omega)$. The powerful result of Mandelbrot's work (Mandelbrot 1983) is that with respect to the (log-log) scaling exponent of correlated random processes, $S_l(\omega) \approx 1/\omega^{\alpha}$ where $\alpha = 2h + 1$. The inevitable sensitization and desensitization processes generated by neural activity is perhaps the most common mechanism of the 'universal' 1/ω, '1/f-like' power spectra found in the time structure of series of neurobiological observations. Summation of normal Gaussian distributed variables is taken for granted in the standard approach to statistical analysis in the life sciences. Many neurobiological examples of the summation of 1/f processes will follow, demonstrating that apparently noisy random 1/f phenomena with no first or second moments can also have well behaved, vertically integrative properties.

3. Convergence of 1/f processes across levels of neurobiological organization: From clustering in K^+ fluxes to bunching in spike trains

Correlated activity on many time scales at all levels of the CNS has been suggested to play an important role in organizing brain function (Cook 1991:387). In his conclusions Cook suggests that we need more information "[...] about the prevalence, strength, patterning and origins of correlated activity within the brain" (Cook 1991:400). However, a more central question involves how activity on many time scales at all levels of the CNS is seamlessly integrated into behavior and the very consciousness you are now experiencing. At the level of the neural-membrane, how are coherent fluctuations present in ionic and molecular behavior passed on to cellular and ultimately global brain activity?

Although noise sources in neural-membrane have been under investigation from the early 1930's, thermal white noise was assumed to be the primary source of fluctuations in excitability and latencies of axonal responses to stimulation.[3] Theoretically the intensity of thermal white noise is not sufficient to influence events such as spontaneous miniature end plate potentials (Hagiwara 1954:234) whereas 1/f processes at the membrane level are. The same clustering or bunching dynamic is observed in these current fluctuations as Machlup (1981:157) describes for the transistor: "Twice as big occurs half as often." The first report of the observation of 1/f processes in neurons was by Derksen & Verveen (1966:1388). Using the frog sciatic nerve fiber containing three nodes of Ranvier and an elaborate amplification system (Varveen & Derksen 1968:906), i.e., contributions from noise sources extrinsic to the middle of the three nodes were filtered out, Derksen & Verveen (1966) found a 1/f spectrum from 1 to 10kHz. In addition they determined that the amplitude of the 1/f spectrum was completely dependent on the flow of K^+ currents. Replacement of Na^+ in the bath by K^+ reversibly abolished the K^+ current and the 1/f spectrum. Depolarizing the node increased the amplitude of the 1/f spectrum, while hyperpolarizing the node to the K^+ equilibrium potential eliminated the 1/f character of the spectrum, ruling out Cl^- as a contributing factor. Subsequent measurements have confirmed these observations in several different nerves (Fishman 1973:876; Siebenga *et al.* 1973:87; Conti *et al.* 1975:45). Are ion channels the exclusive source of fluctuations of the membrane potiental?

Perhaps one of the most interesting findings regarding the subcellular convergence of 1/f processes at the membrane is that of voltage-dependent ion-

independent 1/f current noise in subcellular material isolated by microcapillary from the inner surface of the squid axon (Fishman 1981:249). This suggests that the complex sieving properties of the cytoskeleton may contribute to the observed ion-dependent membrane noise through interactions with the membrane and its embedded channels. This is further supported by the observations of dielectric constants for the subcellular material that follow a power law over a large frequency range (0.5-1,000 KHz). These constants are much greater than those of water for low frequencies (Fricke *et al.* 1940:716). These power law dielectric constants, also found for animal tissues (Dissado 1990:1487), can be conceptualized as occurring in self-similar cytoskeleton-like networks (e.g., gelatin-water) where energy dispersion may be due to nested shells of hydration by water molecules dynamically ordered around gelatin protein networks. Indeed at this level of description, quantum tunneling of hydrogens among the complex statistical shells of water surrounding the cytoskeletal matrix may amplify the effects of fundamental quantum 1/f noise on ionic currents in the system (Handel 1993:162). Handel (1990) describes the origins of quantum 1/f noise and the quantum 1/f effect:

> The physical origin of quantum 1/f noise is easy to understand. [...] for example Coulomb scattering of current carriers, e.g., electrons [...]. Although the wave function of each carrier is split into a bremsstrahlung part and non-bremsstrahlung [bremsstrahlung is lower frequency electromagnetic radiation (e.g., X-rays) emitted when a charged particle (e.g., electron) changes its velocity, which can interfere with the main, non-bremsstrahlung current to yield beats], no quantum 1/f noise can be observed from a single carrier [...]. Many carriers are needed to produce the quantum 1/f noise effect, just as in the case of electron diffraction patterns, where each individual particle is diffracted, but unless we repeat the experiment many times, or use many particles, no diffraction pattern can be seen. A single particle only yields a point of impact on the photographic plate in diffraction, or a pulse in the detector in the 1/f case. While incoming carriers may have been Poisson distributed, the scatttered beam will exhibit super-Poissonian statistics, or *bunching*, due to this new effect which we may call quantum 1/f effect. The quantum 1/f effect is thus a many-body or collective effect, at least a two-particle correlation function (Handel 1990:57; emphasis added).

Therefore, 1/f fluctuations of the membrane potential could theoretically have components converging from 1/f fluctuations at the quantum level.

When it comes to the interpretation of 1/f noise in membranes, not all investigators, however, have agreed on the significance of these findings. Conti

et al. (1975) states what appears to be the tacitly accepted role of 1/f noise in biological systems

> It is now obvious that such noise has little physiological significance. First of all, 1/f noise seems to be a quite general characteristic of thermodynamic systems away from equilibrium, and is present also in synthetic, non-excitable, membranes [...]. On the other hand, the most interesting type of noise which one would like to detect in a nerve membrane is that associated with fluctuations in the number of activated elementary processes, 'the Na^+ and K^+ channels' of the Hodgkin-Huxley theory [...]. (Conti *et al.* 1975:47)

Ion channels and the underlying kinetics of these channels have fractal time properties originating from the complex distributions of conformational states that are now known to exist in proteins (Bassingthwaighte *et al.* 1994:203). The root probability distributions of open and closed durations producing the clustering patterns in the ionic currents of hippocampal K^+ channels have been shown to be fractal (Liebovitch *et al.* 1987b:979). This could be conceptualized in the following way: Channels are never open or closed all the time (unless they have been modified by a drug or toxin); instead they are open or closed a percentage of the time. The length of time a channel is open determines the current or the number of ions passing through the channel. For example, a current of 1 picoamp over 1ms is a result of the movement of approximately 5,000 ions. See Liebovitch *et al.* (1991:256) for a trace of current flow displaying clustering characteristics that result in fractal time 1/f behavior. The number and durations of open (or closed) events and, therefore, clustering, can be determined from measurements made with patch clamped neural membranes containing a single channel (Liebovitch *et al.* 1987a:37). How does this clustering behavior reflect the kinetic properties of ion channels? The standard dogma of ion channel kinetics is based on Markov models that originate with the Hodgkin-Huxley theory (Hodgkin & Huxley 1952:500) in which the channel is assembled from a few subunits to form an open channel and then these subunits disassemble to form a closed channel. The central assumption of the Markov model is the absence of correlations in time, or that channels are only in a few discrete states and the probability of switching between states per second (called the kinetic rate constant) is a random process dependent only on the present state (similar to white noise with no dependency on the past). This idea was based on the understanding of chemical reactions at the time the Hodgkin-Huxley theory was proposed (Bassingthwaighte *et al.* 1994:182). We now know that the proteins that compose ion channels are described more fully by potential energy functions (taking into account all the energy in bonds and

interactions between components of the protein) which contain a multitude of states that do not have equal energy. Therefore the probability to switch states is not constant (Bassingthwaighte *et al.* 1994:184; Liebovitch *et al.* 1991:443). In terms of the conceptual model, clusters of open states contain more clusters of open states which in turn contain clusters of open states. This leads to the realization that the probability per second of switching between states is dependent on the time scale at which the patch clamp trace is analyzed, or the probability of occurence of a channel event depends on the time since the last channel event, called the effective kinetic rate constant (Liebovitch *et al.* 1987a:37). Some of the advantages of a fractal model over the Markov model are its applicability to many types of channels and more realistic assumptions of the complexity of proteins. To address Conti's (1975:47) comments above, the fluctuations in the number of activated elementary processes appear in some cases to have fractal clustering with 1/f spectra implying dependency on past fluctuations, also interestingly, a theme recurrent in the firing patterns of neurons.

Toshimitsu Musha was the first to suggest a relationship between human perception, the transfer of information within biological systems and 1/f-like fluctuations (Musha 1981:143). Neurons impart a history to the information they transmit because passage of an action potential along an axon changes the physiological state of the axon. This modulation of a neuron by the information it carries was the focus of Musha's experiments (Musha *et al.* 1981:616). He placed squid axons in a sea water bath and stimulated intracelluarly at one end of the axon with Gaussian white noise impulses for 2 sec with a rest period every 5 secs to prevent adaptation of the axon. Several wire electrodes external to the axon collected a total of 7,000 responses which were processed by skipping the 5 sec rest period. Musha found that the impulse intervals had very stable 1/f power spectra with slopes of -1 to -1.2. He also observed that the impulse trains of the action potentials appeared to be bunched into groups. He concluded that clustering was due to long-range temporal correlations between impulses. Musha also observed:

> A surprising resemblance is found between a train of action potentials on an axon and a traffic current on an expressway. Both of these are supposed to have approximately the same density dependence of velocity and, hence, can be treated with the same mathematics. Indeed, the observed power spectral density of the traffic current on an expressway has a 1/f component in low frequencies which merges into the white spectrum of shot noise in high frequencies. (Musha *et al.* 1981:621)

1/f spectra have also been found in the spontaneous activity of neurons. For example, isolated snail axons display 1/f patterns in spontaneous firing over many hours (Musha *et al.* 1983:194). In the mammalian nervous system, 1/f spectra have been observed in spike trains from the auditory nerve of the adult cat and in lateral superior olivary single units (Teich 1989:150; Teich *et al.* 1990:41). Although this 1/f activity is not seen over short time scales (< 100 msec), the ordering of interevent intervals of auditory nerve action potentials exhibits long-term fractal fluctuations which may have their origin in the bursting patterns of cochlear hair cell ion channels (Lowen & Teich 1993b:745). Teich speculates that because many sounds have 1/f spectra for low frequencies, the similar fractal time pattern of low frequency activity in the auditory system may be able to match and efficiently sample natural sounds, providing a mechanism to detect the structure of correlations in sound (Teich 1989:150).

In summary, fractal time patterns seem to be recurrent in evoked and spontaneous activity on multiple levels in some invertebrate and vertebrate nervous systems. Although mammalian nervous systems have not been examined extensively with these principles in mind, the work reviewed here is at least suggestive that fractal time processes may underlie human perception. If 1/f processes have properties of convergence in nervous systems, then a profoundly new view of the dynamics of neural organization and the neural basis of sensation and perception is created. One implication of this new perspective may be a central role for 1/f processes in the ontological self-organization of brains and in the origin of behavioral states such as REM sleep.

4. Consolidation of convergent 1/f processes during the developmental self-organization of neural systems and behavioral states: Bunching in breaths and bunching in REMs

In this section we present arguments supporting a role for 1/f patterns with fractal time dependency in neural development and behavioral state self-organization. Neural-developmental processes show a strong dependency on, or correlation with the past. Although we think of memory only as an explicit process, as organisms and human beings we are governed by ultradian cycles of sleep and wakefulness which are a kind of implicit memory carrying information dependent on the recent past (how well we slept last night) as well as our distant developmental past (whether we had a stressful childhood). Events early in the developmental history of an organism can have profound implications in later life, as fetal and neonatal insults such as teratogens, malnutrition and prenatal stress attest.

1/f patterns generated by the consolidation of 1/f processes on many scales in the developing nervous system may have the unique ability to provide *in utero* fractal forgeries of the sensory world which the fetus will encounter at birth. Thus, endogenous self-generation of 1/f activity patterns in the developing CNS and in spontaneous activity patterns in the developing body of the fetus would provide organizing information to coordinate developmental processes on many temporal and spatial scales. 1/f patterns of single unit activity in the reticular formation and in breathing patterns seem to occur in fetuses, neonates and adults during REM sleep (see below). With this observation in mind we propose that the historical continuity of active sleep states or REM states throughout the life span of an organism provides 1/f neural and physical activity patterns both in the fetus to promote neural and physical organization and in the adult to provide for connection to early organizational patterns and to facilitate memory consolidation (see below). Voss (1989:42) says of 1/f processes in general that they simulate "the characteristic way the world changes in time" if this is true then endogenous self-generation of 1/f patterns of activity would provide an evolutionary advantage to the fetus or neonate, and behavioral states such as REM sleep would be predicted to exist during ontogeny and to continue in later developmental stages of an organism.

REM sleep is the most metabolically active state of the brain in the fetus (Abrams *et al.* 1988:65) as well as in the adult (Sakai 1980:471). A role has been proposed for this increased neural activity during REM sleep to counteract the effects of slow wave sleep (SWS) by providing a source of periodic endogenous stimulation (Vertes 1986:371). However, the temporal structure of this periodic endogenous stimulation was not considered important. We predict that this periodic endogenous stimulation will be 1/f-like, based on observations of single unit activity in different regions of the brain during REM sleep by Yamamoto *et al.* (1986:279). They have also demonstrated the behavioral state-specificity of 1/f power spectra in interspike intervals in the mesencephalic reticular formation (MRF), hippocampus and ventrobasal thalamus (Kodama *et al.* 1989:26) of the adult cat during alert states (orienting to birds) and during the state of paradoxical or REM sleep. Yamamoto *et al.* (1993, preprint) have also found that the 1/f spectral structure of REM sleep is negatively regulated by the activity of serotonergic (5-hydroxytryptamine or 5-HT) systems under cholinergic drive during this state. Therefore the activation of 5-HT systems during grooming behavior or, moderately, during SWS (Jacobs & Azmitia 1992:165; Jacobs & Fornal 1993:346) is associated with a

white noise spectrum commensurate with a loss in correlation or clustering between interspike intervals. In fact, in the cat some 5-HT systems show total inactivation during REM sleep and at the start of orienting responses, but become very active again during phasic arousal (Jacobs & Azmitia 1992:165). During REM sleep 5-HT activity resumes at the end of an epoch but at twice the rate of quiet wakefulness; this suggests that REM sleep is, at least in terms of 5-HT systems, a prolonged orienting response. Cats with lesions of brainstem sites important in suppressing motor activity during REM sleep show complex patterns of behavior during REM sleep such as orienting and locomotion. In contrast to those in animals without lesions, 5-HT neurons in these animals show extremely high activity. We will return to these observations in a later section describing 1/f activity in other brain regions during behavioral orienting.

As mentioned, the ultradian activity pattern of REM sleep provides continuity between the developing fetus and the adult. The definitive marker of REM sleep is, of course, aperiodic rapid eye movements which are accompanied by a low voltage, fast desynchronized EEG patterns (in contrast to high voltage, slow synchronized EEG patterns of non-REM sleep), and the concurrent occurrence of ultradian activity patterns such as spontaneous twitching movements of the body (Pilcher *et al.* 1987:45) in most vertebrates and mammals, as well as loss of tonus in antigravity muscles (Berger 1961:840; Jovet 1965:20). These ultradian activity patterns associated with REM sleep in adults emerge ontogenetically before sleep-wake cycles or the basic rest activity cycle (BRAC) become well defined (Corner 1977:279). In fact, spontaneous motility in the chick embryo emerges at day 4 (stage 22-23; Hamburger 1970:141) just as rhombomere segmention of the brainstem and terminal cell division and migration in early reticular formation is complete (Lumsden & Keynes 1989:424). Corner (1990:239) has reviewed the connection between ultradian motility patterns in the embryos of vertebrates and invertebrates, their brainstem origins and the ontogeny of sleep states. He suggests a robust connection between the ontogenetic coalescence of body twitches, REM's, breathing moments, EEG, etc., in the developing animal and the maturation of the brainstem. It is interesting that the patterns of fluctuations of these state markers in the developing animal seem to show the bursting intermittency that characterizes 1/f processes.

Power spectral analysis of ultradian-linked spontaneous motility patterns found in the literature shows a strong bias in that investigators are searching for the emergence of periodicity as a marker of the development of behavioral states (Robertson 1982:1016; Hayes *et al.* 1993:279). Closer

examination of the published data indicates broadband spectra characteristic of 1/f processes, that instead are smoothed, averaged and binned to support hypotheses of dominant periodicities. In stark contrast, the recent findings of 1/f fluctuations of inter breath intervals (IBIs) in fetal sheep (Szeto *et al.* 1992:R141), support the idea that 1/f patterns may be wide spread during the developmental self-organization of neural systems and behavioral states. Breathing in fetal sheep as well as the fetuses of other mammals occurs only during active sleep (Dawes *et al.* 1972:119) and is thought to be necessary for lung development and activity-dependent organization of brainstem systems for respiratory coordination. Szeto observed the *in utero* EMG from diaphragms of fetuses measured for periods as long as 3-5 hrs and determined burst durations (from 7,000 to 13,000) which were used to define IBIs. The distributions of IBIs were found to have log-normal form for short intervals (high frequency) and exponential inverse power law for longer intervals > sec (low frequency). Information about the sequential ordering (or dependency) of IBIs was determined by the power spectrum. Szeto found an inverse relationship (1/f) between power and frequency for IBIs >10 secs long, as well as an increase in the slope of the power spectrum from -0.36 at 102 days to -0.80 at 130 days. The slope was -1 after birth due to more bunching of breaths. The decreases in the slope of the power spectrum suggest progressive increases in the dependency or bunching between bursts. Further support for the power spectral findings of dependency between breaths comes from the application of the effective kinetic rate constant to the same data, demonstrating that as time increases, the rate constant decreases, and breaths become more bunched over longer times (i.e., the probability of taking a breath is dependent on the time since the last breath; Szeto *et al.* 1990:1390). Interestingly, Szeto also found that prenatal insults associated with drugs such as opiate agonists dramatically decrease the percentage of time the sheep fetus spends in REM sleep (Szeto 1983:211) and increase breathing (breathing also occurred in long periods of drug induced persistent wakefulness). However, analysis of IBIs under drug conditions indicated a shift to a spectrum characteristic of white noise and decreased bunching of breaths, as well as loss of correlations (Szeto 1993). Human prenatal exposure to opiates is associated with deficits in attentional processes and developmental delays. If a technique was available to reestablish fractal time patterns in these infants, therapeutic intervention for these and other developmental disorders might be possible.

1/f processes associated with fractal time correlations between events may provide state-specific stimulation to the developing fetus preparing it for interactions with a fractal environment. The coalescence of neural activity

associated with REM sleep into BRACs in the last trimester of human fetal development is not only indicative of neural maturation but also of convergence of neural functions. Hofer (1988) has referred to REM sleep as an ontogenetic adaptation

> whereby early neural function acts as a vital ingredient in the developmental plan of the organism. Presumably, as the infant grows older, its interaction with the environment increasingly takes the place of this state specific internal stimulation. From its peak in the late fetal period, REM sleep proportion declines rapidly during the first postnatal year, possibly representing the decline of its role in neural development. (Hofer 1988:16)

Is there a relation between 1/f-like REM ultradian activity patterns and brain development? A quote from Allen Hobson (1988) on the developmental functions of REM sleep contains the germ of our argument:

> [...] In a paralyzed limb, muscles that are not electrically stimulated fail to develop normally. How does the developing brain avoid such problems and, instead, steadily gain in both mass and capability? Early in development, REM sleep could provide the brain with a highly organized program of internal action. This program is stereotyped, redundant, and reliable — all features useful to a developing system [...]. For example, REM sleep could help prepare the organism's reflex repertoire. From a genetically programmed division of cells into excitatory and inhibitory subpopulations, all with locations specified, how could the organism advance to an organized system that could produce startle reflexes [and orienting]? One way might be to begin by establishing a large pool of central excitatory neurons capable of emitting spontaneous motor commands. The reticular formation would be a good location for such an excitatory cell pool. By firing phasically, such reticular cells could command reflex motor activity and also stimulate the oculomotor and vestibular neurons with which they make excitatory synapses. (Hobson 1988:292)

In fact, as we have seen in the last section, it may be possible that many types of neural membrane, ion channels and neurons are capable of generating 1/f patterns, and that these patterns may converge over populations of cells. This may in some way account for the great flexibility and plasticity of the brain even later in life (see last section). By the time we reach the age of 70, on average we have spent 8.5% or 6 years of our life in REM sleep. Deprivation of

REM and other stages of sleep is fatal (Rechtschaffen *et al.* 1989:68). What is the function of REM sleep? Why is it so critical to our development and survival? The following ideas may provide a framework for a general theory of the function of REM sleep.

The function of REM sleep developmentally may be:

(1) a recurrence of the developing patterns of activity present in the early brainstem which serves as a reference point for further growth. Although little is presently known about the patterns of activity present in the fetal brain, many of the reports describe bursting firings and a general lack of periodicity. These types of patterns are indicative of fractal time processes. We hypothesize that during early differentiation of the brain, spontaneous 1/f patterns in single cells (due to 1/f ion channel processes) plays a role in local and regional organization. The clustering or bunching characteristics of this activity will aid in binding activity between local regions and across larger expanses of the neural axis. After reticular networks are established, proto-REM states would provide stronger stimulation to later developing subcortical and cortical regions. Some results support this view. Electrolytic lesions of pathways from the reticular core to the lateral geniculate nucleus (LGN) in kittens were found to impair the structural and physiological maturation of cells in the LGN (Davenne & Adrien 1985:59). Also selective REM deprivation in kittens by non-invasive awakening produced anatomical changes in the LGN similar to eyelid occlusion (Shaffery *et al.* 1993:891). The reference point for further growth may involve the fractal time correlations as well as clumping and bunching phenomena for the establishment of neural pathways;

(2) to place the brain in a state in which long-range spatial and temporal correlations in the neuronal activity of diverse brain regions can occur, a signature of which is the presence of 1/f activity in the mesencephalic reticular formation, strengthening recurrently used pathways. 1/f patterns due to their broad spectral properties would have long range (low frequency) and short range (high frequency) interactions with the entire neural axis. The ability to stimulate distant regions of the brain with concurrent activity may prove to be an endogenous source of synaptic reinforcement, strengthening newly stimulated connections and eliminating exuberant overgrowth of non-active terminals. It is interesting that visually quite large morphological alterations can be discerned in the MRF during early development (Scheibel *et al.* 1973:301). These alterations suggest that the MRF is developmentally plastic, rendering it more functionally sensitive to modulation by experiences *in utero* as well as early postnatal experiences;

(3) to prepare brain orienting pathways (e.g., amygdala, superior colliculus, MRF (medulla reticular formation), etc.) for postnatal environmental stimuli. The most important behavior of a newborn mammal is to orient to and latch onto a nipple. 1/f patterns of activity in single units in the MRF have been found in association with orienting behaviors in adult cats by Yamamoto *et al.* (1986:279). 1/f patterns of neural activity during orienting may be indicative of a state of global brain coherence (see next section). 1/f states during fetal waking (indicated by neck muscle tonus, low voltage, a fast desynchronized EEG pattern, and a lack of spontaneous movements) and PGO activity may prepare the fetus for this important event. Lavie (1993) has suggested that the semi-periodic occurrence of REM provides the organism with 'privileged gates' that facilitate a smooth transition between wakening and REM. Reports from subjects in isolated sleep situations where outside cues (alarm clocks, etc.) are eliminated so that they must rely on internal cues to wake, suggest that they awake from REM sleep more often. Lavie states: "[...] there is evidence that awakening from REM sleep has a distinctive evolutionary advantage over awakening from [SWS], because it is associated with an activation of [...] orienting mechanisms [...] Thus upon awakening from REM the organism can immediately orient itself in space and avoid maladaptive behaviors" (Lavie 1993:283). The increase in 5-HT activity just prior to awaking may be significant in that it prepares the animal for motor responses. It would also share similarity with orienting responses, where 5-HT activity is suppressed during orienting with a rebound shortly afterwards. Thus, complete 1/f convergence would occur primarily during brain development and during orienting and REM sleep in adults, the two most energetic states of the brain. These two behavioral states could be considered the foundations of consciousness.

The reiteration of 1/f neural activity patterns on a nightly basis during REM sleep in adults may provide a connection to the initial conditions under which key structures in the brain formed (e.g., MRF), or a kind of reference state useful in the long term consolidation of new information, as well as a means of maintaining cognitive and attentional flexibility. Recently, many theories have been proposed and experiments performed examining the association of REM sleep with learning and memory, without definitive results (Hobson 1990:371). Several studies point to neuronal activity patterns present in the MRF during REM sleep as being critical to consolidation of learning. For example, post-learning MRF electrical stimulation during REM sleep, but not during SWS or wakefulness, enhances spatial discrimination in rats

(Hennevin et al. 1989:291). Hennevin hypothesized that a memory trace is reactivated during REM sleep and in a similar fashion, the same neural events occur after acquisition, after a reminder, and during post learning REM sleep (Bloch *et al.* 1979:329). We propose that the fractal time patterns of activity during REM sleep are similar to fractal time patterns during attentional states of the brain. Therefore, electrical stimulation of the MRF could be generating fractal patterns of activity, possibly in a fashion similar to Musha's work with electrical stimulation of squid axons (detailed above).

The MRF may be a central site in the staging, convergence and amplification of 1/f processes from the cellular level, and may further disseminate 1/f patterns throughout the neural axis. Gray *et al.* (1992:29) have reported that stimulation of the MRF enhances the amplitude of long range coherent binding of visual stimuli between different cortical sites in the visual cortex. Extended spatial and temporal correlations within the neural connectivity of the MRF are supported by anatomical and physiological evidence. An example of the spatial connections in the RF involves the dendrites from one neuronal field or nucleus of the RF that can extend deeply into other fields or nuclei, and that appear to be oriented as if "reaching toward their sources of innervation" (Scheibel 1984:240). Further increasing spatial connectivity, reticular neuron axons have been shown to project long distances and show remarkably dense collaterals. In particular, gigantocellularis neurons may project both to the spinal cord and cerebral cortex, as well as collateralizing within the RF itself (Scheibel 1984). Functionally, single cells in the RF show polysensory convergence of heterogeneous afferents, with each cell showing its own unique pattern of inputs; however, some cells seem to be correlated in their temporal activity as well. Investigations of the cross-correlation of firing to the cardiac-related rhythm of sympathetic nerve discharge between pairs of cells in the medullary RF of cats support the view that the MRF is organized into functionally distinct modules (Gebber *et al.* 1987). Gebber points out a purpose for this organization:

> [...] are the afferent connections to the [MRF] and the axon collaterals of reticular neurons distributed in a selective manner, thereby leading to synchronization of the discharges of reticular neurons with the same output address? [...] [t]heir anatomic interdigitation may provide a convenient means of intermodular coupling for the purpose of formulating complex and highly integrated behavioral response patterns involving numerous output addresses. (Geber *et al.* 1987:109)

Taken together, these observations suggest that the MRF has the necessary substrates for long-range spatial and temporal correlations (within and among MRF nuclear groups) in activity. Gebber also reports that coherent 1/f power

spectra have been observed between sites in the MRF (personal communication). The MRF also plays a key role in orienting behavior. Kornblith *et al.* (1972) found that when unit activity in different regions of the MRF was recorded during the learning of an appetitive classically conditioned task (tone-food pairing), the activity tended to be temporally correlated with the orienting response. Electrical stimulation of the MRF induces a state of arousal in many species, and in some cases elicits movements of the head and neck. Stimulation of the MRF elicited both behavioral and cortical orienting responses in rabbits (Skrebitsky *et al.* 1980:117).

In summary, during the development of the nervous system, it may be advantageous to use a 1/f generator possibly in the developing MRF to provide activity patterns that simulate 'the characteristic way our world changes in time' to provide a means of correlating and binding neural activity in preparation for behavioral events such as orienting responses. The association of REM sleep with 1/f phenomena suggests that REM sleep may represent a brain state similar to orienting, but without incoming sensory stimuli, in which broadband binding and long-range spatial and temporal correlations can occur at different functional levels in the brain (e.g., ion channels, neural membranes, nonlinear cortical-cortical oscillators). REM sleep may prepare the brain for waking experience by providing a microcosm of waking experience (esp. the orienting response), which allows significant daily and lifetime events to be integrated and assimilated. The MRF, by virtue of its extended spatial connections throughout the neural axis and its cardinal role in the brain states of REM and behavioral orienting, involving the establishment of widespread temporal correlations, may be one of the preeminent brain sites in the staging, convergence and amplification of 1/f processes from the cellular level. In evolutionary terms, neural systems utilizing endogenously generated 1/f in the form of REM sleep to assimilate and process stimuli would have a selective advantage, and this may explain its wide occurrence among vertebrates. In effect this implies evolutionary selection of proficient and parsimonious dreamers that will in turn have the best adapted orienting responses.

5. The association of coherent broadband 1/f spectra with orienting and attention: Vertically convergent 1/f processes underlying the self-organization of attentional behavioral states and mind wandering

The orienting response is a fundamental behavioral reflex, illustrated in behaviors such as turning one's head to discover "What is it?" (or as Pavlov

would say *Shto eto takoe?* "What is the nature of this thing?"; cf. Kimmel 1979:xi). Because it is such a fundamental and ubiquitous process, orienting is a behavior that links many subfields of behavioral neuroscience, from learning theory and cognitive models of attention, to EEG and electrophysiological explorations of cortical and subcortical activity during the self-organization of behavioral states.

If you have ever owned a cat and observed its behavior when birds are nearby, you have probably observed the birds eliciting an orienting response in the cat. The orienting response is evoked when an animal is presented with a novel stimulus; it is manifested in a quick movement of the head toward the stimulus so that the eyes, ears and nose are facing its source. This orienting movement is frequently followed by exploratory or appetitive behaviors such as approach and sniffing, as well as increased general arousal and activity. Orienting is also accompanied by autonomic arousal, an indicator of which is increased heart rate, due to attenuation of the vagal component of the baroreceptor reflex, thereby temporarily increasing cardiac output to the brain (Schlor *et al.* 1984:157). Repeated presentation of the stimulus leads to habituation of the orienting response, with autonomic arousal decrementing more rapidly than the behavioral response (Martin *et al.* 1976:37). Orienting can be seen as a complex self-organized behavior involving the integration of many central and peripheral subsystems. As Sokolov (1963) points out:

> [...] according to some, the orientation reactions are but reflexes limited to the muscular apparatus of individual analyzers [...] autonomic (e.g., vascular) reactions serve the same purpose as somatic reactions, and facilitate increase of analyzer sensitivity. The orientation reflex is, therefore, a complex combination of somatic and autonomic reactions forming a complete functional system. (Sokolov 1963:12)

In 1983 Yamamoto *et al.* published the first of a series of papers (Yamamoto & Nakahama 1983:1182; Yamamoto *et al.* 1986:279; Gruneis *et al.* 1990:407) in which spontaneous single unit activity recordings were made from the MRF in unanesthetized cats during different behavioral states. Spectral analysis was performed on digitized interspike-intervals of units made during SWS, REM, or the attentive state of bird watching (BW). Although the cats used in this study were immobilized at the time of the recording by two steel support tubes mounted within the microdrive-acrylic cap transversely across the dorsal skull, the cats had been adapted to the restriction of head movements at the time of recording (Yamamoto & Nakahama 1983:1182). The spectral analysis during BW was restricted to a period of time less than 30 sec

after the initial orienting response to a pair of live birds when units first showed stationarity (Yamamoto *et al.* 1986:279). The spectral density of the distribution of spike intervals was described as approximately inversely proportional to frequency from 0.1 to 1.0 Hz, or '1/f-like' in this frequency range only during REM sleep and BW. The period of BW was marked physiologically by changes in other measures of orienting, such as increases in the neck electromyogram, low voltage, fast desynchronized EEG patterns characteristic of orienting responses in cortex, hippocampus and LGN, and a large number of responses in the electrooculogram. This work which has been repeated several times by Yamamoto (personal communication) is the most suggestive of an association of 1/f phenomena with the self-organization of behavioral states. Other observations of 1/f phenomena (i.e., broadband 1/f-like power spectra in most cases) in cortical and subcortical brain structures during the self-organization of specific behaviors, such as orienting responses, have been reported.

Freeman (1989:927) reported 1/f power spectra in the surface EEG of the rabbit olfactory bulb, anterior olfactory nucleus and pyriform cortex preceding inhalation of significant odors. 1/f spectra have also been observed in the surface EEG of the visual cortex of a rhesus monkey performing a conditioned response to a visual stimulus (Freeman & Van Dijk 1987:267). The surface EEG is dependent on correlated firing among large populations of pyramidal cells (except the surface EEG of the olfactory bulb which has its origins in granule cells). The human EEG recorded from the scalp of subjects in quiet wakefulness has also been reported to show 1/f-like power spectral scaling (Pritchard 1992:119). Further support for the association of 1/f-like spectra with self-organization of the nervous system during behavior is the finding of 1/f activity in EEG power spectra during circumscribed behavioral states. Kling *et al.* (1979:88) reported shifts in broadband EEG power spectra recorded from the amygdala of primates during discrete behavioral states such as grooming, aggressive and sexual behavior. Nakata & Mukawa (1989:90) also have reported 1/f-like cortical and subcortical EEG in cats subjected to stress. In brief, 1/f patterns of activity in the MRF, surface EEG, scalp EEG and subcortical EEG seem to be present during highly activated states of the brain such as behavioral orienting, REM sleep, sexual behaviors and stress. These behavioral states that share instances of 1/f spectra also have in common an unstable transitory nature with possible bunching-like 1/f patterns of occurrence if not regimented by experimental circumstance. Paradoxically, this transitory bunching may have important correlations with future and past states of the brain. For example, orienting might lead to aggression, sexual behavior,

or REM sleep. These transitory bunching states are important in that memories which may shape the long term behavior of an animal most probably will be formed in association with orienting, sexual behavior and stress and be strengthened during REM sleep.

Thus far, we have presented an argument for level independent coalescence of 1/f processes from subcellular ion channels to neurons to the developing nervous system and in the behavioral states of orienting and REM sleep. In the remainder of this section, we will review our own findings of coherent 1/f processes underlying functional binding between cortical regions during the self-organization of attentional states in the primate and human experience. How might 1/f processes from cellular and quantum levels be channeled through the MRF to influence cognitive processes? We suggest that our attention displays 1/f fluctuations, under conditions in which it is not too heavily driven by environmental demands. For example, under conditions of mild sensory deprivation and profound relaxation (e.g., Tank Isolation Technique; cf. Lilly 1981) spontaneous fluctuations of thought, images, physical sensations and the sense of time occur. Wegner has made the observation: "Consciousness simply cannot hold itself still." (Wegner, in press). Further, Wegner proposes, through his theory of ironic processes of mental control, that the wandering nature of consciousness is necessary to prevent habituation at sensory and conceptual levels of conscious experience, serving the same purpose as physiological nystagmus to prevent accommodation or habituation of photoreceptors. He also proposes that REM sleep manifests the same mind wandering without the stability of environmental sensory input. In his own words: "Wandering is not just the result of weakness of will in the face of absorbing environmental stimulation, therefore, but rather it is compelled somehow, perhaps even required by the architecture of the mind." (Wegner, in press) The self-control of wandering by the mind activates a feedback loop initiating attentional or internal orienting systems leading to wandering against self-control followed by more loops; this is Wegner's (1994) theory of ironic processes. Mind wandering may be objectively measurable as fluctuations in pupil diameter which has been directly correlated with firing of locus coeruleus (LC) neurons (Rajkowski *et al.* 1993:974). We propose that the intrinsic architecture of the mind is constructed with 1/f processes from subcellular levels to behavioral states, and the nystagmus of consciousness is a manifestation of vertical integration of these states. Fluctuations in mind wandering and the firing of pontine reticular LC neurons illustrate the tug and pull between internal and external states directed by emotion.

How could fractal time patterns originating in the MRF enable the self-organization of integrative behavior (Mandell & Selz 1993:86)? This is the central question motivating our investigation of intercortical EEG (Anderson *et al.* 1993a:737; Anderson *et al.* 1993b:780) suggesting that 1/f processes seem to provide the cement binding the elements of cortical dynamics together. Other work has examined the role of broadband binding of widespread cortical sites during perceptuomotor integration (Bressler & Nakamura 1993; Bressler 1993; Bressler *et al.* 1993). We hypothesized that 1/f-like spectra in the EEG result from correlated activity between cortical and subcortical sites over a broadband frequency range and may be indicative of brain self-organization during attentional states. To test this hypothesis, we examined the slopes of coherence spectra between multiple cortical sites in a monkey performing a GO/NO-GO behavioral task to determine if the slopes, indicative of long-range fractal correlations, changed during the task. The task involved discriminating two visual stimuli on a display screen, each consisting of four dots in either a straight line or diamond configuration (see Bressler & Nakamura 1993 for experiment details). Briefly, the monkey was required to release a lever (GO condition) in response to one stimulus and hold the lever for 500 msec (NO-GO condition) in response to the other configuration. We examined from 6.25 to 93.75 Hz the Fisher z-transformed coherence (or the normalized cross-power spectrum) calculated for transcortical recording sites in multiple cortical areas, specifically those found by Bressler & Nakamura (1993) to have high coherence values prior to stimulus presentation and also during the behavioral response for two sessions (S1, S2). Pairs of electrodes with high coherence accounted for roughly 10% of all pairs in both sessions. The task in S2 was identical to S1 except that a stimulus reversal was imposed on the task (the stimulus that had previously been paired with water — "GO" — was switched to "NO-GO"). In addition, a different montage of cortical sites was sampled in S2. However, comparisons between sites common to S1 and S2 displayed similar coherence. Two 160-msec-long spectra windows were analyzed, one (W1) centered prior to stimulus onset and the other (W2) on the mean response time (MRT). Task-dependent changes in the mean slopes of highly coherent pairs were found (Table 1). Slopes calculated for W1 centered after the monkey had initiated the trial but prior to visual CS onset, a behavioral state similar to tonic arousal (Sheer 1989:339), were consistent across conditions and sessions. Slopes calculated for a spectral window centered on the response portion of the trial (W2), when the monkey was moving his hand or suppressing hand movement, were less uniform with condition and across sessions.

SESSION	W1 GO	W1 NO-GO	W2 GO	W2 NO-GO
S1	-1.07 ± .16	-1.08 ± .17	-.73 ± .07†	-1.14 ± .19
%Change from W1	0	0	32%↓	6%↑
S2	-.87 ± .06	-.85 ± .16	-1.00 ± .14*	-.63 ± .05*
% Change from W1	0%	0%	16%↑	26%↓

†(S.D. from W1GO,NOGO&W2NOGO $F[1, 24] = 11.43$, $p < 0.006$)

*(S.D. $F[1,12] = 7.00$, $p < 0.02$)

Table 1: *Mean slopes of strongly coherent pairs for session 1 and 2 (± standard error of the mean) calculated by linear regression (13 points from each pair) from the Fisher-z transformed coherence spectrum were compared by repeated measures ANOVA (2-within factors [window, condition] and 1-between factor [session]). No main effects were detected; however two interactions were noted: one between condition and session ($F[1, 12] = 6.812$, $p < 0.03$) and one between window, condition and session ($F[1, 12] = 8.205$, $p < 0.02$). Correlation coefficients for all slopes were > .85.*

The presence of 1/f-like coherence spectra is consistent with the idea that temporal correlations between multiple cortical sites at different time scales may underlie the flexibility of the brain in responding to behavioral challenges (see Figure 3 and Figure 4 for the actual coherence spectra). During the first spectral window, W1 GO & NO-GO, the monkey was in an alert tonic arousal state, motivated by water deprivation. Sheer (1989:339) has made a distinction between tonic and focal arousal in relation to cortical EEG. Sheer defines tonic arousal as: "[...] an oscillatory, unstable state of the organism, in which many different subassemblies of the intrinsic electrical activity are firing in different patterns [...] not being focused [...] [this] represents an adaptive ready state for significant occurrences." (Sheer 1989:341) During tonic arousal, activity common to the electrode sites in the cortical sensory and motor areas examined in our work exists in a state of broadband 1/f-like coherence which could be conceptualized as broadband binding. This activity has analogies to the synchronization of chaotic nonlinear oscillators in which two separate systems, one chaotic with 1/f-like broadband spectra, and one a nonchaotic subsystem of the first, will converge quickly to one trajectory when linked (Pecora & Carroll 1991:151; Carroll & Pecora 1993:4). This approach has the

advantage of a strong physical analogy to the complex neurocircuitry of cortical and subcortical structures. Further, chaotic activity in cortical circuits has been observed (Freeman 1992:451).

Another interpretation involves the self-organized criticality (critical state) postulated in physical systems (Bak *et al.* 1988). In dynamical terms, the critical state would be the attractor for the process (in an orienting response the evoking stimulus could be considered the attractor; in our system the monkeys attentional focus on the display screen preceding onset of the visual stimulus would be the attractor). In the process of orbiting the attractor, 1/f noise is generated by the system. Per Bak and others have suggested a unifying principle explaining the mysterious ubiquity of 1/f noise as well as the equally unexplained phenomenon of scale-invariant, self-similar or fractal properties found in spatial structures such as growth aggregates, cellular automata, earthquakes and sandpiles. Per Bak explains:

> [a]lthough fractals appear throughout nature, investigators have only begun to understand the dynamics that create fractals [...] [w]e and our colleagues suggest that fractals can be viewed as snapshots of self-organized critical processes [...] [f]ractal structures and flicker noise [1/f noise] are the spatial and temporal fingerprints, respectively, of self-organized criticality. (Bak & Chen 1991:51)

These spatial structures are large interactive systems that tend to spontaneously organize themselves into a critical state (demonstrating 1/f properties) in which a seemingly minor event can lead to long range changes in the structure. As the preceding quote indicates, the spontaneous emergence of statistically reproducible relations between distant parts of large interactive systems guides the system to a critical state, and has led Per Bak and others to group these systems under the rubric of self-organized criticality, the best physical experimental example of which is a small sandpile. As single grains of sand are added to a pile of similar grains, a number of processes begin to occur. The added sand will accumulate to a slope.

> Now and then, when the slope becomes too steep somewhere on the pile, the grains slide down, causing a small avalanche. As more sand is added and the slope of the pile steepens the average size of the avalanches increases [...]. The pile stops growing when the amount of sand added is balanced, on average, by the amount of sand falling off the edge. At that point the [sandpile] has reached the critical state. (Bak & Chen 1991:48)

Avalanches of all sizes can occur with the addition of a single grain of sand at the critical state; however, on average, large slides occur less frequently than

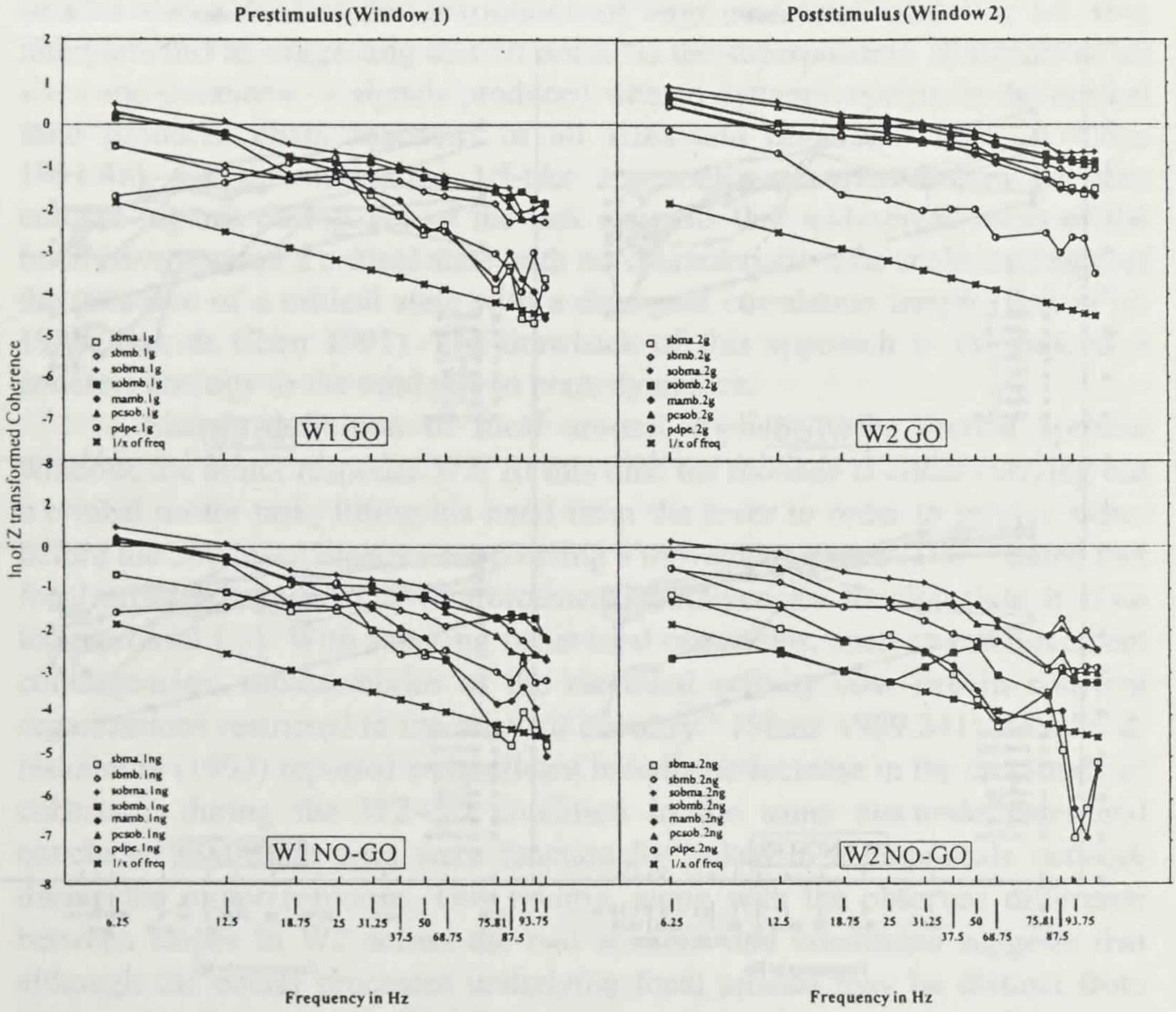


Figure 3: *Coherence spectra calculated for Session 1. The data from Session 1 consisted of 470 correct go trials and 458 correct nogo trials. From a total of 55 pairs in Session 1, 7 pairs with the highest overall coherence were chosen and a similar number was chosen from session 2. Coherence ranged between 0.97 and .001 with the mean equal to 0.128, n = 728. The biases for coherence values used to generate slopes were generally no greater than .02, although the majority were <.001. Each line represents the Fisher z transformed coherence for an electrode pair, with a 1/f line for comparison (see text for description of windows and conditions).*

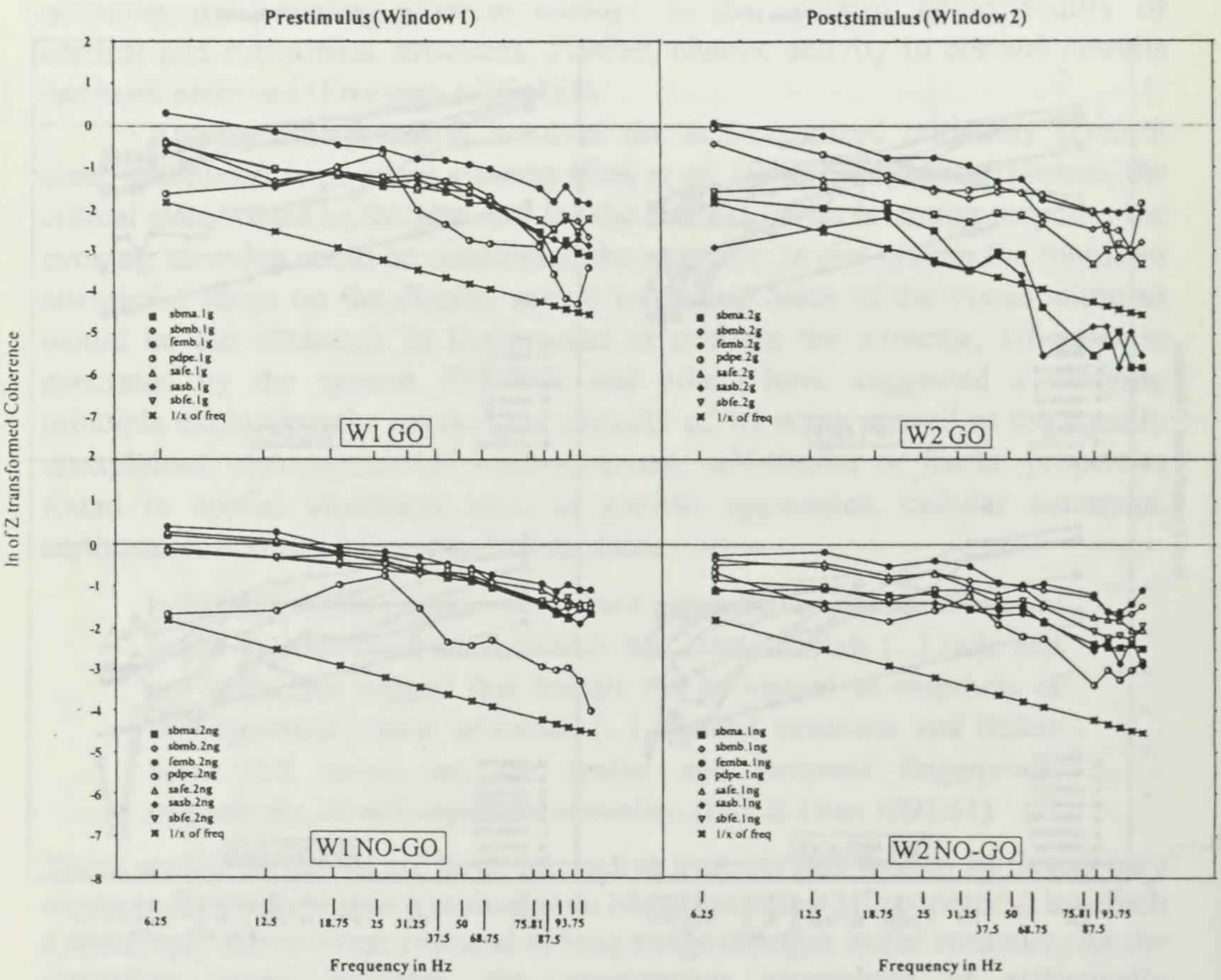


Figure 4: *Coherence spectra for Session 2, data collected in a similar fashion but several weeks after Session 1. The strong 1/f appearance of spectra for most pairs is evident.*

smaller slides. In fact the distribution of large and small slides is 1/f. Bak interprets this as suggesting that 1/f noise "is the superposition of signals of all sizes and durations — signals produced when a dynamic system in the critical state produces chain reactions of all sizes and durations" (Bak & Chen 1991:48). By definition, the 1/f-like appearance of cross-spectra between cortical regions during W1 of the task suggests that widespread areas of the brain have entered a critical state with no characteristic time scale, one sign of the presence of a critical state with a divergent correlation length (Bak *et al.* 1988; Bak & Chen 1991). The drawback of this approach is the lack of a concrete analogy to the sand pile in brain dynamics.

Sheer's definition of focal arousal applies to the second spectral window, the motor response W2. At this time the monkey is either carrying out a critical motor task, lifting his hand from the lever in order to receive water before the 500 msec limit, or suppressing a movement. Sheer (1989) stated that focal arousal "needed [...] reinforcement contingencies to dissociate it from tonic arousal [...]. With focusing behavioral operations, such as reinforcement contingencies, subassemblies of the electrical activity now fire in coherent organizations restricted to the relevant circuitry." (Sheer 1989:341) Bressler & Nakamura (1993) reported a significant broadband increase in the amplitude of coherence during the W2-GO condition in the same electrode pairs and concluded that these sites were functionally linked in a large-scale network during the motor response. This finding, along with the observed difference between slopes in W2 across the two sessions and conditions suggests that although the neural processes underlying focal arousal may be distinct from tonic arousal, they are still 1/f-like, although complex motor activity and, therefore, 5-HT activity may be increased (see previous section). One of the central implications of these still tentative results is that the slope of the coherence spectra may serve as an important new measure of changes in intercortical dynamics during changing behavioral states.

How is 1/f coherence in intercortical interactions coupled with neurochemical events during changing attentional behavioral states? During the onset of orienting, in response to auditory or visual stimuli in the cat or monkey, activity increases in noradrenergic (NA) neurons in the LC (Rasmussen *et al.* 1986:324; Rajkowski *et al.* 1993:974). Orienting responses can be elicited in many mammals by stimulation of the LC (Skrebitsky *et al.* 1980:117), which in turn has been demonstrated to increase cortical single unit activity and the amplitude of the EEG (Berridge & Foote 1991:3135). With the exception of some dopamine (DA) cell bodies, virtually all centrifugal projecting DA, NA and 5-HT groups are located within the boundaries of the

brainstem reticular formation (RF) (Moore 1980:67). Although complete anatomical and functional information about the RF is still lacking, data support the view that it is organized into functionally distinct but interactive or coupled modules (Gebber *et al.* 1987:106; Langhorst *et al.* 1987:347). In addition, these modules have interconnections with centrifugally projecting cell bodies (Ennis & Aston-Jones 1988:3644) and receive efferents from forebrain centers such as the amygdala (Stock *et al.* 1981:503). Selz & Mandell (1991:717) investigated the Bernoulli partition-equivalence of interspike intervals of NA, 5-HT, and DA neurons projecting to wide-spread areas of the cortex and found they exhibited inverse power-law 1/f distributions. They proposed that NA and the other monoaminergic brain stem cell body groups with fractal time power spectral patterns may play a role in stabilizing the widespread quasiperiodicity of the cortical EEG during specific behavioral states (Mandell & Selz 1993:355). The role of the RF in general and the MRF in particular in dissemination of these fractal time patterns throughout the neural axis appears to be state-dependent in terms of the neurotransmitter involved. An understanding of how these brainstem cell body groups are regulated in a state-dependent fashion by forebrain areas such as the amygdaloid complex and the basal forebrain is the subject of the next section.

7. Fractal time, emotional memory and the amygdala: Multisensory integration, temporal lobe epilepsy and 1/f-like coherence

In this section, we will provide hypotheses relating the previously described broadband 1/f-like coherence between multiple cortical regions during attentional states to fractal firing patterns in sensory pathways (fractal time) and their role in multisensory integration in the temporal lobe of emotionally relevant information. Thus far the themes presented are:

(1) 1/f phenomena in biological systems create fractal correlations in time allowing vertical integration over all levels of neural organization in the organism;
(2) Broadband 1/f-like brain states, characterized by interactions on multiple time and frequency scales in the developing MRF, are of prime importance in the developing brain and reappear in adults during REM sleep;
(3) 1/f processes at different levels of brain function may enable efficient processing of fractal environmental information found in natural scenes (Keller *et al.* 1987:621), human sounds (Voss & Clark 1975:317, 1978:258) and fractal music (Hsü & Hsü 1990:938, 1992:3507).

Drawing an analogy with the proposed function of fractal patterns in the auditory system, the fractal time patterns of low frequency fluctuations in perceptual systems (e.g., temporal lobe) may be able to match and efficiently sample natural fluctuations in meaning, providing a mechanism to detect the structure of correlations in information from the natural environment. The affective significance of environmental information for the organism would be a key determinant of which correlational structures receive attentional resources.

The temporal lobe, in particular the amygdaloid complex, has long been proposed as a behavioral, neurological and neurochemical substrate of affective or emotional states and emotional memory (Gloor 1986:159). The amygdaloid complex and other temporal lobe cortical structures may play a central role in focusing multisensory integration of emotionally relevant sensory information through multiple and largely reciprocal connections with the cortex, basal forebrain, and RF monoaminergic cell body groups. Broadband 1/f spectra in the subcortical EEG of the amygdala range from 0.001 to 3 KHz suggesting a large frequency range over which multisensory integration can be rescaled in time (Nakata & Mukawa 1989:90). These structures are uniquely positioned in terms of sensory processing to utilize multiple time scales in the recall and storage of memory as evidenced by the rescaled-in-time nature of amygdaloid stimulation. Within the last decade, due to discovery of vast new cortical and subcortical connections of the amygdaloid complex, its central role in behavior has been extensively reinvestigated (Angleton 1992). One subnuclei group of the amygdala, the basolateral amygdala (BLA), is distinguished phylogenetically by its immense expansion in close concert with the phylogenetic explosion of multisensory associative neocortical areas in higher mammals. The BLA receives discrete afferents which are thought to contain processed multimodal information from the pinnacle of the associative cortical processing hierarchy in temporal cortex (Amaral 1992:1). Perhaps the most striking aspect of the BLA is the vast flow of efferent information back to all levels of the cortical processing hierarchy. For example, cells in layers III and V of the anterior inferior temporal cortex (area TE, where some dynamic aspects of the visual perception of complex objects such as faces and memory for these objects is thought to be associated with other forms of memory) project into the lateral nucleus of BLA; however, the basal nucleus of BLA completes this feedback circuit not only by reciprocating these projections back to TE but also by projecting extensively in a gradient fashion to all stages of visual cortex including the prestriate and striate cortex. The BLA is also distinguished by its unique classification as 'vicarious cortical' or a subcortical

cortex-like structure, having many of the neurochemical and anatomical markers of cortex but lacking discrete lamination (Heimer *et al.* 1991:109).

Perhaps the most unique and fascinating property of this area of the temporal lobe is the 'experiential phenomena' electrically evoked from the BLA in humans which is perceived as dream like episodes. Amygdaloid stimulation is a necessary procedure in mapping the temporal lobes of conscious epileptic patients in order to locate epileptic foci for surgical removal (Gloor 1992:505). During the course of this procedure, patients frequently experience 'experiential phenomena', so called because to the patients they take on an astonishingly vivid immediacy which they liken to the experience of actual events (Gloor 1986:159). Such experiential phenomena activated by discharges in and near the BLA, but almost never in cortex, manifest as complex visual or auditory or combined auditory-visual hallucinations or illusions, memory 'flashbacks', *déjà vu*, and fear. Another commonly reported phenomenon is temporal distortion, the experience of being trapped in eternity while only a few moments may pass in the external world. These distortions of time perception during temporal lobe epilepsy, as well as during normal states of consciousness such as dreaming or waiting for a pot of water to boil, are possible examples of dynamic rescaling in time afforded by 1/f processes. In other words, rescaling in time is due to shifting across self-similar domains in frequency space. For example, a sensory event encoded in low frequency time frame, with self-similar patterns of action potentials at the sensory level (Gerstein & Mandelbrot 1964:41; Wise 1981:211; Teich 1989:150) or patterns of firing in intercortical connections between temporal lobe and widespread cortical structures, because of the existence of 1/f self-similar information at all frequencies, could be rescaled into a faster frequency domain during electrically evoked recall during temporal lobe stimulation or even during normal recall. The recall of an experience is a temporally compressed summary of the original sensory experience. This rescaling in perceptual time as experienced by epileptics seizing in temporal lobe structures would entail associative interaction between multisensory cortical areas, multiple sensory representations, and the inclusion of long and short term memory.

Reentrant fractal time bursting cells in the BLA, embedded as they are in a behaviorally appropriate milieu of neurotransmitters and neuromodulators and ongoing multisensory flow, function as a complex interface between cortical binding mechanisms during attention via both direct cortical efferents and the extended amygdala and basal forebrain connections, as well as the hierarchy of brainstem integrative and regulatory structures such as the RF, pedunculopontine tegmental nucleus (PPT), parabrachial nuclear complex

(PB), nucleus tractus solitarius (NTS) and embedded monoaminergic groups (DA, NE, 5-HT) which are involved in cortical feedback and EEG desynchronization control. To summarize, we suggest that the BLA provides binding between cortical desynchronization control and brainstem autonomic feedback to emotionally significant sensory experience in order to, as Gloor states, "attach affective tone [...] [to sensory experience] to make a perception or memory emerge into consciousness, thus enabling it to be experienced as an event 'one is living or has lived through'" (Gloor 1986:167). In other words, the feedback between BLA and TE may be critical in the perceptual delineation of emotionally significant visual elements (e.g., Grandma's face) as well as their emotional content (i.e., whether she is happy or sad).

This is why electrical or epileptic stimulation of the intrinsic circuitry of BLA-temporal feedback loops can evoke experiential phenomena. This proposed conceptual model of these 'experiential phenomena' considers the fractal neuronal firing distributions of the many contributing sensory and central neuronal types as well as the reentrant (possibly fractal) bursting neurons in the BLA and their interconnections. Also involved are the amyg-thalamic-cortical, amyg-striatal-thalamic-cortical and amyg-brainstem-cortical feedback loops. The observation of 1/f-coherence in cortical EEG suggests a role for broadband processes in enabling binding between the subcortical BLA complex and multiple cortical sites during attention, emotional memory and emotional states. In fact, the BLA in concert with the basal forebrain could play a role in directing the 1/f-coherence between cortical areas. During these attentional states, long-range spatial and temporal correlations probably occur between forebrain structures such as the extended amygdala (EA), basal forebrain (see Heimer *et al.* 1991 and Alheid & Heimer 1988 for excellent reviews of the new perspectives on limbic organization), thalamus and brainstem structures such as the RF, PPT, PB and the NTS. Langhorst (1983:411, 1987:343) has investigated how the EA and RF interact to regulate somatomotor, cardiovascular and respiratory activity during complex behavioral patterns in freely moving cats. He concludes that groups of neighboring neurons in the RF become organized into sub-populations discharging under the influence of somatosensory afferents in a frequency range of 0.2 to 0.07 Hz. He also describes the commonality with respiratory and other rhythms:

> [t]his reticular rhythm is not identical with the respiratory rhythm, but both rhythms can influence each other in the sense of relative coordination according to E. von Holst. [...] [i]n this type of functional organization both rhythms occur in the simultaneously

> recorded heart frequency, arterial blood pressure, respiration and in the degree of synchronization of the EEG [...]. (Langhorst 1987:350)

Langhorst found that amygdala neurons, unlike those in the RF, react to complex, preprocessed information and respond by "tuning the somatomotor, the visceral motor and the emotional components of behavioral patterns" (Langhorst 1987:348). On the basis of anatomical and physiological evidence he postulated that the amygdala and RF interact by various feedback loops to regulate heart rate and breathing, as well as desynchronization of the cortical EEG during arousal.

All of these processes suggest a focal control of the activation of brainstem cell body groups followed by fluctuations of global 1/f-like states during internal or externally or internally evoked orienting or shifts of attention. The reoccurrence of 1/f-like states during REM sleep reactivates these amygdaloid-cortical, -thalamic, -brainstem loops active during wakefulness. In this way, 1/f patterns may provide a stable pseudoenvironment in which to consolidate synaptic changes. The REM 1/f state may also allow fractally bursting amygdaloid-cortical, -thalamic, -brainstem loops to be chaotically resynchronized and readied for integration of new multisensory information on awaking.

8. Therapeutic implications of vertical 1/f convergence: Reinstating global coherence in biological systems with different forms of 1/f stimulation

Perhaps the most important implications of the concept of vertical 1/f convergence is in application to the therapy of many types of medical problems including non-pharmacological treatments for chronic pain, treatments for some varieties of cancer, reestablishing 1/f patterns in infants exposed to drugs of abuse *in utero* and stress relief. One of the persistent problems in the use of constant electrical stimulation for pain relief is the use of monotonous patterns to which the nervous system quickly habituates. However, stimulation of patients with 1/f patterns in time visually, auditorily or transcutaneously, as well as combinations of these, provides soothing relief from chronic pain or stress due to trauma, inflammation, herpes, cancer, backpain and lumbago (Takakura *et al.* 1979:314). A 1/f pulse train consisting of 1/f variations in the rate and duration between 4-40 pps and 0.5 to 4 seconds, respectively, was used. Two sources for the 1/f patterns were used — one, a digitally filtered Gaussian white noise which was also used to generate white and brown noise

stimulation, and the other, the extracted long period frequency changes of classical music. In the last case, auditory stimulation with the classical music was sometimes combined with the electrical stimulation. For the first case, stimulation with $1/f^0$ Gaussian white noise was considered too abrupt and sometimes elicited fear reactions. Subjects habituated quickly to stimulation with $1/f^2$ due to its monotonous nature. $1/f^1$ was found to be more effective than the constant standard medical stimulation (a constant electrical current) and was enhanced by auditory presentations of the music. All patients preferred 1/f stimulation to the constant standard medical stimulation. If the 1/f pattern originated from music, the benefits were enhanced when the patient enjoyed the music. Interestingly, for a treatment period of 30 minutes, more patients reported prolonged relief for up to several hours with the 1/f simulation. There may be several mechanisms underlying the analgesic effect. It is not clear from the report whether patients were informed of the 1/f treatment; therefore, the placebo effect cannot be completely ruled out. However, the fact that all patients reported 1/f stimulation as superior argues against this explanation. Possibly 1/f patterns are more effective in releasing endogenous agents, or impeding impulse conduction in pain pathways. A more intriguing possibility is that 1/f patterns of stimulation interact directly with the subcellular and cellular processes involved in creating the pain. Thus unlike pharmacological approaches that involve blocking receptors, 1/f stimulation may resonantly support the endogenous 1/f processes that are affected by the pathology. This idea is supported by the prolonged relief period and could easily be tested by administering naloxone to rule out the role of endogenous opiates.

The possibility of a direct effect of 1/f stimulation on cellular mechanisms is also supported by the work of Muzalevskaya *et al.* (1993). They have reported that 1/f magnetic stimulation can provide many beneficial effects such as normalization of cardiac function and EEG, immune response, lengthened survival after exposure to radiation, reduction in cancer growth in animals and humans (Timoshinov, personal communication) and even stimulate the perception of light, colors and geometrical patterns in humans (Timoshinov, personal communication). The magnetic field used was of constant field amplitude (field strength was on order of the earth's geomagnetic field) but had a 1/f frequency spectrum from < 0.1 to 1 Hz generated by a 'specially designed generator' of 1/f noise with Helmholtz coils.[4] They suggest that magnetic stimulation is a good carrier for 1/f patterns because it deeply penetrates tissues and may interact with the dipoles in the cell membrane. Evidence to support this theory comes from the findings that 1/f magnetic fields constructively interact with 1/f surface fluctuations in a nonliving nonequilibrium system (Muzalevskaya *et al.* 1991).

Premature human infants can have many developmental problems, and these can be exacerbated by a lack of tactile stimulation normally available *in utero*. In addition, prenatal exposure to opiates is associated with deficits in attentional processes and developmental delays. The work of Hazel Szeto suggests that opiate exposure can lead to interference with the occurrence of REM sleep and loss of fractal time correlations. One possible approach to these problems would be the use of 1/f patterns of sound, tactile stimulation or magnetic stimulation to reinstate fractal time correlation into the environment or cellular processes of these infants. As Szeto has stated the presence of fractal time correlations in the physiological variables (implying increasing variance with the length of measurement) of the healthy human fetus may be misinterpreted as abnormal fluctuations and lead to the premature diagnosis of fetal distress (Szeto, personal communication). This may partially explain the increased use of Cesarean surgery with the increased availability of fetal monitoring (Haverkamp 1975:1; McCutcheon-Rosegg & Rosegg 1984:201). The implications of fractal time processes for a more complete understanding of fetal life and for the logical development of new therapeutic strategies could be considerable.

9. Conclusions

Consciousness evolving in a fractal world would seem parsimoniously to require the incorporation of fractal structures as well as fractal processes, and these in turn would be integrated into sensory systems, recognition, memory, and adaptive behaviors. Fractal 1/f-power spectra have been observed at fundamental levels of processing in the major auditory pathways, olfactory and visual systems and in the underlying activity of ion channels which are fundamental to the function of these self-organized non-equilibrium biological systems. According to Machlup (1981:157), the universal appearance of 1/f phenomena in physical and biological processes appears to suggest a limit law "or one of the approximate symmetries of nature [...]. The ubiquity of 1/f noise spectra is our evidence for conjecturing this symmetry property." (Machlup 1981:159)

Fractal, i.e., 1/f, power spectra imply a fundamentally new view of time in biological systems, whose processes have traditionally been interpreted in the context of linear time. It implies that biological systems manipulate and rescale complex correlational patterns in time. For example, in the dream state most people experience distorted time; dream events that seem to take hours in

reality only require minutes of clock time. Recent findings in cats suggest that fractal 1/f-power spectral patterns are widespread in the brain during REM sleep as well as orienting, arguably two obligatory brain states in humans for the existence of mind. If these findings can be extrapolated to humans, they suggest that broadband 1/f states may underlie shifts of attention as well as our moment to moment perception of time. This insight into the dynamically changing patterns of brain activity argues for a new conceptual approach to understanding realtime brain activity patterns (Usher *et al.* 1993:771).

How might fractal patterns in the auditory system or other sensory systems interact with fractal sounds or visual patterns? Why do fractal shapes and sounds evoke visual attention and auditory paradox? How is fractal information shared and compared between sensory systems in subcortical and cortical structures? There is no current agreement on these questions. However, we have attempted to integrate some recent findings from our work with intercortical dynamics in macaques during a behavioral task with the wide base of observations of 1/f patterns in other aspects of neurobiology and psychology. A conceptual revolution in neuroscience has recently occurred in understanding how different cortical regions 'bind' interactively during information processing (Bressler *et al.* 1993). In our work, we have observed broadband 1/f-like coherence spectra between cortical regions active during a GO/NOGO behavioral task, suggesting that cortical regions, at least in the macaque, may dynamically rescale interactions in time allowing interactions on many time scales, from high frequency molecular-membrane potential fluctuations to global interbrain low frequency interactions. This common echoed pattern, unifying to distant cortical sites during tonic, focal and possibly REM brain states of self-organized neural masses calls to mind the universality of the dream state to mankind and an Aztec poem: "That we come to this earth to live is untrue: We come but to sleep, to dream." (Campbell 1981:1)

In a phrase "*it takes a fractal to know a fractal*". The work and ideas presented in this chapter suggest that this cliché of recognition applies not only to mathematical idealizations and physical structures but to the very nature of our consciousness.

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Notes

1. See the following references for excellent reviews of this subject (Buckingham 1983:143; Press 1978:103).

2. This concept is extensively reviewed in a number of publications (Barns & Allen 1966:176; Press 1978:113; Buckingham 1983:157) and will not be detailed here. A listing of other methods generating 1/f noise are cited in Lowen & Teich (1993:992).

3. A wonderful review of the subject is given by Verveen & DeFelice (1974).

4. Muzalevskaya *et al.* (1993) do not include sufficient information on the design of their stimulator and, therefore, it is difficult to evaluate their work.

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Fractal Thinking:
Self-Organizing Brain Processing

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1. Introduction

The human brain represents a most unusual computational device composed of deterministic chemical, electrical, and biological systems which combine into a self-organizing process, the future events of which cannot be entirely predicted. Many neuroscientists have investigated the brains of cats, monkeys, and rats with the hope of discovering how networks of neurons operate to produce various behaviors. These studies often assume a reductionist position confident that if one understands the operations of individual neurons, one can learn how neurons aggregate to form patterns that control both reflexes and voluntary behavior. Opponents of reductionism agree that while reflex activities like breathing and the operation of organs like the heart can be predicted by learning the causal basis of inputs, voluntary behavior defies a deterministic reductionist description. The argument becomes inconclusive when reductionist neuroscientists rebut with the assertion that given enough time, they will formulate reductionist explanations not only of involuntary but also voluntary actions.

Central to these discussions are the concepts of mind and consciousness and how they are related to the brain, our organic computational machine. Materialists who deny the existence of either minds or consciousness represent the polar extreme to voluntarists who claim that minds and/or consciousness have an existence independent of brain. Most scientists, whether or not they

adopt materialism, agree that minds and consciousness exist in some relationship to brains. Many on both sides of the argument view minds and consciousness as emerging from neuronal processes leaving their disagreement to whether seemingly deterministic processes based upon an assumption of materialist reductionism will extend upwards in a hierarchical organization and explain apparent voluntaristic acts. And both sides agree that physical processes in the brain affect thinking as in the case where drugs alter behavior and that mental processes affect physical processes as in the case of biofeedback that can control pulse rate and blood pressure. We shall not attempt to solve the reductionist question but rather present a case for the use of nonlinear dynamical systems like fractals that can give an explanatory account which describes both the behavior that we have traditionally called involuntary (reflex) and that which we have traditionally called voluntary (will).

Considerable evidence has been presented showing that both the firing of individual neurons and the activation of patterns of neurons are nonlinear dynamical systems. Walter Freeman's investigations of the olfactory bulb of the rabbit concluded not only that olfaction was nonlinear but also that this process could serve as a model for cognition (Freeman 1990). Skarda and Freeman state the following:

> The observations that brains employ not only self-organization but chaotic dynamics to produce behavior places yet another nail into the coffin of reductionism. Chaotic phenomena preclude long-term predictions. It may seem paradoxical that a deterministic phenomenon is inherently unpredictable, but in systems that exhibit chaotic behavior, small uncertainties are amplified over time by the nonlinear interaction of a few elements. The upshot is that behavior that is predicable in the short run becomes intrinsically unpredictable in the long term. As a result, physiologists cannot make strict causal inferences from the level of individual neurons to that of neural mass actions, nor from the level of receptor activity to internal dynamics. The causal connection between past and future is cut. (Skarda & Freeman 1990:282)

Gregor Schoner and J.A.S. Kelso agree with these conclusions but cast their nonlinear net to include all neural behavior claiming "that it is possible to understand behavioral pattern generation on several levels of description (kinematic, electromyographic, neuronal) by means of the concepts and tools of stochastic nonlinear dynamics" (Schoner & Kelso 1989:311). This comprehensive claim is correct and we will attempt in this paper to

demonstrate that fractals, a subset of nonlinear dynamical systems, can present a scientific explanation of neuronal behavior. Further, positron emission tomographic (PET) studies of cognitive behavior hopefully will confirm the fractal nature of specific neuronal processes. Before outlining our thesis and program for confirmation, however, we will present our underlying assumptions.

2. The computational metaphor

An oversimplified version of the computational metaphor assumes that the brain can be viewed as a computational device similar to a computer and that the mind serves as a software program controlling the operations of the brain. But this version of the computational metaphor divides the brain and the mind too strictly. Human thinking and neuronal processes combine to produce a computational process. And this computational process is interactive: the mind affects neuronal processes as demonstrated by phenomena like biofeedback. The brain affects the mind as shown by the effects of hallucinogenic drugs upon thinking. In our interpretation of the computational metaphor, the mind emerges from neuronal processes establishing a self-organized independence and is not fully reducible to those processes.

Rummelhart *et al.* (1986), advocates of a parallel processing approach to modeling the mind (Parallel Distributed Processing), have argued that one should reject the computational metaphor and replace it with the 'brain metaphor'. Their argument against the computational metaphor rests upon the slowness of the mind to compute, a limitation of the number of algorithms that can be processed.

> Neurons are remarkably slow relative to components in modern computers. Neurons operate in the time scale of milliseconds whereas computer components operate in the time scale of nanoseconds -- a factor of 10 faster. This means that human processes that take on the order of a second or less can involve only a hundred or so time steps. [...] Thus although a serial computer could be created out of the kinds of components represented by our units, such an implementation would surely violate the 100-step program constraint for any but the simplest processes. (Rummelhart *et al.* 1986:75)

The Parallel Distributing Processing (PDP) objection to the computational metaphor that the slowness of neuronal activity restricts computations to less

than 100 serial steps assumes that the algorithms employed are linear. The PDP researchers believed that the complexity of neuronal activity demanded the replacement of computational algorithms by an emphasis upon connections. Recognizing that neurons activate nonlinearly according to the achievement of threshold levels of firing, PDP developed the following nonlinear algorithm:

$$u_\nu(t+1) = F[\Sigma_\mu W_{\nu\mu} G(u_\mu(t))] \quad [1]$$

where $u_\mu(t)$ denotes the activation of unit ν at time t

$W_{\nu\mu}$ denotes the strength of the connection from unit ν to unit μ

F denotes a particular nonlinear sigmoid function and G denotes a nonlinear threshold function.

PDP, however, linearizes this algorithm by projecting it upon a three-dimensional hypercube which they call a 'quasi-linear dynamical system'.

If one admits the full nonlinearity of neuronal processes as suggested by Skarda and Freeman, then the computational metaphor can be retained. PDP is correct in claiming that the brain fires its neurons in massively parallel patterns; it is incorrect in assuming that such requirements eliminate the possibility of a computational metaphor as a presupposition for mental activity.

Under certain values, a nonlinear algorithm will produce chaos and under other conditions, a stable pattern. The time limitation of 100 steps does not prevent those 100 steps from being executed in thousands of simultaneous connections. Nor must the computations of algorithms be of 'linear' systems; they can be fully nonlinear with the computations executing iterations of different values. The adoption of the computational metaphor presumes the context of a fully nonlinear dynamical self-organizing system with thousands if not millions of interconnections. We will not attempt to model all of these connections but rather provide an explanation of patterns of activated neurons.

3. Rational reconstruction

In seeking a mathematical description of neuronal processes, we are constructing a rational reconstruction rather than a simulation. In looking at brain functions, one can investigate various hierarchical levels of explanation beginning with the operation of individual neurons, how their excitatory and inhibitory actions take place through ionic exchanges across membranes that produce changes in electrical potential. In the reductionist dreams of some

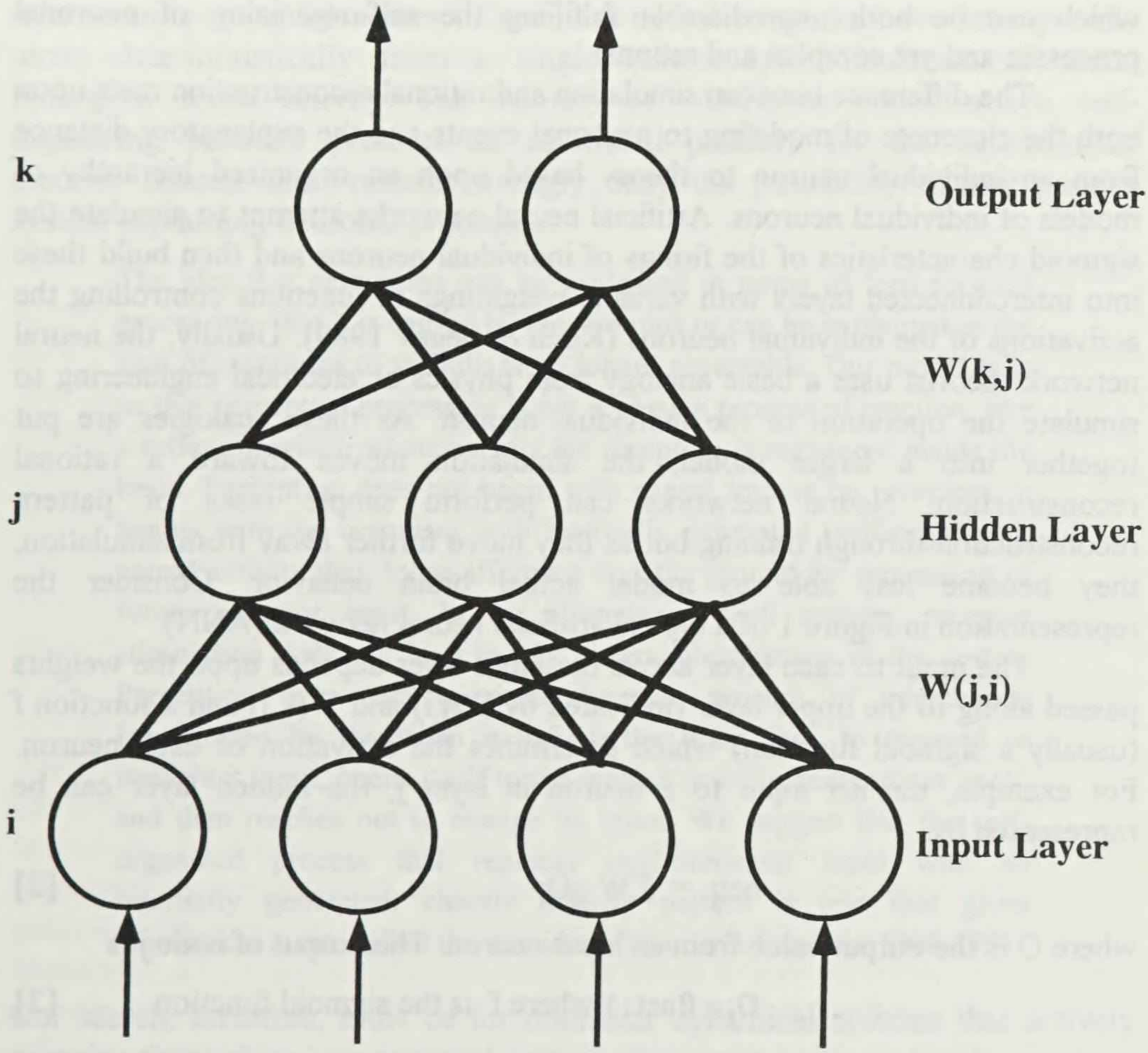


Figure 1: *An artificial neural network.*

biophysicists, starting with these basic units, one can then constructively move up to gross behavior like visual perception. Unfortunately, the empirically confirmed nonlinearity of both the activation of individual neurons and aggregates of neurons shatters the reductionist dream. The question becomes whether these nonlinear processes are completely random, or chaotic and rational. By rational, we mean that these processes are mathematically well formed and recursive. Modern mathematical chaos theory offers a description

which can be both unpredictable fulfilling the self-organizing of neuronal processes and yet complex and rational.

The difference between simulation and rational reconstruction rests upon both the closeness of modeling to neuronal events and the explanatory distance from an individual neuron to theory based upon an organized hierarchy of models of individual neurons. Artificial neural networks attempt to simulate the sigmoid characteristics of the firings of individual neurons and then build these into interconnected layers with variable weightings of functions controlling the activations of the individual neurons (Koch & Segev 1989). Usually, the neural network theorist uses a basic analogy from physics or electrical engineering to simulate the operation of the individual neuron. As these analogies are put together into a larger model, the simulation moves toward a rational reconstruction. Neural networks can perform simple tasks of pattern reconstruction through training but as they move further away from simulation, they become less able to model actual brain behavior. Consider the representation in Figure 1 of a typical artificial neural network (ANN).

The input to each layer above the input layer depends upon the weights passed along to the upper layer (indicated by W(j,i) and W(k,j) and a function f (usually a sigmoid function) which determines the activation of each neuron. For example, the net input to a neuron in layer j, the hidden layer can be represented by:

$$net_j = \Sigma W_{ji} O_i \qquad [2]$$

where O is the output value from an input neuron. The output of node j is

$$O_j = f(net_j) \text{ where } f \text{ is the sigmoid function} \qquad [3]$$

$$O_j = f = \frac{1}{1 + e^{-(net_j + \Theta) / \Theta_0}} \qquad [4]$$

Θ = a threshold

One can present a similar set of values for the output layer k which can be trained to recognize certain patterns like those of simple alphabetic letters by varying the weights on the layers of neurons, especially the hidden layer. But could such a network represent an internal pattern of neuronal processes capable of representing a cognitive act? Probably not, not only because of the simplicity of this kind of ANN compared with the extreme complexity of the interconnections in the human brain, but also because of the nonlinearity of brain activity. Where determinists have attempted to build up from individual

microcosmic units, advocates of artificial neural networks have attempted to move deterministically from a single macroscopic simulation to actual biological neural activity. The inability of ANNs to exhibit active, self-organizing behavior presents an additional problem for the deterministic theorist. Skarda and Freeman strongly deny the possibility of any passive system explaining neuronal processes.

> The idea that perception can be explained in terms of feed-forward processing, that it is caused by the stimulus or can be explained as the sum of responses to stimuli, is no longer acceptable. Our model tells us that perceptual processing is not a passive process of reaction, like a reflex, in which whatever hits the receptors is registered inside the brain. Perception does not begin with causal impact on receptors; it begins with the organism with internally generated (self-organized) neural activity that, by re-afference lays the ground for processing of future receptor input. In the absence of such activity, receptor stimulation does not lead to any observable changes in the cortex. Perception is a self-organized dynamic process of interchange inaugurated by the brain in which the brain fails to respond to irrelevant input, opens itself to the input it accepts, reorganizes itself, and then reaches out to change its input. We suggest that the self-organized process that replaces environmental input with an internally generated, chaotic activity pattern is one that gives "biological meaning" to the stimulus. (Skarda & Freeman 1990:279)

Our search, therefore, must be for nonlinear dynamical systems that actively organize themselves into neuronal patterns that result in recognizable cognitive behavior. Rather than beginning with a simple simulation of the firing of a neuron (a sigmoid function) and then building up from that simulation to hierarchical layers as in artificial neural networks, we will attempt to employ nonlinear systems, especially fractals, as rational reconstructions of neuronal processes. The words "rational reconstruction" describe this enterprise so as not to mislead the reader into thinking of an adoption of a reductionist program. This also avoids the criticism that this explanatory exercise ignores the need to find empirical confirmations. A rational reconstruction of neuronal processes can be likened to the postulation of a theory constructed upon analogies to observed brain behavior and confirmed or disconfirmed by experiments employing positron emission tomography (PET) brain scans of cognitive tasks. Rational reconstructions differ not only in degree from simulations but also in

kind. They are more speculative than simulations but hopefully also more adventurous and more promising.

4. Analogies between neuronal processes and glycolysis

Our search for nonlinear systems to rationally reconstruct neuronal processes begins with the analogy between nonlinear systems that explain the chemical process of glycolysis and the activation of neurons. That analogy arises from the consumption of glucose by neurons when they are activated. But why would one seek an analogy from an underlying physical process to explain cognitive behavior? This seems like trying to explain the meaning of telephone messages by giving an explanation of the physics of how sounds are transformed into electronic signals, transmitted by photons in fiber optics and then reconverted into sounds at the receiving end. Why then can one have any confidence that an underlying physical process can have any integral relationship to a mental process?

Few would deny that physical processes like the activation of neurons and mental processes like recognizing words are related. The question, however, is whether the explanation of how neurons operate is like the explanation of how cognitive acts take place. Hope for such an analogous correlation was provided by a series of ingenuous experiments conducted by Georgopoulos and his research group. (Georgopoulos *et al.* 1989:234-236) They trained a rhesus monkey to move a handle in the direction of a light when it came on dim and perpendicular to and counterclockwise from the direction of the light when it came on bright. During these tasks, they measured the activation of neurons in the motor cortex and constructed a population vector of these neurons. With the bright light, the monkey had to rotate the image 180 degrees and counterclockwise; here was a cognitive task that was measured in a motor cortex, the basis of physical movement. Georgopoulos *et al.* state:

> The rotation of the neuronal population vector is of particular interest because there was no a priori reason for it to rotate at all. It is also interesting that the population vector rotated consistently in the counterclockwise direction: this suggests that the spatial-motor transformation imposed by the task was solved by a rotation through the shortest angular distance. Given that the mental rotation is time consuming, this solution was behaviorally meaningful, for it minimized both the time for the animal to get the reward and the

> computational effort which would have been longer if the rotation had been through 270 clockwise. (Georgopoulos *et al*. 1989:235-236)

In their abstract for the article, the authors make an even stronger claim: "These results provide direct, neural evidence for the mental rotation hypothesis and indicate that the neuronal population vector is a useful tool for 'reading out' and identifying cognitive operations of neuronal ensembles". (Georgopoulos *et al.* 1989:234) This direct evidence shows that the explanation of a physical neuronal process describes the structure of a cognitive process.

Armed with this insight that a genuine analogy exists in at least one case between a physical and cognitive process, glycolysis offers another possible candidate as a real analogy between physical and cognitive. Benno Hess, Stefan Müller, Theo Plesser, and Mario Markus of the Max-Planck Institut für Ernährungsphysiologie in Dortmund have investigated the nonlinearity of glycolysis through an ingenious method of capturing the dynamics of the reaction by employing a video camera to record spectrophotometry (Müller *et al.* 1989; Markus *et al.* 1988; Hess 1988). Pictures of the spectrophotometry of these reactions reveal not only a scientific beauty but also a suggestive analogy to computer graphics representations of other nonlinear systems like fractals. Two of the computer renditions of spectrophotometric images for glycolysis are shown in Figures 2 and 3:[1]

Explorations of nonlinear dynamical systems analogous to chemical reactions like glycolysis led these researchers both to an exploration of the underlying mathematics and to biological systems. (Markus & Hess 1989; Rössler *et al.* 1988; Markus *et al.* 1987) Markus began with an investigation of the following algorithm which crudely models the growth of biological populations and the epidemic spread of diseases.

$$x_{n+1} = f(x_n) = r_n x_n (1 - x_n) \quad [5]$$

where r_n represents a parameter that can change according to empirical conditions.

For values of r_n greater than 3.56994567.... x becomes chaotic. Markus further allowed r to vary in a sequence of two numbers A and B to represent the changes that occur in actual conditions of population growth or the spread of an epidemic or the oscillations of a chemical reaction like glycolysis.

$$r_n = \{BBABA\ \ BBABA\ \ \ldots\}$$

Typically, A and B could be greater than 3.56994567 as in the case where

$$A = 3.85232\,,\ B = 3.84971$$

To measure the degree of chaos in the system, the Lyapunov exponent was computed. For each dynamic system, the Lyapunov formula produces a single number which if less than 0 indicates that the system is stable and if greater than 0, unstable and chaotic. To model the conditions of population growth or an epidemic or a chaotic process like glycolysis, Markus and his colleagues plotted the Lyapunov exponent on a graph with the y axis as the values of A and the x axis as the values of B. Creating a Lyapunov space with the black values representing non-negative values or chaos and white representing negative values or stability (Dewdney 1991). They also found, however, that chaos also ensues in for certain values of either A or B greater than 3.5699457... and the other respectively less than that value. Figure 4 represents a typical graph of the Lyapunov exponent plotted on the A,B plane.

5. The emergence of mind and consciousness from neuronal processes

Mental activities (mind) are a subset of neuronal processes and consciousness is a subset of those neuronal processes generating cognition. Without neuronal processes, thinking cannot take place; but not all neuronal activation represents mental activity as in the case of motor reflexes. Nor does consciousness encompass all cognitive activity, we are unaware of much information processed a portion of which can sometimes be recalled by cued consciousness. Intelligence officers have debriefed pilots by helping them to recall images of which they were unaware when they overflew the territory. Accounts also abound of researchers who come up with solutions to problems unaware of the mental process by which the result was achieved.

Even though cognition and consciousness depend upon neuronal processes for their very existence, each maintains an emergent independence from the brain. Conscious thinking can and does change the physical activity of the brain as in the case of biofeedback where the subject can consciously lower blood pressure, pulse rate and other bodily functions. Mind and body interact as changes in neurotransmitters through drugs direct the contents of thinking. Neuronal processes are a necessary but not sufficient condition for cognition and consciousness. One cannot, however, predict the contents of cognition by fully understanding the organization of neuronal patterns as these activations are nonlinear and self-organizing. The neuronal chaos described by these nonlinear algorithms is both complex and unpredictable. Calling these systems

'deterministic' means that various patterns of neuronal activation can be described by algorithms but not that every future event can be predicted. This is contrary to the more traditional assumption that deterministic systems generate precise predictions about future behavior. But these more familiar deterministic systems were composed of linear rather than nonlinear equations. The chaos of nonlinear systems does not imply a formless interdeterminism. Instead, nonlinear dynamical systems can produce a self-organizing organism with rational but unpredictable future behavior.

The brain operates as an organic machine generating self-organized patterns of neuronal activation that yields unpredictable, creative cognitive behavior. Ingredient in this self-organizing machine that produces chaos are both mind and consciousness. Both emerge from neuronal processes in ways that remain mysterious. Each may be a series of subsets of these processes or they may be a collection of activations of definite geographical areas of the brain. Investigations like those described in Section 7 hopefully will eventually answer these questions. Until then, one way to speak of both the interrelationships and the independence might be to designate these entities as brain/mind/consciousness with the understanding that in moving from left to right, each concept represents a small number of neuronal activations begging the question of how they are organized.

6. Chaos and fractals

'Mathematical chaos' describes the properties of nonlinear dynamical systems, namely, algorithms that are complex and deterministic and yet unpredictable. For some variables, these algorithms are stable with results clustered around point attractors. For other variables, the results are scattered or chaotic and unpredictable. For still other variables, the results unexpectedly cluster around strange attractors and may even oscillate between or among them. These strange attractors may have a dimension that is not an integer and hence are fractal.

Examples of mathematical chaos abound in the history of mathematics; nonlinear dynamical systems are not new. The relative newness of this field arises from the realization that these equations can be used to model physical phenomena allowing for the abrupt changes like the shift from laminar flow to turbulence in the flow of air over a wing. The ability of the modern digital computer to produce the results of hundreds of thousands of iterations of these nonlinear equations has also provided an impetus for an exciting and

continuing investigation of chaos. Before the computer, it was almost impossible to comprehend the various values for which the algorithms would be stable and unstable because of the excessive time required to make the calculations by hand. Many of the nonlinear algorithms are quite well known (Rasband 1990; Thompson & Stewart 1986; Grebogi *et al*. 1987). We have already described the algorithm of population growth and epidemics often called the 'logistic map'.

$$x_{n+1} = f(x_n) = r_n x_n (1 - x_n) \qquad [6]$$

A second is the 'tent map'.

$$\Delta\mu(x) = \mu(1 - 2|x - 1/2|) = \begin{array}{l} 2\mu \{ x, \text{ if } 0 \le x \le 1/2\} \\ \text{or} \\ 2\mu \{1 - x, \text{ if } 1/2 \le x \le 1\} \end{array} \qquad [7]$$

As in the case of the logistic map, the tent map results from successive iterations of the following algorithm.

$$x_{n+1} = f(x_n) \qquad [8]$$

For values of μ close to 0.75, the map appears to be chaotic. Rasband describes the operation of the tent map as follows.

> One of the best ways to understand the appearance of chaos in noninvertible maps like the tent map is to think of them as consisting of two parts: (i) a stretching and (ii) a folding back. Stretching is produced by having the slope of the map be greater than one in magnitude. The folding back is produced by the decreasing part of the map on the interval (1/2,1). The stretching feature of the map produces sensitive dependence on initial conditions by making the iterated images of neighboring points diverge from each other. The folding back feature, which is required to keep the points confined to a bounded interval, mixes up these images making chaos possible. Such maps are not one-to-one and therefore not invertible. Linear maps are always invertible, and so we see once again the need for nonlinearity. Note that although the tent map is piece wise linear, it is still not invertible. (Rasband 1990:17)

Nonlinear algorithms from the past abound. The following examples will serve as a sample of their range. This examples of a strange attractor was first studied by Hénon.

$$x_{n+1} = \alpha - x_n^2 + \beta y_n \quad [9]$$

$$y_{n+1} = x_n \quad [10]$$

The next equation is that for a forced damped pendulum where Θ is the angle between the pendulum arm and the rest position, ω is the coefficient of friction, r is the frequency of natural oscillation, and f is the strength of the forcing.

$$d^2\Theta/dt^2 + rd\Theta/dt + \omega_0^2 \sin\Theta = f\cos(\omega t) \quad [11]$$

Three ordinary differential equations studied by Lorenz as a model of the Rayleigh-Benard instability are:

$$dx/dt = Py - Px \quad [12]$$

$$dy/dt = -xy + rx - y \quad [13]$$

$$dz/dt = xy - bz \quad [14]$$

where P, b, and r are adjustable parameters.

Finally, the following extremely simple equation becomes unstable as C, a constant is varied and the initial x is fixed at different values and then for each initial x, x is iterated for the next 1000 values.

$$x_{n+1} = C - x^2_n \quad [15]$$

Nonlinear dynamical systems offer the possibility of describing an interrelated network of neurons that move abruptly from chaos to stable patterns. Self-organized slight perturbations of initial values or the values of constants in the algorithms, force transitions from chaos to stable patterns and from stable patterns to chaos. These properties of nonlinear systems present an opportunity to give a mathematical description of neuronal processes. But which kind of nonlinear algorithm should we seek to model neuronal activation? The field of possibilities is almost infinite.

The word 'fractal' was coined by Benoit Mandelbrot from the Latin word 'fractus' where the corresponding Latin verb *frangere* means "to break", "to create irregular fragments" (Mandelbrot 1983:4). Fractals express a geometry where the dimensions are not necessarily integers. Instead of having one, two or three dimensions as in Euclidean geometry, fractal dimensions can be numbers like .6 or 1.2 or 2.3 between the integers. Fractal geometry produces irregular and jagged rather than smooth shapes as in Euclidean geometry. Mandelbrot believes that fractal geometry models nature much better than traditional geometries.

Fractals are related to mathematical chaos in an unusual manner. Mandelbrot claims that "every known 'strange' attractor is a fractal". He expands on this claim by exploring the concept of "strange".

> Whether or not all fractal attractors are strange is a matter of semantics. Increasing numbers of authors agree with me that *for most purposes an attractor is strange when it is a fractal*. This is a healthy attitude, if strange is taken to be a synonym to "monstrous," "pathological," and other epithets once applied to individual fractals. (Mandelbrot 1983:197)

Although the formal relationship between fractals and nonlinear dynamic systems remains unclear, some fractals seem to be a geometrical subset of nonlinear systems even though not all nonlinear systems are fractals. Among fractals, the property of resemblance would seem to be an extremely useful analogy in attempting to model the nonlinear activation of neurons. When fractals are scaled up or down with larger or smaller values, topological patterns recur unexpectedly over and over again. This property is called 'resemblance'. Since neuronal activations during various cognitive tasks involve at least some similarities in the areas of the brain activated, a property of resemblance in mathematical rational reconstructions would be desirable. Unfortunately, however, many fractals that can be used to model biological forms involve geometrical inversion of their forms (and are called self-inverse fractals) and do not possess the property of resemblance (self-similarity) (Mandelbrot 1983:166-179). Even some of these fractals, however, are 'nearly' self-similar and perhaps it is those which we shall seek in our investigation of cognitive neuroscience. Many random fractals possess the property of self-affinity; even though their patterns do not *exactly* resemble each other in scaling, they are affine, meaning that they possess some similar properties but not exact resemblance. Richard Voss states: "This non-uniform scaling, where shapes are (statistically) invariant under transformations that scale different coordinates by different amounts, is known as *self-affinity*" (Voss 1988:44). This is the property necessary for a mathematical reconstruction of patterns of neuronal activation: statistical similarity with differences in detail at different scales.

Fractals also offer the advantage of representing temporal changes in geometrical forms for explaining cognitive neuronal processes. Neurons activate over time in various regions of the brain often physically separated. The dynamics of fractals allow for temporal and spatial changes. The Mandelbrot set, one of the most interesting and robust fractals, combines aspects of self-similarity with aspects of infinite change.

$$z_{n+1} = z_n^2 + c \quad [16]$$

where z is a variable and c a complex number.

The Mandelbrot set can be displayed graphically by beginning with z = 0 and then iterating the algorithm for various values of c. If one fixes c and then varies z in the field of complex numbers, beautiful Julia sets are obtained (Douady 1986). While Julia sets are self-similar, the Mandelbrot set exhibits patterns that are affine. It is most likely that if neuronal processes can be represented by fractals, they will be rationally reconstructed by random fractals or fractals like the Mandelbrot set that are infinitely varied, complex and unpredictable, but still self-organized.

The mathematics of chaos, especially fractals many of which are subsets of chaos, offer an ideal series of algorithms to rationally reconstruct the nonlinear self-organizing activation of neurons. In a search for the mathematical algorithms which reconstruct how billions of interconnected neurons are activated to account for both motor and cognitive actions, one must find representations that are nonlinear, that form recurring patterns, that are capable of self organization, and that move rapidly from order to disorder. Fractals fulfill all of these requirements. There are both deterministic and random fractals, with the latter and perhaps the former combining determinism and unpredictability. And all fractals possess a property either of exact resemblance or at least self similarity (affine) under scaling. But which fractals rationally reconstruct which neuronal processes? Of the infinite number of fractals, how can we select those appropriate to represent particular neuronal processes? We must find an empirical method of discovering which nonlinear algorithms (fractals) will represent which neuronal processes. Non-invasive imaging, especially Positron Emission Tomography (PET), offers the best possibility.

7. Positron Emission Tomography (PET) as an investigative tool

Positron emission tomography (PET) depends upon collisions of electrons and positrons producing gamma rays that are recorded by cameras and then reconstructed into images by computer algorithms (tomography). Subjects are given positron-emitting radionuclides either by injection or by inhaling. Active neurons consume glucose thereby releasing electrons to collide with the positrons of the radionuclide. Fluorodeoxyglucose (FDG) as a glucose based radionuclide concentrates at the sites of active neurons allowing increased

collisions of electrons and positrons thereby measuring metabolism by this method; FDG is taken up by the active neurons producing positron annihilations with concurrent release of two gamma rays in opposite directions.

Active neurons not only have a higher metabolism than less active neurons, they also have a higher rate of blood flow. Understanding this property, one can employ Oxygen 15, another positron-emitting radionuclide carried in water for brain imaging. Active neurons require oxygen for glucose consumption which is carried by a heightened blood flow. FDG has a much longer half life (109.4 minutes) than Oxygen 15 (123 seconds). For studies of cognitive behavior, even though Oxygen 15 studies have a lesser spatial resolution, the shorter half-life of the radionuclide allows more studies of different behavior of the same subject.

Both spatial and temporal resolutions pose difficulties for PET images of neural activity. Spatial resolutions are of the order of six or eight millimeters and temporal resolutions of the order of 30 seconds. This means that in mapping the brain, one cannot be precise about the locations of small areas of active neurons. In cognitive behavior, visual perception, for example, takes place much more rapidly than over a period of two minutes. If one attempts to map thinking, one must concentrate on a single thought for at least two minutes to obtain an accurate location of where in the brain that particular concept produces neuronal activity. By utilizing a combination of Evoked Response Potential (ERP) one might be able to overcome problems of temporal resolution. ERP is an expanded version of electroencephalogram (EEG) which measures the electrical responses to physical and cognitive events of points on the scalp. One might be able to measure both the ERP and the PET of a single cognitive event like the visual recognition of a word. The ERP would measure the event over 100 milliseconds while the PET imaged neuronal activity over 30 or 40 seconds. By measuring the blood flow quantitatively over time, one also might correlate the 100 millisecond event within the 30 second duration of the acquisition of data for the reconstruction of the PET images of the brain. (Hillyard 1994)

Mapping the brain has already begun. A group of researchers at Washington University in St. Louis have studied the differences among visually perceiving symbols (false fonts), alphabetic letters that make no sense, alphabetic letters that are not words but sound like words, and words (Petersen *et al.* 1990). They attempted to design an experiment that allowed the subtraction of common visual features of neuronal activity so that it might be possible to locate the specific areas of the brain that are associated with particular tasks. They state:

These stimuli were designed to separate activations related to processing at the level of the simple visual properties of the stimuli, letters, orthographic and phonological regularity, or lexical-semantic processing where real words are discriminated from other letter strings on the basis of meaning.

All four stimulus sets produced lateral extrastriate responses. This activation indicates processing at a level common to all four stimulus sets, that is, the complex visual features of the stimuli. The foci of activation for each of these four conditions were identified by subtraction of a fixation scan from the test scan.

Real words and pseudo words produce responses in the left, medial extra striate cortex that are not seen with false fonts or letter strings. Two explanations for the medial extra striate activation by real and pseudowords were considered: (i) the activation is due to the fact that the string of letters follows the spelling rules of English and could be seen as a legitimate visual word form or (ii) the activation represents the difference between the pronounceability (phonological characteristics) of the pseudo words and real words on the one hand, and the false font and letter strings on the other. We believe that the visual word form argument seems stronger. The activation is

> posteriorly located near regions otherwise devoted to aspects of visual processing. These regions are activated by the visual presentation of words, but not by the auditory presentation of words. (Petersen *et al*. 1990:1042) [2]

Teasing out the specific regions of the brain associated with particular tasks challenges research design and the methodology of image reconstruction. When one visually recognizes a word, for example, many regions of the brain activate: those necessary for vision itself, probably the motor cortex necessary for saccadic movement, areas necessary for memory and recognition of the word, and areas prerequisite for selective attention and possibly awareness (consciousness). The method of subtraction of similar pairs of cognitive events with only slight differences attempts to limit the *significant* areas of neuronal activation. These eliminations, however, may also hide significant relationships. In the recognition of a word, semantic memory is essential, but for someone for whom the word is a 'loaded' one because of past experience, the episodic memory may also be activated. And the plasticity of the brain is so great, that not everyone may utilize the same neuronal mechanisms for recognition and understanding. Thus far, the numbers of cognitive PET studies

are few and involve an extremely small sample of the population. Nevertheless, given these limitations, the reproducible results of these early PET studies are amazing.

Dr. David Madden of the Duke University Medical Center's Psychiatry Department has begun a series of PET studies of aging based upon this methodology. He seeks to study the effects of aging upon word recognition by both measuring reaction times of young and old to words and non-words while simultaneously using Oxygen 15 to study the areas of the brain affected. Madden starts with measurements of simple tasks like button pushing, passive word and non-word recognition and then proceeds to study the reaction times and brain images of the young and old to words and non-words and finally to letters of words and non-words separated by asterisks. Two of his images of these tasks are shown in Figure 5. These are taken from the same subject and indicate activation of the motor cortex and visual cortex.

In these experiments, subjects were first asked to push a button when a cursor appeared on a computer screen during the scan. Then in a second scan, they were asked to push a button when words and non-words appeared. Using software developed at Hammersmith Hospital in London and called Statistical Parametric Mapping (SPM), the results of the first scan were subtracted from the second one. Hence, in Figure 5, the image on the left showing both visual stimulation and motor stimulation shows the PET image for the second scan, the scan in which the subject pushes a button when every time a word or non-word appears. The image on the right showing only visual stimulation results from subtraction of the first PET scan of pushing a button when a cursor appears on the screen (not shown in the figure) after SPM analysis. The experiment continues when subjects next push the button only when words appear, and from this scan (again not shown) the subtracted image shown on the right in Figure 5 is itself subtracted from this third scan. This method of SPM analysis and subtraction attempts to locate those specific areas of the brain concerned with the particular cognitive activation under study -here semantic processing involved in word recognition.

PET studies of attention have also located various attentional mechanisms in different parts of the brain. Michael Posner and Mary Rothbart have identified a posterior attention network (parietal lobes), a vigilance network (right frontal) and an anterior attention network (anterior cingulate, supplementary motor area) (Posner & Rothbart 1992). The posterior attention network binds visual information to spatial locations. The anterior attention network seems to detect perceived events signaled in humans by verbal

responses. Even though studies of cognitive behavior indicate an independence of these two networks, in the monkey, there are strong anatomical connections between these two areas. Finally, the vigilance network maintains a high state of alertness in cognition so that reaction times to external events are faster. Posner and Rothbart state:

> Another close connection between awareness, control and the anterior cingulate arises from its relation to the third network of attentional areas that we have labeled the vigilance system. We believe that this system involves locus coeruleus norepinephrine input to the cortex. When subjects are required to maintain the alert state in the foreperiod of a reaction time task or when they attend to a source of signals while waiting for an infrequent target to occur (vigilance), there is strong activity in this system. This activity shows up in PET scans in the right lateral frontal lobe. When lesioned, this area gives rise to deficits in the ability to develop and maintain the alert state. (Posner & Rothbart 1992:95-96) [3]

PET studies also indicate differences among these areas in the case where the anterior attention system is activated when listening passively to words, but not when watching those same words. Employing behavioral PET studies allows the study of these three attentional systems. Analysis of the operations of these systems also allows inferences about 'awareness' (consciousness).

> The distinction between the anterior and posterior attention systems may be very important for understanding dissociations between attention and awareness. It has become commonplace to believe that attention can be dissociated from complex information processing. Studies of semantic priming, blind sight, amnesia and implicit learning discussed in this volume have all revealed that complex forms of information processing and storage can take place without the subject attending to or being aware of them. If one believes in a separate attention system as outlined above, the ability of other information processing systems to carry on some of their computations without the involvement of attention seems quite reasonable. Thus, evidence that lexical items can contact semantics without attention, or that simple linear sequences can be learned when one is not attending, appears consonant with this fundamental separation. (Posner & Rothbart 1992:99)

Posner's and Rothbart's postulation of three related attentional networks illustrates a first step in mapping the brain with PET as a series of patterns of

complicated interrelationships. They recognize neuronal processes as a position in a system of relationships moving from the macro-relationships of behavior to the micro-relationships of neurotransmitters acting across membranes. Along this explanatory journey, they also identify the self-organizing activities of attention and awareness that directly affect the process. Yet they stop short of attempting to represent these networks mathematically.

David LaBerge, however, has attempted to construct a quasi-mathematical network for selective attention using PET for empirical confirmation. (LaBerge & Buchsbaum 1990; LaBerge 1990) He begins with the cognitive question of how humans identify interior alphabetic letters of words like the "o" in *hot*. LaBerge builds a series of relationships among areas that perform the functions of (1) registering features; (2) locating position; (3) selective enhancement; and finally, (4) shape identifier (identifying the "o"). LaBerge locates this activity in the Pulvinar of within the Thalamus. He then postulates an interactive map of how the Pulvinar interacts with other regions of the brain and attempts to simulate this neuronal activity in computational circuitry similar to that of artificial neural networks. He also constructs a model of the circuitry of the Pulvinar.

LaBerge's investigations come very close to our proposed program for the investigation of the nonlinear mathematics of neuronal activity. He recognizes the following structural levels of the brain (moving from macro to micro): systems; maps; networks; neurons; microcircuits; synapses; membranes; and molecules and ions. His decision to seek to develop algorithms at the level of networks brings him closer to 'rational reconstruction' rather than 'simulation' or 'modeling'. His program is very similar to that which we have undertaken at the Duke University Medical Center. The notable differences are the stresses of our program on nonlinearity and self-organization and our method for searching for these nonlinear algorithms.

Our method stresses the discovery of interrelationships by statistical comparisons of heightened blood flow during cognitive activation studies utilizing PET. We employ a software program called Statistical Parametric Mapping (SPM) developed by Friston (Friston *et al*. 1990; Silbersweig 1993) at Hammersmith Hospital in London. This software analyzes differences between PET images detecting significant changes in patterns of regions of cerebral blood flow (rCBF).

SPM will enable the researcher to establish a network of significant regions of the brain active during a particular cognitive task. For example, if a

subject visually perceives a particular word, many areas of the brain are activated including those associated with vision, attentional spatial location, feature recognition for the letters, semantic processing and semantic memory (not necessarily completely different from semantic processing). Presently, without a methodology like that employed by SPM, the various PET slices of the brain will show many areas of heightened metabolism (FDG) or increased blood flow (O^{15}). How important each one is and how they are related remains unquantified. With SPM, one can map the connections of the brain measuring statistically the relative importance of the connected regions for different cognitive tasks averaging them over a number of subjects performing the same tasks. To account for the variances of brain size from subject to subject, regions are averaged and normalized to the Talairach and Tournoux brain atlas (Talairach & Tournoux 1988). This process of averaging and normalizing increases the initial spatial resolution of 4-6 mm of the PET scanner, meaning that the significance of small regions of the brain for cognitive activities may be lost. Some areas of memory which is spread throughout the brain may therefore be undetected as significant for a visual semantic task. Nevertheless, the employment of SPM to analyze both the connections of regions and their significance will mark the first step on a journey to understand the mathematical reconstruction of neuronal processes.

To complete a rational reconstruction of these cognitive neuronal processes, one must develop nonlinear mathematical models of the parametric statistical relationships. What these will look like cannot be answered until we have completed the statistical analysis. One method might be to attempt binomial or Poisson expansions of the statistical relationships and where they do not fit attempt to find nonlinear fractal algorithms that allow a better 'fit' in the model. This might be accomplished by modeling software but that remains uncertain at present.[4]

A. R. McIntosh has employed path theory to model networks of neuronal activation during visual cognitive tasks (McIntosh 1994; Gonzalez-Lima & McIntosh 1994). Right-handed young males were asked to undertake face matching and dot-location matching with their regional blood flow recorded by PET scans after injections of bolus water ($H_2{}^{15}O$). Using PET data to identify the regions with the greatest increases of blood flow (SPM analysis), structural equation modeling was used to determine the path analysis of the network of connected regions, the assumption, of course, that the regions with increased blood flow are necessarily connected during the cognitive task. McIntosh describes the mathematical modeling as follows:

> Mathematically, the goal of structural equation modeling is to obtain a solution to a set of structural equations that minimizes the differences between the observed covariance relationships and those that are implied by the solution. The process begins by giving each unknown parameter a starting value. These values are then used to start a series of successive "guesses" (iterations) for the parameters, given the correlations between variables. Using the "guesses", structural equation modeling programs compute the implied covariances and compare the values with the original covariances. Adjustments in the parameters are made based on the deviation of the implied covariances from the original covariances (optimization). This data-fitting procedure is performed until the deviation lies within an acceptable range. (McIntosh 1994: 657)

McIntosh concludes that structural equation modeling "constructs systems-level neural models; it does not simply describe the relationships found with the brain imaging data set" (McIntosh 1994:664). This is exactly the direction in which we hope to move in our efforts to achieve a rational reconstruction of neuronal activity, only we wish to capture the nonlinearity of this activity.

Our program for rationally reconstructing cognitive neuronal processes remains unfulfilled at present as we in the process of installing and using SPM to develop statistical relationships which will be modeled by nonlinear fractals. The reader may be unsatisfied by the incompleteness of this study but there is no alternative but to present where we are. The results thus far are extremely heartening: (1) various regions of the brain can be identified by PET as necessary for particular cognitive tasks; (2) the temporal resolution can be reduced enormously by combing PET with ERP; the brain can be statistically mapped with software like SPM; and (4) while nonlinear modeling remains a hope and promise, most of what we know about neuronal processes from work like that of Freeman with the olfactory bulb and analyses of individual neurons and patterns of neurons by numerous neuroscientists with animals and humans confirms the nonlinearity of neuronal activity. What remains now is the discovery of *which* fractal algorithms effectively represent *which* particular cognitive process.

8. Speculations about mind and consciousness

Non-invasive imaging of the brain using PET suggests that the concept of mind exists as a subset of neuronal processes. 'Mind' in this sense is not a traditional substance different from the body, but rather part of a physical process. This sounds like a traditional determinism where mental activity can be reduced to physical activity. Such a conclusion falls into the dualistic trap of assuming that real things must be some form of substantial materiality or substantial mentality. Mental activity is deterministic in the sense that definite algorithms describe neuronal processes out of which thoughts arise. But this deterministic activity is not predictable because of the nonlinear nature of the algorithms. Discovery of the nonlinear algorithms of neuronal activity will not mean that we can predict the outcome of behavior because under certain conditions the neuronal processes form patterns and under other conditions they fire in a chaotic fashion producing noise rather than patterns of activity. Mental acts of thinking, however, produce PET images of neuronal patterns of activity rather than noise. And thinking about thinking, a form of consciousness, contributes an additional nonlinear factor. Thinking about thinking modifies the physical neuronal processes like a double feedback loop in an electronic circuit producing a possible chaotic instability in the network.

Our program for deriving a new concept of mind from biomedical imaging of the brain comes very close to what Owen Flanagan calls *constructive naturalism* (Flanagan 1992). Flanagan believes that a concept of mind can be constructed through a reflective equilibrium which takes into account data from phenomenology, cognitive psychology, and neuroscience, especially PET. We agree with Flanagan but place a much heavier stress upon computational neuroscience. Our approach might be entitled *constructive computational naturalism* or *constructive computational neurophilosophy*. 'Mind' is a self-organizing nonlinear physical process with a reflexive property allowing it to modify its own process. As a self-reflexive process, mind can be represented in a series of nonlinear algorithms. And these algorithms can generate computer images different from, but related to computer generated PET images of mental activity. This program of constructive computational naturalism suggests that one speak of the 'brain/mind' rather than of the 'brain' and the 'mind' separately.

Early proponents of the computational metaphor referred to the mind as software and the brain as hardware (wetware). But this view seems to assume that the mind controls all of the brain's neuronal processes ignoring automatic

processes like breathing. One can consciously hold one's breath, but normal breathing continues unconsciously and does not seem to need conscious thinking to function. Yet the claimant to the software metaphor might argue that not all mental activity needs to be conscious as in dreams and problems that are solved without conscious awareness. Thinking can take place without awareness that one is thinking as in puzzle solving. Many other bodily processes like not only breathing but also the circulation of the blood, however, seem to require no mental acts for their normal operation. Mental acts can alter these processes as in biofeedback that can change pulse rate and blood pressure. These are willful and overt. Mental acts remain a subset of neuronal processes and are not in complete control of the operation of the brain as software would be for the operation of a computer.

Similar to mind which exists as a subset of neuronal processes, consciousness exists as a subset of mental activity. That makes consciousness a further subset of neuronal processes which also can be represented by nonlinear dynamical systems. Like the designation of 'brain/mind', we have already indicated this relationship by the term 'brain/mind/consciousness'. John Searle also locates consciousness in the neurobiological arena.

> Consciousness, in short, is a biological feature of human and certain animal brains. It is caused by neurobiological processes and is as much a part of the natural biological order as any other biological features such as photosynthesis, digestion or mitosis. (Searle 1992:90)

Even though we may present several prominent features of consciousness such as its intentionality (the 'of-ness' of consciousness — consciousness is always conscious *of* something), we can say very little of how or where it occurs in the brain. Searle goes on to state:

> The "mystery" of consciousness today is in roughly the same shape that the mystery of life was before the development of molecular biology or the mystery of electromagnetism was before Clerk-Maxwell's equations. It seems mysterious because we do not know how the system of neurophysiology/consciousness works, and an adequate knowledge of how it works would remove the mystery. Furthermore, the claim that we could always conceive of the possibility that certain brain states *may not* cause the appropriate conscious states might simply depend on our ignorance of how the brains works. Given a full understanding of the brain, it seems to me

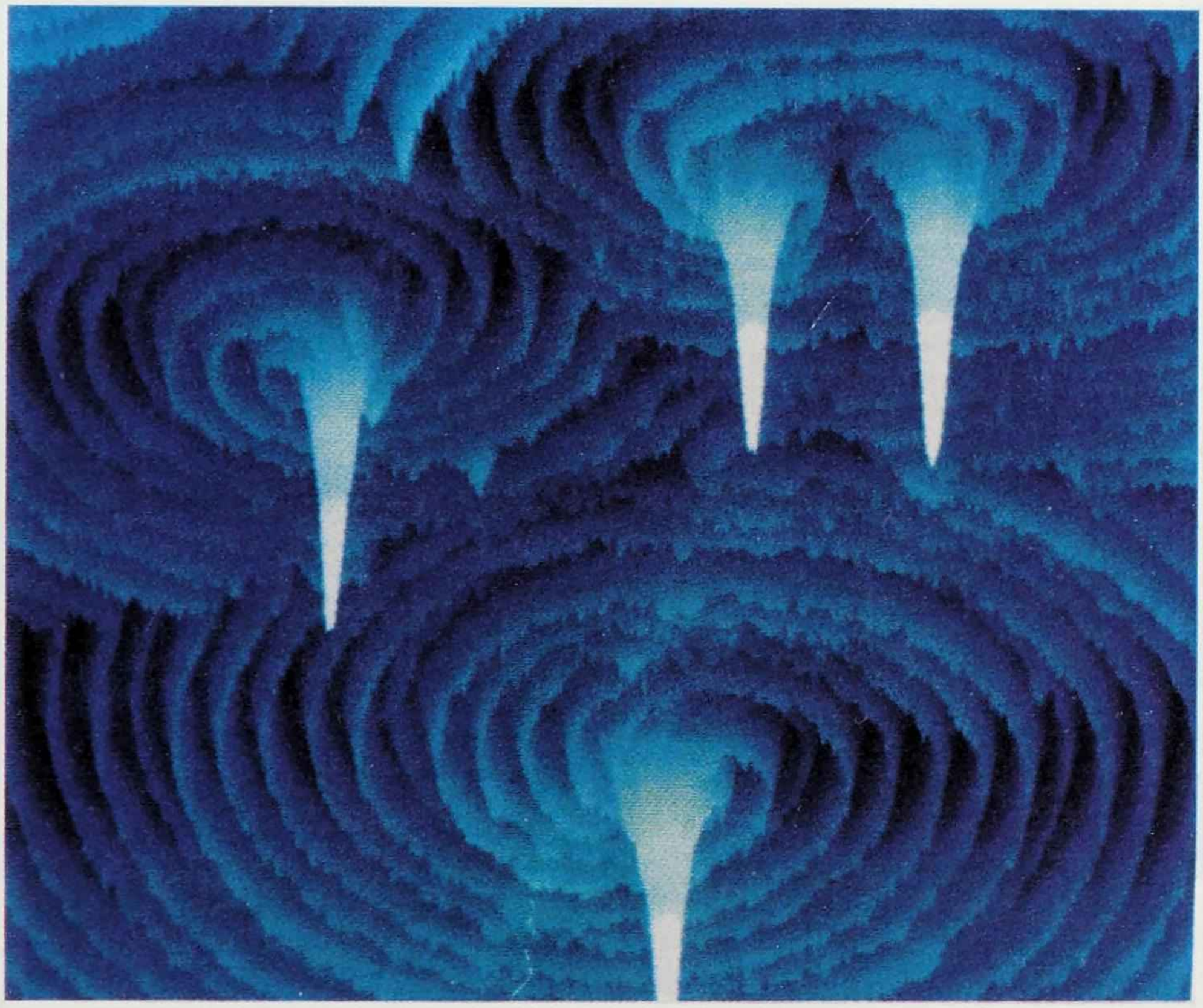


Figure 2. *A computer generated spatial pattern derived from spectrophotometer recording of the Belousov-Zhabotinski reaction*

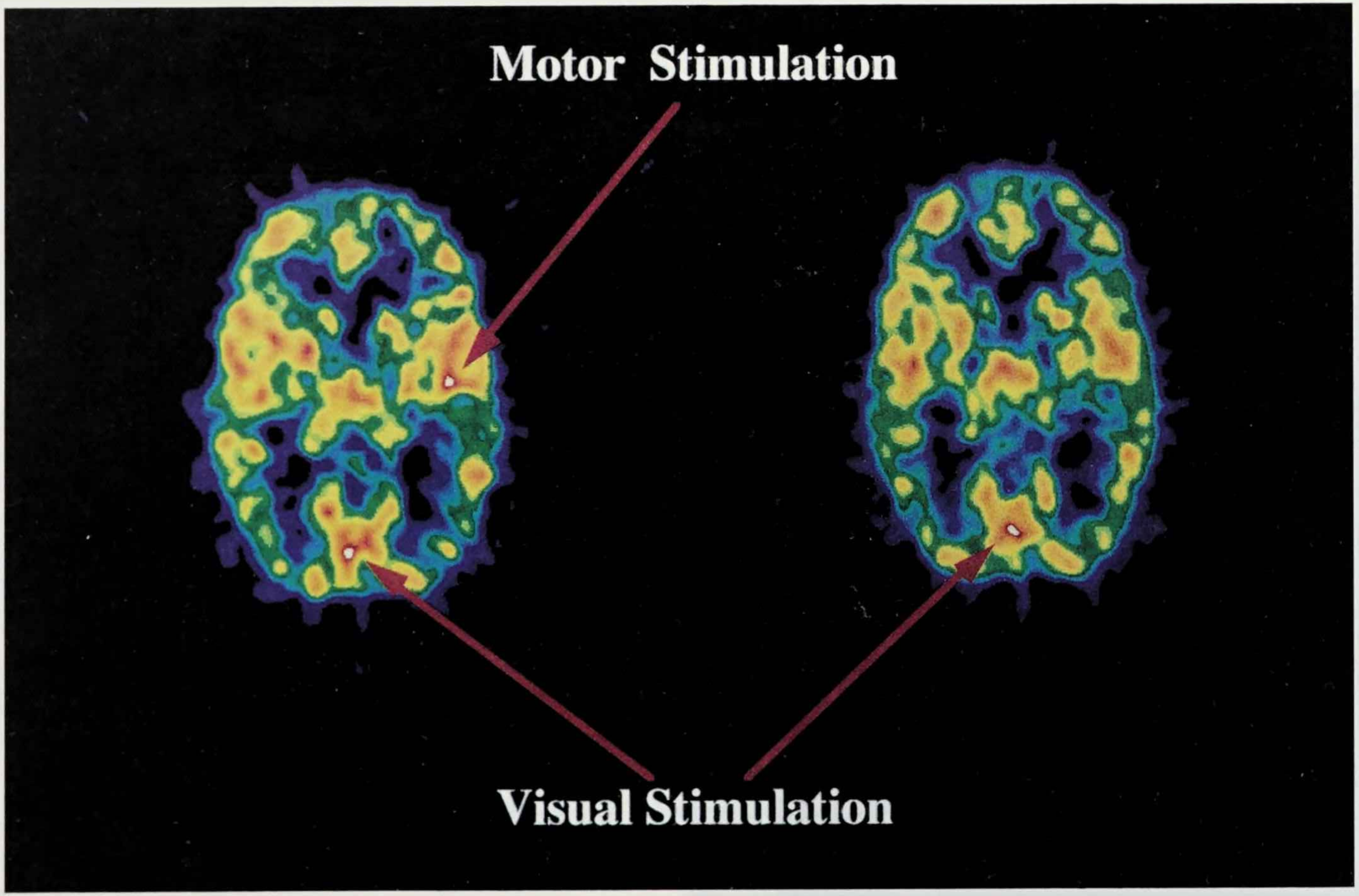


Figure 5. *PET images of cognitive activation*

> likely that we would think it obvious that if the brain was in a certain sort of state, it had to be conscious. (Searle 1992:101-102)

In our PET studies of the brain, one might attempt to locate both mental activity and consciousness in particular regions like the location of attentional systems by Posner and Rothbart described earlier. This seems unlikely because mental activity can accompany perceptual processes without apparent changes in the PET scans of the same perceptual process that occurs without awareness. There may be, however, neuronal activations on such occasions that cannot be displayed because of the low spatial or temporal resolution of PET.

One might also seek thinking and consciousness in patterns of neuronal activation; this might be much more promising an approach than looking for regions of mentality and regions of consciousness. There must be literally billions of patterns of neuronal activation associated with the myriads of thoughts and moments of consciousness for each individual. Designing experiments with PET to discover the neuronal basis of both thinking and consciousness will require focusing the problem down to a manageable task.

Where can consciousness be found in our program for nonlinear mathematical reconstructions of neuronal processes? Since consciousness and thinking can produce order and rationality in knowledge, the fractal strange attractors of the nonlinear dynamical systems might be the theoretical locations of consciousness. These are the points where order develops out of chaos; therefore, they might be the places where we become aware of our world and ourselves.

9. Conclusion

Mapping the brain with PET and discovering the nonlinear relationships among neurons for cognitive tasks offers one of the most exciting prospects for modern science. And we are far enough along to glimpse the promise of success in the future. The landscape of these nonlinear mathematical maps of the brain will probably be best rationally reconstructed by fractals.

Although just how and in what fractal patterns or at what strange attractor fractal points, mind and consciousness appear remains a mystery, there exists a strong likelihood that explanations for these phenomena will be revealed. Most likely, the underlying symmetry will be found in either self-similarity or the self-affinity of the fractals governing the generation of mind and consciousness. The program described in this chapter is already underway

and has enough confirmed empirical evidence to suggest the possibility of success. Yet nature often has a way of surprising us and the actual conclusions may be slightly different from what our conjectures now suggest. But they will not be so different as to reject the nonlinearity of neuronal processes. The brain probably does organize itself into cognitive activity that can be captured by fractals. With time, careful and sustained research will remove the 'secret' from symmetry.

Notes

1. These images are reproduced with permission.
2. The references to other works presented in this article and to the figures have been omitted.
3. Internal references in this quotation have been omitted.
4. LISREL developed in Scandinavia in 1989 in version 8 may have this capability. We are in the process of exploring this possibility.

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n-Dimensional Nonlinear Psychophysics:
Intersensory Interaction as a Network at the Edge of Chaos

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Nonlinear psychophysics uses some of the methods and mathematics of nonlinear dynamics, popularly but misleadingly called 'chaos theory', to model a range of established results in human sensation and perception. These results have all previously been modeled over the last 150 years, using linear and stochastic theories, and usually treated as the consequences of separate and unrelated phenomena. The fundamental change in using nonlinear dynamics is to replace stochastic processes in the mappings between stimulus and response, and to treat apparently separate phenomena as instances of one central generic group of mappings. A diversity of collaborative papers have teased out extensions and applications of the theory, some in analytical mathematics, most in experimental mathematics (the current name for simulation explorations of analytically intractable processes) and as applications to specific sensory and perceptual phenomena (Gregson 1988, 1989, 1992a,b, 1993a,b,c, 1994; Gregson & Britton 1990; Gregson & Harvey 1992; Gregson & Wiggins 1990; Gregson & Campbell 1991; Campbell & Gregson 1990; Price & Gregson 1988). I and colleagues, using $n\Gamma$ models (n simultaneous channels, $n = 2,3,4$), explored topics such as adaptation level in domestic fowls, the size-weight illusion, binary up to quaternary odor mixtures, sensory overload in brain damage, vibrotactile perception on the human forearm, response latency frequency distributions, brightness induction, outliers in the method of limits,

neural networks, pattern discrimination, and similarity judgments, and of course have published pictures of the Julia sets, the fractal boundaries of the Γ attractor.

More recently the comparisons, and more importantly contrasts, with neural network and cellular automaton theory, and the use of minimum Boltzmann entropy identification of response surfaces, has approached the questions of process description with more computational elaboration (Gregson, in preparation).

Traditional psychophysical models are essentially, in their simpler forms, used for scaling relationships between stimulus properties and psychological outcomes; they say little, but assume simple isomorphisms with residual superimposed Gaussian errors, concerning the internal processes of the organism in real time. Parameters in a process model do not have necessarily to match one-to-one in their status or functions any of the parameters in traditional psychophysics. As a consequence one is led to ask different questions, and to meet different conceptual problems in theory construction. One is concerned with retaining some compatibility with what we know about the dynamics of mass action in the brain, though not with the highly specialized peripheral transduction mechanisms of one or two special senses. This concern of course goes back to Fechner's *innere Psychophysik*, but the sort of algebra used, putting events lying between input-output relations into nonlinear deterministic evolutions, extending and not instantaneous in time, treats inputs as transient destabilizations of an ongoing central equilibrium dynamics. The recent resurgence of interest in the relationships between brain dynamics and conscious awareness have thrown up parallels between some features of mass action in sensory brain physiology on the one hand, and the dynamics of nonlinear psychophysics on the other. This chapter selects a topic which shows underlying dynamics of a phenomenon which in traditional psychophysics would be treated as autonomous, modeled algebraically in special ways.

1. The core representation of gamma recursions

The Γ recursion in Nonlinear Psychophysical Dynamics (NPD) (Gregson 1988, 1992a) is what physicists sometimes term an *evolution equation*. Such equations are often analytically intractable, for example they exhibit bifurcation sequences with increasing parameter values and can also exhibit quasiperiodicity with frequencies that are not powers of two, and are treated by

piecewise linearization, or by invoking the center manifold theorem. Even if generalized approaches are proposed, the mathematical conditions for obtaining existence theorems, or solutions to such properties as first passage times, appear to be restrictive and we have no sure advance information concerning what conditions are reasonably to be met in psychophysical models. It is now well known that the sort of problems we are faced with in psychophysical theory are in the mathematical sense ill-posed; the most we can be sure of is that the psychophysical evolution from stimulus to response has a dissipative component and is nonstationary. The Γ recursion is defined as the cubic complex polynomial:

$$Y_{j+1} = a(1 - Y_j)(Y_j - ie)(Y_j + ie) \qquad i = \sqrt{-1} \qquad [1]$$

where $j = 1,\ldots,\eta$ discrete steps in time, and the Y_0 value (a system environment baseline, available for input at the start) is set at $(.5,\varepsilon),\varepsilon \not> 10^{-4}$. The algebraic properties of [1], and the reasons for its use, have been previously covered in extensive detail (Gregson 1988, 1992a; Campbell & Gregson 1990); it serves as the core of a family of psychophysical transformations. Y is the internal complex state variable of the system, continuously present, and stimulation is treated as transient modification of the parameter a, which is for gain from external inputs. Outputs are affine transformations of Y of which only the real part (Re) corresponds to response levels, and e is an internal Γ system variable that modifies the dynamics, ε is an internal (Y(Im)) noise level constant. The imaginary part of Y, (Im), does play a crucial role in the evolution and stability of the process, which can run onto a point, or a limit cycles, or into chaos. The distinction between e and ε must be is maintained throughout; suffices on either may indicate periods of process evolution.

To see how time series analyses (Gregson 1983) are related to Γ, we require the autoregression statistics. For example, if we multiply both sides of [1] by $(1 + Y_j)$, giving

$$Y_{j+1} + Y_{j+1}Y_j = a(1 - Y_j^2)(Y_j - ie)(Y_j + ie) \qquad [2]$$

and expand the complex product $Y_{j+1}Y_j$ within the covariance as

$$\mathrm{cov}(Y_{j,\,j+1}) = (Y_j(\mathrm{Re})Y_{j+1}(\mathrm{Re}) + Y_j(\mathrm{Re})Y_{j+1}(\mathrm{Im}) + Y_j(\mathrm{Im})Y_{j+1}(\mathrm{Re}) + Y_j(\mathrm{Im})Y_{j+1}(\mathrm{Im})) \qquad [3]$$

then below the first bifurcation the recursion runs to an attractor on the real line, the autocorrelation runs in the limit to unity, the terms in (Im) can vanish for low e and large η. It is not this limit which interests us, but the dynamics in their evolution before stability. It is these dynamics which are the substrate of

stimulus-response mappings in NPD.

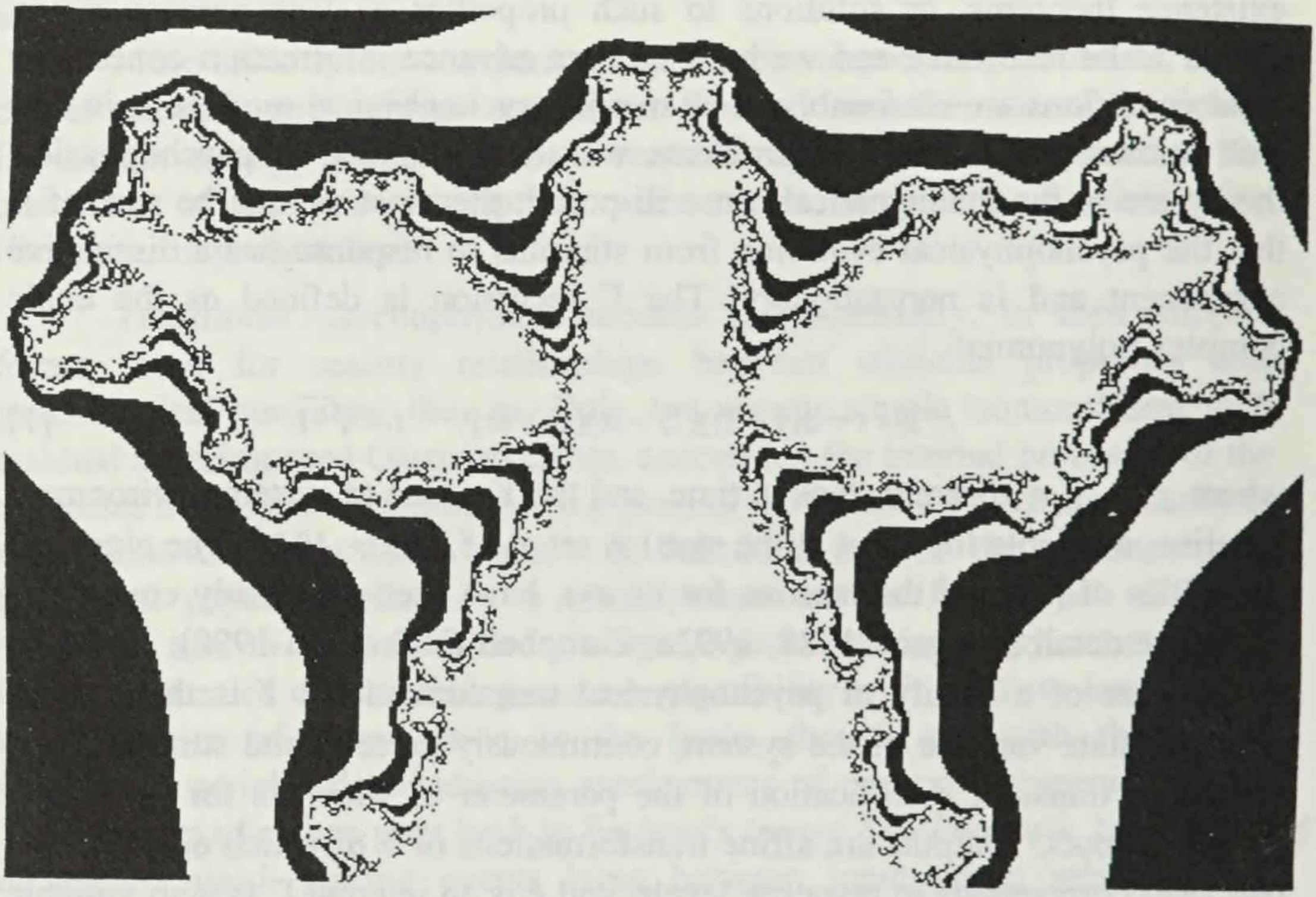


Figure 1: *A small part of the Julia set for the* Γ *recursion; if the resolution is increased in fineness connections between apparently isolated regions emerge along axes of symmetry.*

The Julia sets of Γ even in its simplest single-channel form are intricate, and exhibit symmetries as is usual in such figures. The black and white pictures used here (Figures 1 and 2) are obvious simplifications sufficient to show the self-similarity in their fractal boundaries; they may be compared with the extensive collection of examples from physics pictured in the same way by Becker & Dörfler (1989), though the Γ recursion is one only shown here. They have symmetry about major and subordinate axes, if the parameter space (a,e) is plotted to reflect about zero values, but these symmetries do not, in fact, play a role in the psychophysical use of Γ theory, because only very small ranges of the parameter space are used in the simulation of real data, and only positive values of a,e are psychologically meaningful. Further, as psychophysics is concerned with brief transient evolutions of Γ trajectories the computations necessary to induce explosive divergent recursions, that is outside the attractor basins, are not always attained even for parameter values that are plotted here

as unstable. It is important not to over-interpret these plots and read into them a significance for symmetry properties that does not arise.

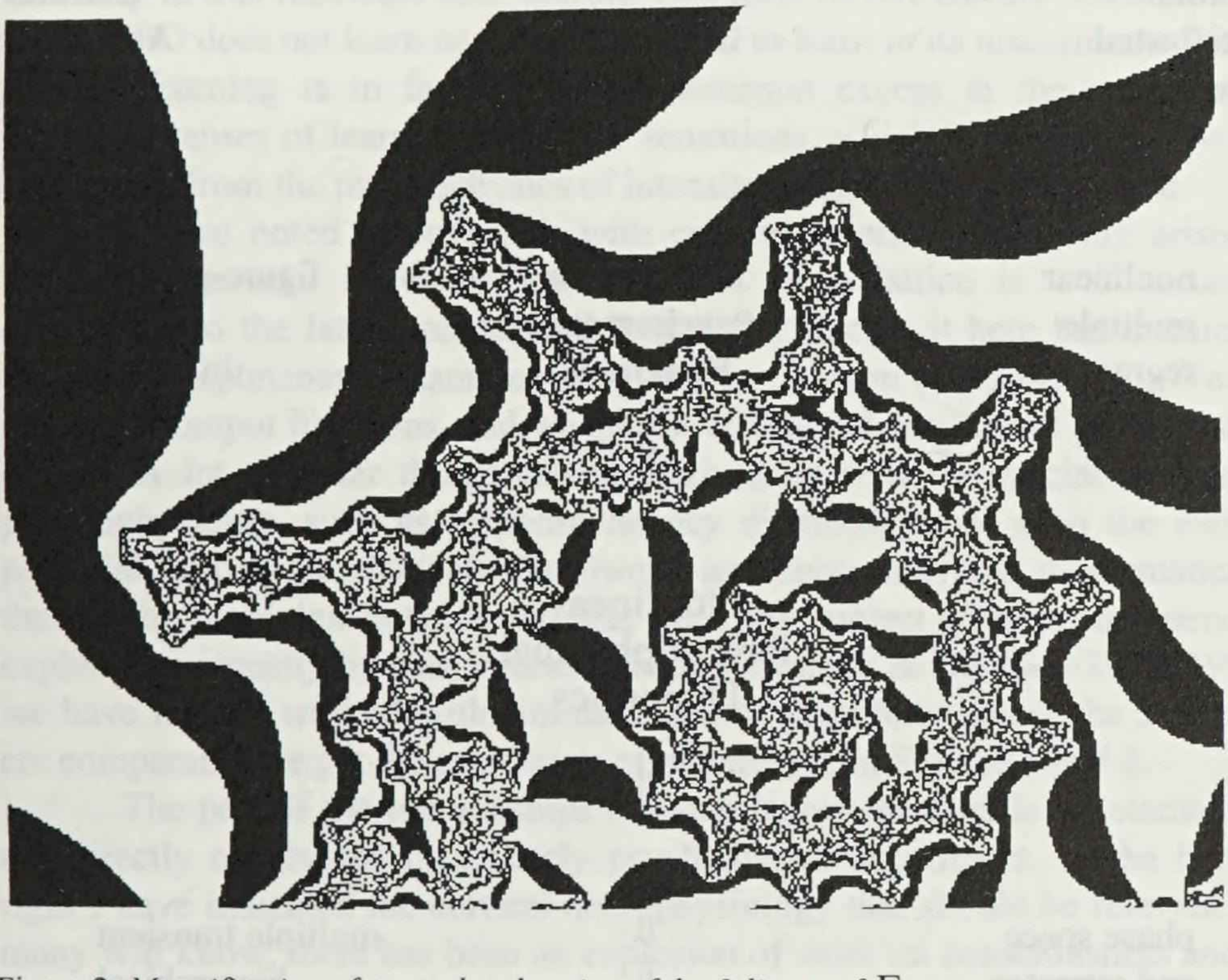


Figure 2: *Magnification of a very local region of the Julia set of* Γ.

More important for system interpretation are the global features, namely the multiplicity of local separated basins of attraction with thread-like connections upon which it is virtually impossible to land, and the fractal character of the Julia sets on the edge of stability. From the point of view of outcomes visible to an external observer, the structure implies that the system has accessible a diversity of alternate stable regions which can support individual differences in response modes. It also has regions with high error variance in replicated data such as can be observed in the breakdown of Weber's law at high stimulus inputs.

We need to explore briefly the relationships diagram (taken from Gregson, in preparation) which is metatheory and not theory, and can be approached in three ways of representation; regressions, time series, and neural networks (NN). In fact the literature of psychophysics does that, if viewed collectively.

Relationships and Analogies

Parallel Distributed Processing ↘

Cellular Automata Diffusion ↙

nonlinear multiple regression ↖

Observable Psychometric Functions ⇑

figure-ground noise diffusion ↗

Nonlinear Psychophysical Dynamics ⇓

phase space and attractor representations ⇓

multiple transient hierarchical recursions ↖

Global Topology of Cubic Polynomials ↗

Γ $n\Gamma$ $(n\times n)\Gamma$ Trajectories ⇓

Cortical Sensory Neuro-physiology ↖

The most familiar sort of neural networks, at least to cognitive psychologists, I have labeled PDP because that it what some psychologists call the package programs they buy. There is, in the restricted case where a NN has settled down to parameter stability in its attractor basins, and is used as a processor of nonlinear multiple regression data, a close correspondence existing with what NPD does for the case with n inputs and one output based

on the sum of the inputs. That output is the total sensation intensity from a mixture, such as in odor perception. This is the $n\Gamma$ case in the sources cited; but it is only in this restricted case that the two sorts of NN closely resemble each other. NPD does not learn and is not intended to learn in its unaugmented form; sensory learning is in fact a rare phenomenon except in the cognitive or linguistic senses of learning labels for sensations, which is a different level of processing from the psychophysics of intensity information transmission.

I have noted a loose link with cellular automata, this only arises in bivariate networks in which each element of a lattice is a Γ recursion orthogonal to the lattice plane; and I shall not discuss it here but mention it only for completeness; examples are given in Gregson (1992a, 1995). We can plot input-output functions, and we get the traditional families of psychometric curves. A lot of other things can be derived as well, of special interest to psychophysicists, such as response latency distributions or even the evoked potential in a single channel. The formal and deep analytical mathematics of these cubic complex polynomials has been the subject of quite independent exploration recently by pure mathematicians (Branner & Hubbard 1988, 1992); we have mainly worked with simulations, but thankfully where the Julia sets are comparable we get the same sorts of pictures, as in Figures 1 and 2.

The part of the relationships diagram below the middle is internal and not directly observable in a purely psychological experiment. In the bottom right I have indicated the cortical neurophysiology that should be relevant. As many will know, there has been an explosion of work on consciousness and its correlates in brain dynamics, including some amazingly undisciplined speculation by physicists (the neurobiologists are much more cautious and better informed), but the point I wish to expand on here is that sensory processes which go along with conscious experience involve recursive loops, often coupled in the subiculum of the hippocampus and running through relays in the thalamus and neocortex; the so-called Papez loop is involved. There is also evidence that these complex loops float into and out of synchrony, and only when they are bound dynamically then consciousness arises. That is speculative; the point I want to make is that the multichannel and network versions of NPD do necessarily involve recursive coupled loops with sometimes synchronous and sometimes asynchronous attractor dynamics. Binding between parallel channels is often transient, particularly near the edge of the regions of stable dynamics. With slight instability in system parameters the dynamics will float in the phase space. This again is exactly what we wish to happen in order to represent the brief destabilizing action of sensory inputs, pulling down out of chaos into limit cycling.

Beyond that I would not wish to go: we should remind ourselves of von Neumann's words (1954): "the outward forms of our mathematics are not absolutely relevant from the point of view of evaluating what the mathematical or logical language truly used by the central nervous system is [...] the system [...] cannot fail to differ considerably from what we consciously and explicitly consider as mathematics."

There are more properties of Γ recursions which lead to multiple response outcomes for a given single stimulus input, and which are simpler to illustrate by using a Markov transition matrix (M) representation. The condition $0 \leq Y(\mathrm{Re}) \leq 1$ and the boundedness of $Y(\mathrm{Im})$ in trajectories makes it possible to coarse-grain the Y values by cutting their ranges into ω equal segments, and then computing the matrix of j to $j+1$ iterations as a ω×ω matrix; different matrices evolve for different regions of the phase space. The nonlinear properties of Γ mappings from a to Y, given a $Y_0 \simeq 0.5$, are relevant here. The destabilization consequent upon a,e usually makes the $Y(\mathrm{Re})$ values run away from the middle range and asymptote at high or low values; this is just another way of noting that the $a \mapsto Y(\mathrm{Re})$ mapping is a cubic and approximately a cumulative ogive in its form. Let us define $\omega^* = (\omega - 1)/2$, where ω is odd. The actual value of ω is immaterial throughout this analysis, provided it is sufficiently large to map small but important differences in Y. Then the first $Y_{0,\eta}(\mathrm{Re})$ output probability vector $<p>$ can take the extreme form

$$p(\Gamma_k) = < 1/2, ((\omega - 2) \times 0), 1/2 > \qquad [4]$$

which becomes the two alternative inputs to a new Γ_{k+1}. The effect of restabilization is to squash the extreme Y values back towards the middle $Y(\mathrm{Re})$ range, so that

$$p(\Gamma_k) = < (\omega^* \times 0), 1/2, ((2\omega^* - 2) \times 0), 1/2, (\omega^* \times 0) > \qquad [5]$$

where the notation $(x \times 0)$ means an unbroken sequence of x zero probability values. The next step is to examine in greater detail the expected forms of the transition matrices within Γ, because these have to be the focus of simulation by numerical representations of Γ trajectories that are coarse-grained into ω steps. The row-column notation is ξ,ζ so that an element of M is $p(Y_{\xi,\zeta})$. The dynamics of the Γ trajectories are fundamentally different according to whether they run onto point attractors or quasi-limit cycles; the simplest case is below the first bifurcation. There will in the long run be a single Y absorbing state, on the real line, which is a function of a, e, η, Y_0. Only some predictable properties are shown in Matrices 1 and 2.

Matrix 1:
Transition Matrix within a Destabilization Phase of a Cascade Below the First Bifurcation

$$\begin{Bmatrix} d_{\xi,\xi} > \varepsilon & & & & & & & & & \\ & d_{\xi,\zeta} \simeq d_{\zeta,\xi} & & & & & & & & \\ & & d_{\xi,\xi} > \varepsilon & & & & & & & \\ & & & d_{\zeta,\xi} \simeq d_{\xi,\zeta} & & & & & & \\ & & & & d_{\xi,\xi} > \varepsilon & & & & & \\ & & & & & d_{\zeta,\xi} \simeq d_{\xi,\zeta} & & & & \\ & & & & & & & & d_{\xi,\xi} > \varepsilon \end{Bmatrix}$$

Matrix 2:
Transition Matrix within a Destabilization Phase of a Cascade Above the First Bifurcation

$$\begin{Bmatrix} d_{\xi,\xi} < \varepsilon & & & & & & & & & \\ & d_{\xi,\zeta} > \varepsilon & & & & & & & d_{\xi,\zeta} \to \max & \\ & & d_{\xi,\xi} < \varepsilon & & & & & & & \\ & & & d_{\xi,\zeta} > d_{\xi,\xi} & & & & & & \\ & & & & & & d_{\xi,\xi} < \varepsilon & & & \\ d_{\zeta,\xi} \to \max & & & & & & & & d_{\zeta,\xi} > \varepsilon & \\ & & & & & & & & & d_{\xi,\xi} < \varepsilon \end{Bmatrix}$$

2. Intersensory interaction

Having sketched out the contextual dynamics we can now turn to a specific case study of interest. The phenomena of intersensory interaction, usually weakly facilitative, are summarized by stating that the perception of events in one sensory modality is changed by concurrent stimulation of one or more other sensory modalities.

The existence of such changes appears to be difficult to demonstrate consistently or conclusively. Welch & Warren (1980, 1986) provide a valuable

review of experimental results up to the mid-1980s, and taken with earlier surveys of work which originated in the Soviet Union (London 1954), enable us to summarize some empirical findings and list competing theories. It is necessary to mention some of these first, though the present objective is to use a multidimensional psychophysical model, as an abstract algebraic structure, and to examine its properties in direct comparison with some reported phenomena. As might be expected, the psychological theories so far advanced are not in themselves expressed in sufficient detail to be unambiguously mathematized, and ancillary assumptions may need to be introduced.

Various psychological mechanisms have been defined by theorists in terms of the demand characteristics and structure of experimental situations which incorporate multimodal stimulation. Direct intersensory effects have been attributed variously to physiological processes, to attention deployment and distraction, to suggestibility, and to changes in response criteria. Nonspecific accessory stimulation (the term is Welch and Warren's, and aptly describes much of the earlier Russian work) refers to any second modality sending collateral signals alongside the target modality, and the consequences are expressed in one or more of three ways; changes in detection thresholds of the target modality, changes in response latencies of detection, and changes in perceived sensation intensities. It is clear that processes extending through time, and not instantaneous, are involved, which leads to distinctions being drawn between warning signal effects, where obviously the collateral stimulation precedes the target in time, accessory signal effects, with near simultaneity of channel onset times, and switches of attention between modalities, where both signals are concurrent and temporally sustained.

It has been suggested that intersensory effects might be cognitive rather than sensory, but evidence against this interpretation has accumulated (Pylyshyn 1980; Radeau 1992), and the term *cognitive impenetrability* has been used to describe the fact that at least auditory-visual interactions are computationally autonomous in their effect magnitudes, and are not driven by suggestions to, or prior beliefs of, the observer.

When inputs are in two or more modalities simultaneously, a sort of total channel overload can arise, and three kinds of theories have thus been advanced; intersensory bias, (some modalities are more heavily weighted in terms of their inputs) divided attention (the observer switches selectively between inputs) or something called *modality appropriateness*, which refers to some sorts of stimulus variation in space and time being more readily encoded through a particular modality, for example spatial localization tasks are better done through vision.

It is believed that the resolution of an intersensory discrepancy, where signals conflict in their information or meaning, will always be in favor of the modality which can encode signals more precisely (this sort of precision corresponds to Weber fractions) and so a dominance order, d^*, on modalities will be, with reasonable stimulus levels,

$$\textit{vision}\ d^*\ \textit{proprioception}\ d^*\ \textit{audition}\ d^*\ \textit{chemical senses}$$

Most studies in work reported in English appear to favor vision-audition interactions as more readily amenable to experimental control, visual-chemical senses is a rare pairing (Gregson 1964).

Welch and Warren advance an hypothesis (their part is italicized, my interpolations are in parentheses) that

> *The greater the number of redundant stimulus properties* (which presupposes some measure of intercoherence of signal strings across modalities) *and the greater the familiarity of the intersensory relationship* (which implies some prior establishment of a bias on cross-coupling parameters between modalities), *then the more unified the intersensory percept will be* (this again implies measures of statistical concordance across time series), *and the greater the contribution of the more appropriate channel will be to the total percept* (there will be various ways of measuring relative contributions of components to a total outcome). (Welch & Warren 1986:23-25)

In moving to consider if intersensory effects are a special case of NPD, which is the sole purpose here, it is proper to ask if variables such as precision, familiarity, appropriateness, are necessary in themselves or can be replaced by derivatives from more primitive operators. It is helpful initially to note that a sensory modality can and normally does support more than one psychophysical dimension (which we will call in its dynamics a *channel*) and that the onset time of channels in a multisensory context is rarely, if ever, realizable in exact temporal synchrony. It follows that in $n\Gamma$ theory the simplest case whose dynamics could be relevantly similar would be 4Γ with stepped inputs. This case has been previously studied briefly as purely intramodal with one cross-coupling parameter λ. With four channels (U_1,U_2,U_3,U_4) in order of onset, the innovation here is that two may be allocated to one hypothetical target modality and the other two to a second accessory source of stimulation. That is, the minimum of two psychophysical channels within each modality is represented, as in Figure 3.

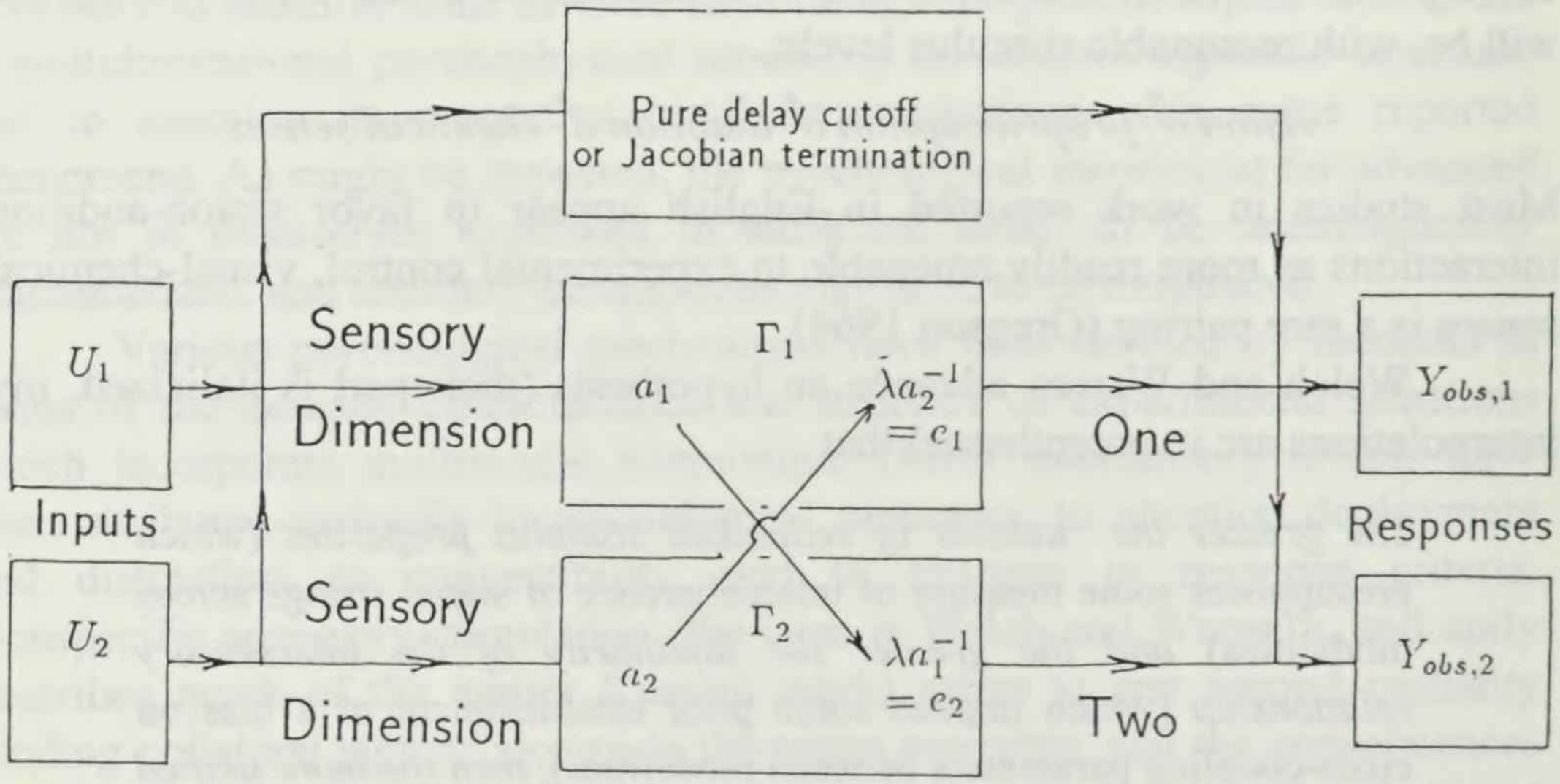


Figure 3: *Two channels cross coupled, modified from Gregson (1992a).*

This $n\Gamma$ cross-coupled process, where sensitivity in a channel is modified by gain in collateral neighboring channels, corresponds to the hidden layer in more familiar networks. But the intrinsic mathematics are different from those used in PDP, or for example by Hopfield or Kohonen.

3. Extension of the model

As here we are, by definition, in a multichannel situation it requires $n\Gamma$ which has in **Case 2**, as defined next, interaction between channels. We consider two cases, which differ in their cross-coupling between channels; the first is simpler and would not generate the anomalies which might, for example, characterize some visual illusions.

Case 1: If the (Im) output associated with Y_{obs}, (which is the real part of the value of Y after η recursions), is taken as interpretable as a form of internal noise, as has been shown to be plausible in other contexts (for example it exhibits intermittency), then let us take the total within-loop noise level at any step in the recursion to be the union of the component noises. So in each cycle the two Y(Im) are replaced by the term $max(Y_{1,j}, Y_{2,j})$(Im) and as the (Im) components go into limit cycling more readily (that is, at lower system parameter values) than their (Re) counterparts, the effect will depend crucially on the set of values (a_1, e_1, a_2, e_2). It can be shown, by simulation, that high (e_1, e_2) values induce some curious effects for large U_J (inputs); a paradoxical 'turn-over' effect in $U \mapsto Y_{obs}$ graphs for at least one component is observable. At the same time the other component may create a monotonically *decreasing* graph of $U \mapsto Y_{obs}$.

For a double loop put, for **Case 1**, where the two dimensions are denoted by *h* and *i* suffices,

$$Y_{hij}(\text{Im}) = \max(Y_{hj}(\text{Im}), Y_{ij}(\text{Im})) \qquad [6]$$

and then define

$$Y_{hj}^{*} = (Y_{hj}(\text{Re}), Y_{hij}(\text{Im})) \qquad [7]$$

and

$$Y_{ij}^{*} = (Y_{ij}(\text{Re}), Y_{hij}(\text{Im})) \qquad [8]$$

Case 2: A second cross-linkage is possible if the *e* terms are made to be functions of the *a* terms in the opposite dimension. This represents a process of mutual inhibition. Each dimension is desensitized to differences in its own input as the input to the other dimension is increased, viz.:

$$e_1 = \lambda_1 \cdot a_2^{-1} \ , \qquad e_2 = \lambda_2 \cdot a_1^{-1} \ , \qquad [9]$$

where $\lambda_1 > 0$, $\lambda_2 > 0$, and $2.6 < a_{min} < 4.4$ is a working range for $0.05 < e < 0.40$, and approximately $.20 < \lambda < 1.2$ will avoid an explosive condition of $ae > 1.7$.

The advantage of writing [9] is that the number of parameters in the model is reduced by one, e_1 and e_2 are removed and λ is introduced, with $\lambda_1 = \lambda_2 = \lambda$. The assumptions [6-8] are in already in **Case 1**, and for **Case 2**, additionally we now have

$$Y_{h(j+1)} = -a_h \cdot (Y_{hj}^{*} - 1)(Y_{hj}^{*} - i\lambda_h \cdot (a_i)^{-1})(Y_{hj}^{*} + i\lambda_h \cdot (a_i)^{-1}) \qquad [10]$$

and correspondingly

$$Y_{i(j+1)} = -a_i \cdot (Y_{ij}^{*} - 1)(Y_{ij}^{*} - i\lambda_i \cdot (a_h)^{-1})(Y_{ij}^{*} + i\lambda_i \cdot (a_h)^{-1}) \qquad [11]$$

In higher dimensionality the divisor in [9] for each e is then the maximum of the a values from the other $n-1$ dimensions.

Referring to the $n\Gamma$ equations, we vary the cross coupling between channel dynamics in their evolution. As soon as the constraint on λ=*const* is relaxed, and a different λ is allowed for each channel, the situation becomes complicated. The model is now $n\Gamma$ **Case 2** with unconstrained interchannel cross-linkage, for brevity this will now be denoted by $n\Gamma_{2,u}$, n=4, the corresponding **Case 1** with no cross-coupling will be $n\Gamma_{2,u}$, n=4. The relations between a, e, λ are summarized for $n\Gamma$ in Table 1;

Table 1: Interrelation of parameters
in 4Γ recursions
substitutions for the e parameter in each Γ

Channel	$n\Gamma_1$	$n\Gamma_{1,u}$	$n\Gamma_2$	$n\Gamma_{2,u}$
U_1,a_1	e	e_1	$\lambda/a_{m,c}$	$\lambda_1/a_{m,c}$
U_2,a_2	e	e_2	$\lambda/a_{m,c}$	$\lambda_2/a_{m,c}$
U_3,a_3	e	e_3	$\lambda/a_{m,c}$	$\lambda_3/a_{m,c}$
U_4,a_4	e	e_4	$\lambda/a_{m,c}$	$\lambda_4/a_{m,c}$

For Table 1 all these terms are substitutions for the second parameter. The notation $a_{m,c}=max\{S_c\}$, where for c=1,2,...,n $S_c=\{\{a\}-a_c\}$, is needed.

It can be deduced from Table 1 that under some restricted input patterns $\{U\}$ the constrained and unconstrained models with yield the same $U\mapsto Y$(Re) for a given set $\{a\}$. This is the situation called *compensation* (Gregson 1992).

$4\Gamma_{2,u}$: The most unrestricted case considered; the logic is the same as the previous case, but the restriction on λ is lifted, so that the total ($2n$) parameter set is now a_1,a_2,a_3,a_4, (gains proportional to inputs) and $\lambda_1,\lambda_2,\lambda_3,\lambda_4$ (cross-couplings modifying sensitivities). The effect of fixed λ in $n\Gamma_2$ is to push the highest channel, the one with $a=a_{m,c}$, into the upper part of the psychophysical ogive for $a\mapsto Y$(Re) and the remaining channels to some degree into the lower part. This is loosely analogous to pushing the system onto a mapping resembling the supremum metric; the dominance of the largest input is always enhanced. This can happen also for some parameter settings in $n\Gamma_{2,u}$, but not invariantly. Under some restricted and specific settings of the parameters, this case can be indistinguishable in its input-output mappings from $n\Gamma_{1,u}$.

There are various alternative predictions that can be derived from the evolution of the trajectories in $4\Gamma_{2,u}$; using all the available theory, the mean

and s.d. of outputs Y, and the mean and s.d. of latencies in j (recursion) steps, and the terminal values $Y_\eta(\mathrm{Re})=Y_{obs}$ are all computable. The *meanY* correspond approximately to values fitted in traditional psychophysics where equations such as Fechner's or Plateau's are used. For the methods see Gregson (1992a).

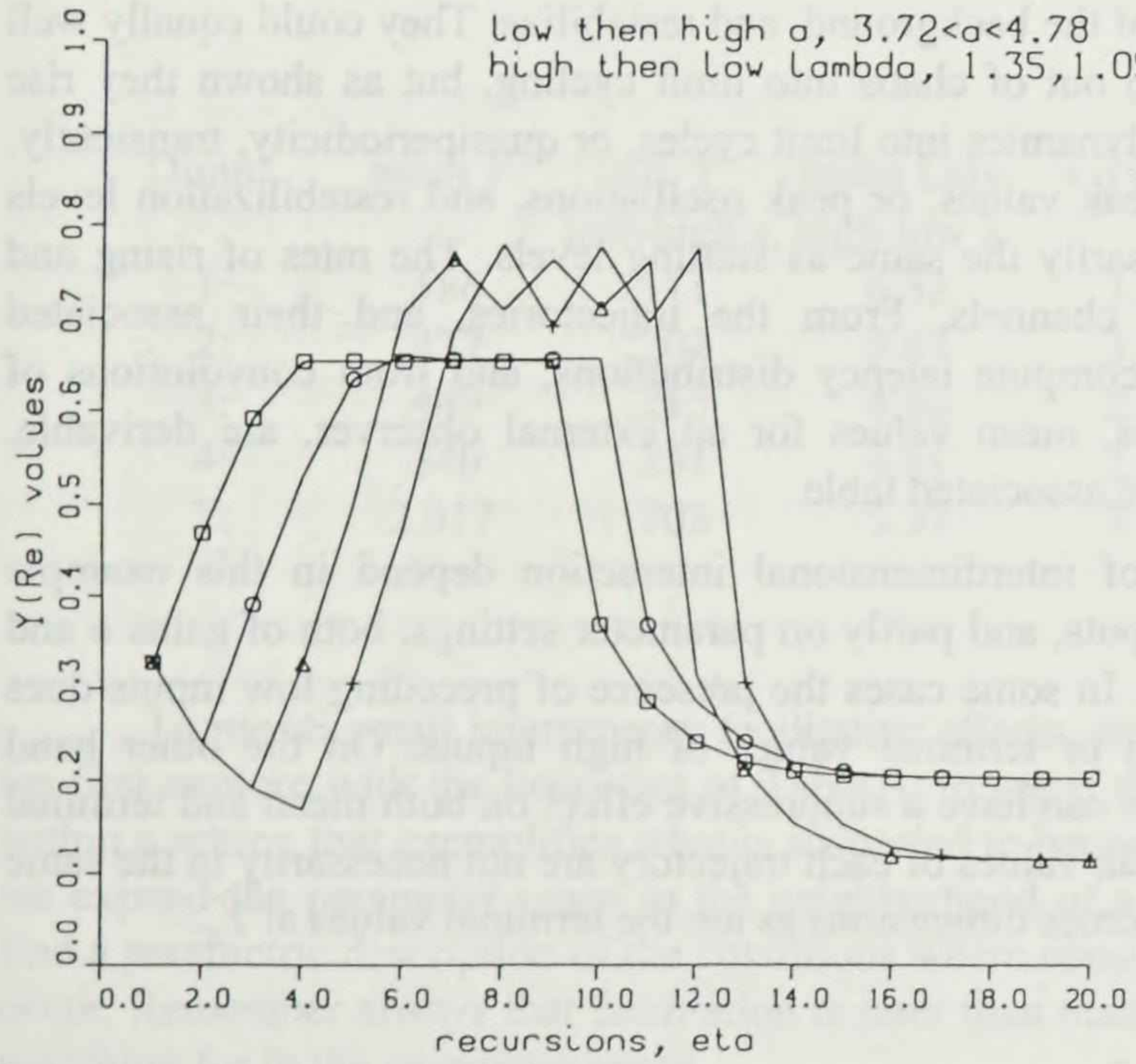


Figure 4: *Trajectories in four channels, two for each sensory modality.*

This simulation makes each input a rectangular a pulse of a short duration $\nearrow 10j$, the plotted trajectories are thus destabilization and restabilization curves (Gregson, in preparation) in immediate succession for each channel, with the onset and termination points slightly staggered between channels. The first point to notice is that the nonlinearity of the system creates intricate patterns with the interplay of the order of input, and the λ and a values used. The terminal $Y(\mathrm{Re})$ values are not always in the same rank order as the means (*meanY*s in Tables 2 and 3 to come later) and the trajectories of channels cross over one another during the system's evolution to $\eta=20$. This is shown in the plots of trajectories, in Figure 4. It is also possible to plot the convolutions of the Y_j and the probabilities of termination of the evolution at any j using the derivative of the Jacobian of the evolution; this is used to obtain *meanY* and the

mean latencies shown in the tables. The ΣY terms correspond to the total sensation intensity, obtained by summing across channels at each iteration. These results may also be needed to compare with other intersensory phenomena.

The trajectories are each for an internal component channel; they rise with destabilization of the background, and restabilize. They could equally well be computed to drop out of chaos into limit cycling, but as shown they rise from point attractor dynamics into limit cycles, or quasiperiodicity, transiently. Each curve shows peak values, or peak oscillations, and restabilization levels which are not necessarily the same as starting levels. The rates of rising and falling vary across channels. From the trajectories, and their associated properties, one can compute latency distributions, and from convolutions of latency and Y values, mean values for an external observer, are derivable. These are given in the associated table.

The effects of interdimensional interaction depend in this example partly on order of inputs, and partly on parameter settings, both of gains a and of cross couplings λ. In some cases the presence of preceding low inputs does nothing to the mean or terminal values of high inputs. On the other hand preceding high inputs can have a suppressive effect on both mean and terminal Y(Re) values. The peak values of each trajectory are not necessarily in the same order of magnitude across dimensions as are the terminal values at Y_η.

4. Intersensory induction effects

The point of the first example was to illustrate the potential variability in predicted outcomes arising from small parameter changes in the internal nonlinear process dynamics. That is quite general, we now turn to the phenomenon of specific interest to psychophysicists, namely the apparent paradox of intersensory facilitation. To model intersensory effects such as facilitation, it is necessary to compare different parameter settings, using cases where some channels are set with $a=a_0$. An example is worked through in Table 3; this treatment is in effect using the a_0 conditions as a control, with two dimensions acting as dummy information carriers to hold the total system dimensionality constant over comparisons. The same framework as used in Table 2 is employed, but now a comparison is made between outputs which result from two parameter settings for the total 4-d system.

Table 2: Interdimensional Interactions
An Introductory Example
4Γ outputs
high $\lambda = 1.35$, low $\lambda = 1.05$
a values drawn from 3.72, 3.74, 4.76, 4.78

Dimn:	*mean Y*	s.d. *Y*	mean Laty	s.d Laty	Y_η(Re)
		low-high a, high-low λ			
1:	.586	.111	6.32	3.00	.202
2:	.477	.204	5.67	3.16	.202
3:	.449	.215	4.46	2.19	.114
4:	.340	.231	4.81	2.07	.115
Σ:	2.017	.703	5.37	3.14	.633

To model small intersensory facilitative effects, two stages are needed; we first explore with the heuristics of Table 3, to see if there exists a domain within a setting that exemplifies what is suspected to happen. Then if this is so, we expand the parameter space in the neighborhood of a result of interest to find a parametric description of the conditions where consistent facilitation can occur. Remember always that facilitation is rarer than masking, so it may need searching for in the parameter space.

In Table 3, for Panels 3 and 4, Target dimension 2, (the first in order to be input), has as a shift in *meanY* from .345 to .350 when the collateral channel is lifted markedly from zero, and the λ values for target and collateral are as shown in the lower half of the table. The associated s.d. *Y* is reduced from .137 to .129, the latency is reduced from 4.01*j* to 3.86*j*, and its s.d. correspondingly drops. But the total *Y* is also reduced.

The means the simulated phenomenon is weak, even if consistent in all its parameter shifts, but could vary if responses are delayed. The predictions for the first stage of the simulation analysis are that the intersensory facilitation of a target channel depends on that channel being initial within the target modality, and that the λ parameters have to be set so that the collateral inputs whose activity precedes the onset of the target stimulation, have to be more resistant to intersensory inhibition than the target. It is as though the context drags the target levels upwards.

Table 3: Interdimensional Interactions
Contrast of two Situations
4Γ outputs

Target dimensions are 2 and 3; $a = 3.76$, $\lambda = 1.35$
Collateral dimensions are 1 and 4; $\lambda = 0.85$

Panels 1 and 2:

Dimn:	mean *Y*	s.d. *Y*	mean Laty	s.d Laty	Y_η(Re)
Setting with zero collateral channel $a = 2.03$					
1:	.129	.029	5.54	2.88	.114
2:	.378	.130	6.68	2.89	.313
3:	.369	.127	6.55	3.00	.313
4:	.135	.035	5.41	2.89	.114
Σ:	.928	.154	6.79	3.05	.928
Setting with high collateral channel $a = 4.03$					
1:	.348	.155	3.89	2.85	.098
2:	.331	.101	6.55	3.01	.273
3:	.329	.105	6.35	3.09	.273
4:	.314	.122	4.38	1.95	.098
Σ:	1.161	.472	5.74	3.23	.742

Target dimensions are 2 and 3; $a = 3.76$, $\lambda = 0.85$
Collateral dimensions are 1 and 4; λ=1.35

Panels 3 and 4:

Dimn:	mean *Y*	s.d. *Y*	mean Laty	s.d Laty	Y_η(Re)
Setting with zero collateral channel $a = 2.03$					
1:	.316	.002	5.97	2.74	.313
2:	.345	.137	4.01	2.38	.114
3:	.333	.133	4.30	2.17	.114
4:	.298	.041	6.24	2.63	.313
Σ:	1.239	.342	5.14	2.66	.855
Setting with high collateral channel $a = 4.03$					
1:	.435	.211	6.26	2.79	.273
2:	.350	.129	3.86	2.05	.098
3:	.333	.124	4.31	1.88	.098
4:	.388	.175	6.12	2.92	.273
Σ:	1.268	.532	5.84	3.01	.742

From the outside of the Black Box, these dynamics would look like facilitation, shortening of response latencies, and improvement in response precision and the estimation of target intensity. Increase in precision is analogous to threshold suppression, or to a change in the gradient of the psychophysical function; that is modifiable by *e* (and hence λ) which is the single channel sensitivity. But all this happens in a narrow parameter region, critically dependent on the time interval between target and collateral stimulus onset. It takes some experimental exploration to find such a region in a real system, which could account for the inconsistency of different reported studies, and the advancement of special theories about attention or about nonlinear physiological masking.

It should be noted that there are effects in the opposite direction which can be quite marked. Consider for example a reinterpretation of the channels 1 and 4 results in panels 1 and 2 of Table 3, if the meaning of target and collateral is reversed so that 1,4 becomes target and 2,3 becomes a collateral pulse during a longer target presentation. This is like a brief switching of attention. We now have, with this reversal of interpretation, zero target level becoming high target level, and the results are quite simple; when the target *a* increases the *meanY* and associated properties are shifted compatibly. Here the higher target activity suppresses the collateral pulse (channels 2 and 3) *meanY* levels slightly.

What is not usually explored experimentally is the effect of the target on the collateral stimulation, in other words, reversing the sense of the judgments part way through a series of stimulus presentations.

Suppose we have again the case reported in panels 3 and 4 of Table 3, and elicit judgments on channel 4 only. This is then a replication of the case just considered, output goes up with input monotonically.

Another important comparison is made by holding the target — collateral interpretation as given originally, and matching the 2nd and 3rd channels across panels. This in fact makes a big difference for the parameter values used. If λ for the target channels is much higher than for the collateral channels, then the contrast between *meanY* values (channels 2 and 3 versus 1 and 4) is biggest in the first panel. The shift is in the opposite direction if the 2nd and 4th panels are compared, which would be represented as an interaction effect if an attempt were made to use Manova to disentangle a full factored experimental design. The higher λ setting for the target channels apparently corresponds to what was called *modality appropriateness* by Welch & Warren (1986).

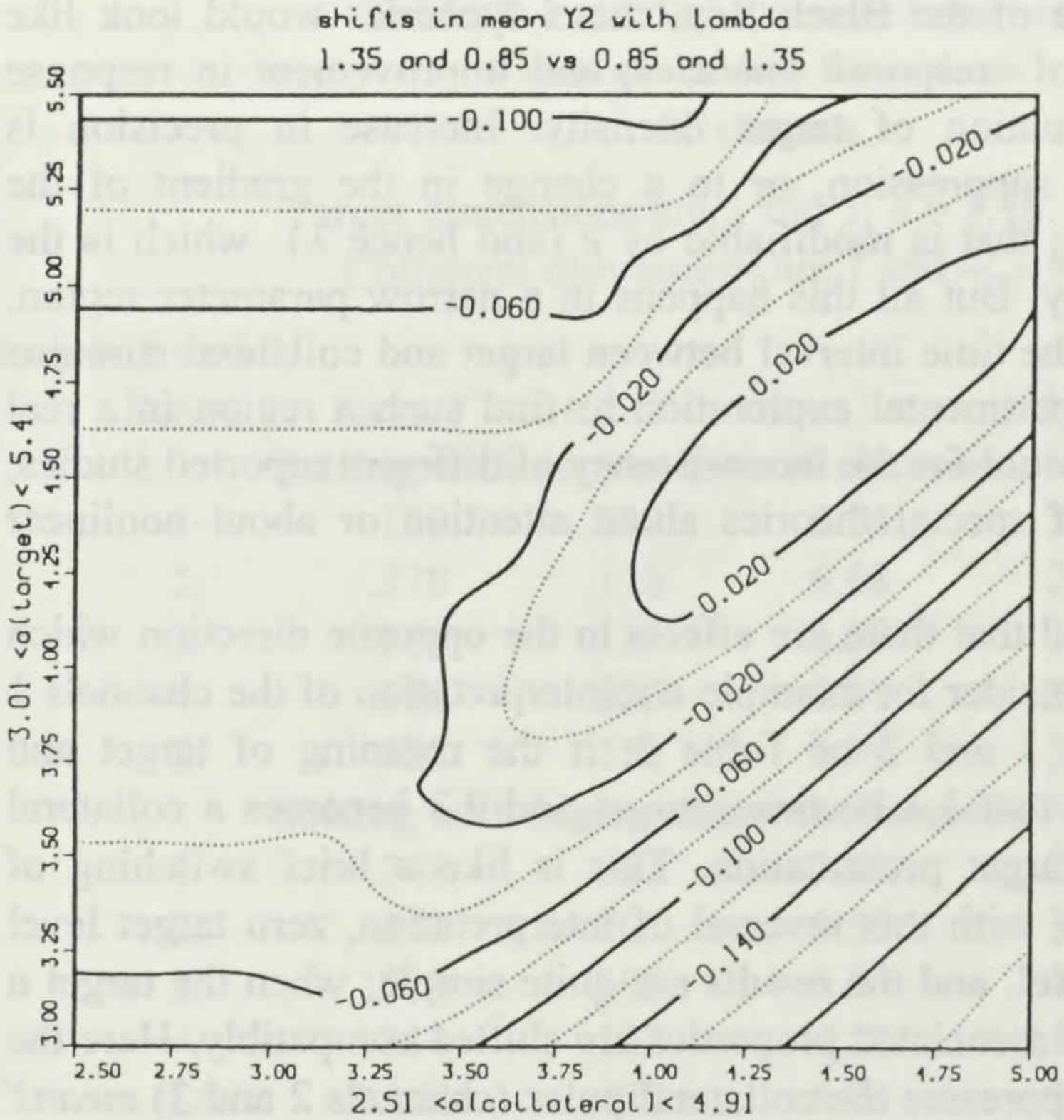


Figure 5: *Response surface contour map for* $\Delta meanY_2/a_{1,4}$.

Expansion of the exploration of the parameter space can now proceed; the independent variables of interest are $\lambda_{1,4}$ and $\lambda_{2,3}$. The dependent variables are *mean* $Y_2|a_{1,4}$=2.01, and *mean* $Y_2|a_{1,4}$=4.01. As *a* are fixed, this situation can be reduced to one dependent variable ΔY, but the bivariate plot of ΔY on $\lambda_{target} \times \lambda_{collateral}$ has to be explored as a contour map. This turns out to be rather odd; the shift in the target *Y* is independent of λ(collateral) but changes from positive to negative to positive as λ(target) is increased.

The expansion of the comparison between panels 2 and 4 in Table 3 is made by varying $a_{1,4}$(collateral) against fixed $a_{2,3}$(target) with the two λ settings employed. The dependent variables are $\Delta meanY_2$ and $\Delta meanY_3$ so two plots are required; $\Delta meanY_2/a_{1,4}$ and $\Delta meanY_3/a_{1,4}$ in Figures 5 and 6.

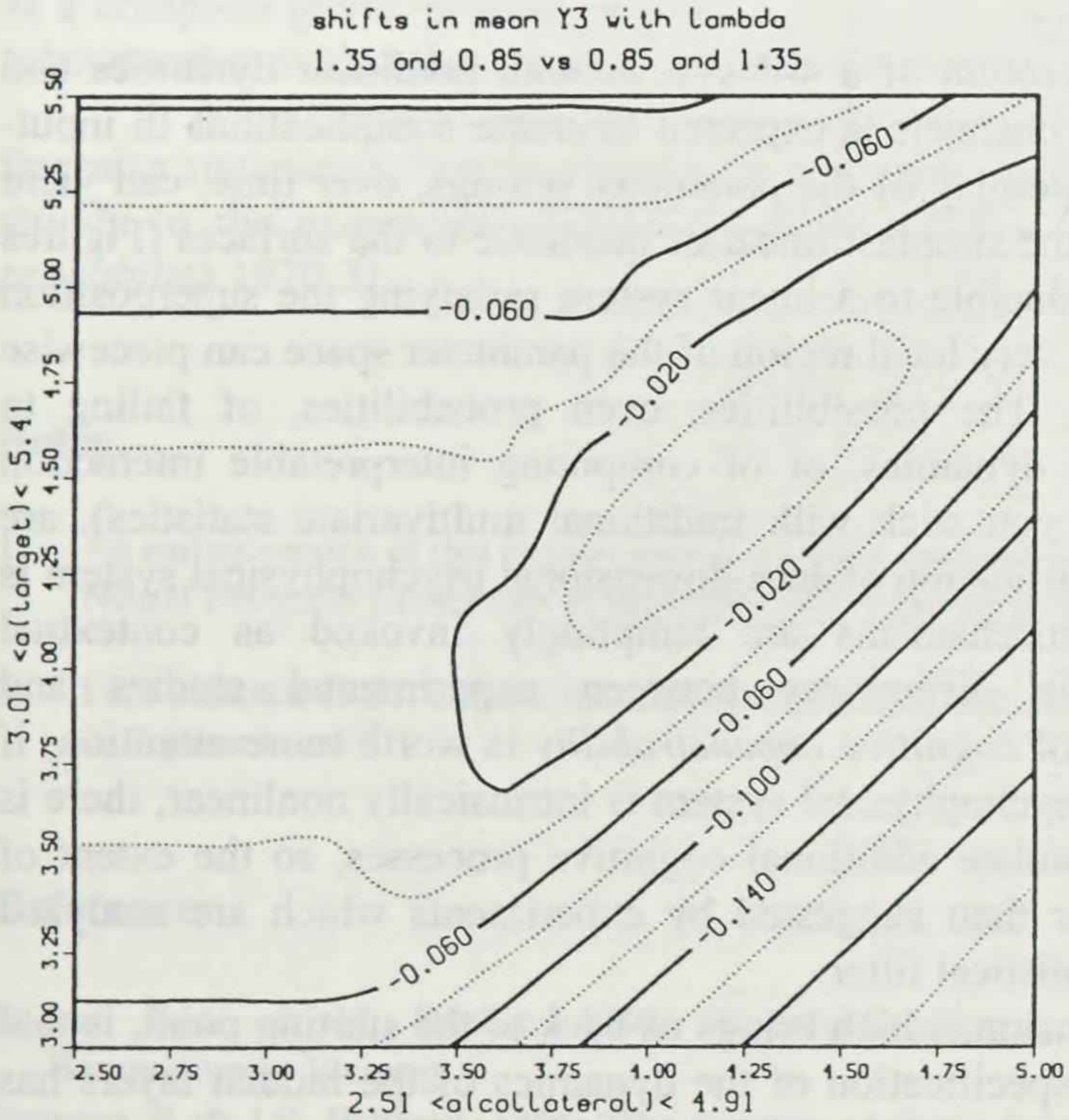


Figure 6: *Response surface contour map for* $\Delta meanY_3/a_{1,4}$.

The comparison between Figures 5 and 6 generates the predictions about the effects of target onset delay on relative judgments of intensity. The settings for $a_{1,4} = a_{2,3}$ (one line at 45° to the axes, which is virtual on the Figures) are a homogeneity condition, there only λ effects are operative.

The small differences between Figures 5 and 6 are due to order effects between the stepped inputs of the four channels. The two target channels have the same parameters (a and λ) but their evolution is sufficiently different to make some small changes in their trajectories. It is unlikely that a real experiment could reliably identify these differences if tested within a statistical model that has $H_0 : (meanY_2 = meanY_3)$.

5. Conclusions

It is possible to argue that intermodal and intramodal interactions may be mediated by the same nonlinear multichannel processes but with different

internal parameter settings.

Inevitably the creation of a 4-d system with nonlinear dynamics and cross-coupling between channels is expected to create complications in input-output mappings; the interplay of the parameter settings, over time, can yield maps which vary from the simplest linear or quadratic to the surfaces (Figures 5 and 6) which are irreducible to a linear system satisfying the superposition principle. Only within a very local region of the parameter space can piecewise linearization be useful. The possibilities, even probabilities, of failing to identify the underlying dynamics, or of computing interpretable interaction terms in a Manova (if you stick with traditional multivariate statistics), are high. It is when misidentification of an *n*-dimensional psychophysical system is made that cognitive mechanisms are temptingly invoked as contextual processes, to reconcile differences between experimental studies and conditions. The notion of *cognitive impenetrability* is worth more attention; if the starting point of a psychophysical system is intrinsically nonlinear, there is even less reason to postulate additional cognitive processes, so the extent of impenetrability is wider than suggested by experiments which are analyzed only through a linear statistical filter.

A general conclusion, which brings us back to the starting point, is that a NN without detailed specification of the dynamics of the hidden layers has negligible chance of being a valid process model in biology or psychophysics, but it may often be an outcome model which approximates real systems deceptively well, in the short run over a limited parameter space. That is, in fact, what traditional statistical models did in psychology when we knew very little about exactly what goes on inside our heads.

One may still wonder about the relative success of NPD in modeling a diversity of psychophysical phenomena, when its core equations are of low dimensionality and it is reflecting the mass action of networks with 10^{12} partially connected elements. I would suggest, to trail my coat, that it works because it focuses only on the dynamics of the active coordinates of the system, leaving the passive ones out of the picture (Tu 1994). Mathematically there are various ways of reducing the dimensionality of a dynamical system to something manageable; the center manifold theorem can justify local linearization, which I have strongly avoided because I want to retain jumps in the phase space, one might want to suggest that the $n\Gamma$ equations ought to be the end results of Lyapunov-Schmidt reduction from some equations whose explicit form is unfortunately not yet known. If we did know them, it is doubtful if the human observer could, without symbiosis with heavy simulation, get any understanding of their implications. I see no reason why we should ever be able to understand our own brains, treated as a full description,

as a complete global process psychology. We can, however, disentangle some subsystems provided that we never forget they are not closed in their dynamics.

It is pertinent to conclude with a quotation from de Finetti, the great Bayesian statistician, "mathematics is an instrument which should conform itself strictly to the exigencies of the field in which it is applied" (*Theoria delle probabilità* 1970:3).

Notes

1. An earlier version of this chapter was given as an invited address to the Sixth Australian Neural Networks Conference at the University of Sydney in February 1995.

2. I am indebted to Dr. Lubosh Hanuska for generating the computer graphics of Julia sets in Figures 1 and 2.

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Fractal Neurodynamics and Quantum Chaos: Resolving the Mind-Brain Paradox Through Novel Biophysics

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1. Mind and brain, chaos and quantum mechanics

1.1. *Paradigms in scientific discovery and the enigma of consciousness*

The twentieth century has seen the unification of the microscopic and cosmic realms of physics in theories such as inflation, in which symmetry-breaking of the fundamental forces is linked to cosmic expansion. Molecular biology has had equally epoch-making successes unraveling the intricate molecular mechanisms underlying living systems, from the genetic code through to developmental structures such as homeotic genes. Despite these conceptual advances, the principles by which the brain generates mind remain mysterious. The intractability of this central unresolved problem in science suggests its principles run deeper than the conventional biochemical description, requiring novel biophysical principles. This paper develops such a model based on linkage between the fractal aspect of chaotic neurodynamics and quantum non-locality, giving brain science a cosmological status at the foundations of physical description.

1.2. *Chaos and quantum mechanics: Unpredictability as a basis for mind*

Although mechanists tolerate mind as a passive shadow representation of physical causality in such theories as epiphenomenalism and brain-mind identity, free-will conjures up the specter of active causal interference. To

quote Sir John Eccles (1977:282): "It is a psychological fact that we believe we have the ability to control and modify our actions by the exercise of will, and in practical life all sane men will assume they have this ability". Nevertheless free will has a very unpopular history in science because of the paradox of mind acting on a supposedly deterministic physical system. The controversiality of consciousness and free-will in science stems from their supposed inconsistency with causal scientific description — but is this so? Chaotic dynamical systems and quantum mechanics both share attributes which are more consistent with these two features than biochemical reductionism would suggest:

1.2.1. *Chaotic dynamics* possess both *sensitivity to initial conditions* and *computational unpredictability* (see Fig. 1a) (Devaney 1986:49; Stewart 1989:134) because exponential spreading of adjacent trajectories with increasing time occurs with a positive Lyapunov exponent $L > 1$ (see Fig. 1a). Similar considerations apply to complex systems in transition in and out of chaotic regimes, where L crosses 1. Arbitrarily small fluctuations are thus inflated into global instabilities by the 'butterfly effect', in which a perturbation such as a butterfly can become the source of a subsequent tropical cyclone. A chaotic system is arbitrarily sensitive to perturbation and hence responsive. Sensitivity also prevents a chaotic system from being precisely modeled. It is thus unpredictable, though it may be deterministic. Such systems behave in a way which makes it impossible for an observer outside the system to describe it precisely enough to determine its outcome and hence test its causal nature.

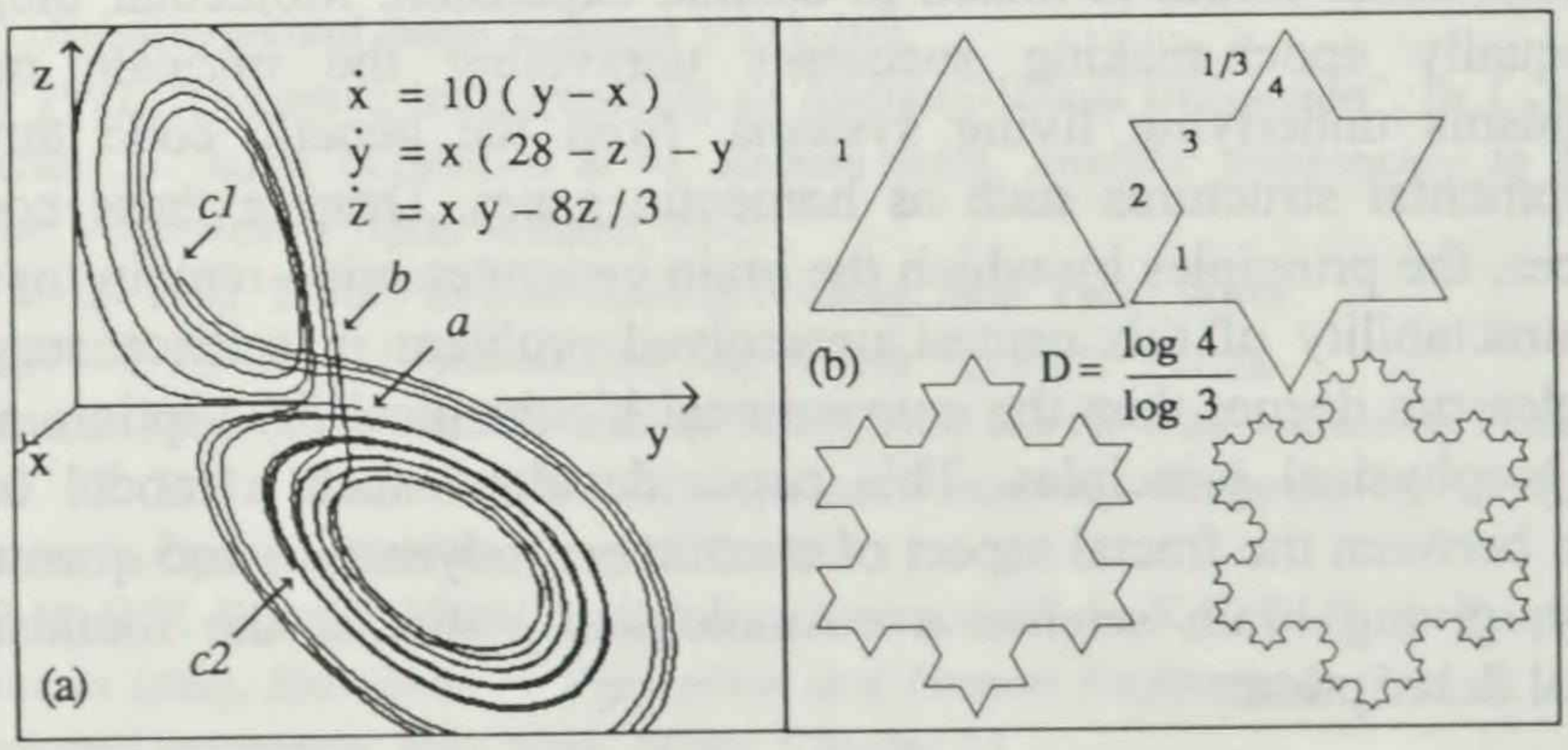


Figure 1: *(a) Positive Lyapunov exponent causing sensitive dependence on initial conditions is illustrated by the Lorentz flow. Trajectories starting ε-close at a have exponentially separated by b and are in distinct parts of the flow by c1,2. Computational unpredictability follows from the incapacity of any approximation to model the flow over increasing time. The Lorentz flow has a strange attractor which has a correlation dimension of 2.06. (b) Non-integer fractal dimension D of the Koch flake. Each side is repeatedly replaced by 4 sides of length 1/3.*

1.2.2. *Quanta* possess a *global internal model* of their environment in the form of the wave function and violate causality through *uncertainty* during *reduction of the wave packet*. These attributes, although somewhat different in nature from sensitivity and unpredictability, cap off the causality of chaotic physical systems at the microscopic level and have parallels to consciousness and free-will. Although a quantum behaves like a particle in terms of its emission and absorption, its wave function extends throughout space-time, forming a global representation of its environment. Subsequent absorption of the particle appears to collapse the wave function into only one of its superposition of possible states. Thus although averaged ensembles of events conform to the probability distribution of the wave, the absorption foci of individual quanta cannot be predicted. The stochastic nature of the theory makes it possible in effect for each quantum to both be *conscious* of the universe through the extended wave function and to exercise *free-will* in its demise in wave packet reduction, while conforming to the principles of quantum mechanics.

1.2.3. *Fractal linkage*. These two levels of physics have a natural link of scale through the *fractal* nature of chaotic dynamics. Many chaotic systems display conserved sets such as attractors and basins which are *fractal* in the sense that they are replicatively self-similar on descending microscopic scales, resulting in a non-integer dimensionality (King 1991:282). In Fig. 1(b) the Koch flake illustrates a simple geometrical fractal in which each side is repeatedly replaced by 4 sides of 1/3 the length l. The number of units thus scales as $l^{-log4/log3}$, giving a fractal dimension D = log4/log3. The correlation dimension is a similar measure (King 1991:283).

The term *quantum chaos* has been used to describe a variety of quantum systems which have analogous dynamics to classically chaotic systems. Electrons, atoms and small molecules traversing a molecular *milieu*, have dynamics well approximated by a chaotic system. Complementing this frontier is the link between quantum uncertainty and sensitive dependence. In a chaotic physical system, quantum fluctuations will become amplified into global instabilities by the butterfly effect — *quantum inflation*. The fractal nature of chaotic dynamics results in a disseminated set of increasingly unstable regimes which can serve as nuclei for global fluctuation (King 1991:297). Complex systems in the chaotic transition region may also enter a state of self-organized criticality in which a local perturbation leads to global bifurcation.

Although our sensory experiences, particularly visual representations of the physical world, have obvious stability properties, the necessity of sensitive

dependence on the external world guarantees that the internal model must include unstable dynamics, as is confirmed by study of optical illusions, hallucinations and dreams. Recent studies of the chaotic dynamics of a variety of neurophysiological processes support such attractor-bifurcation models at both the cellular and neurosystems level.

1.2.4. *The mind of the uncertain brain.* Such a linkage could be used by the brain to allow *mind* states to critically perturb brain states through quantum non-locality. Such an interaction is possible only if the time evolution of the brain is formally unpredictable when observed externally as a physical system. This unpredictability must also be advantageous in evolutionary terms, and hence must assist the brain in the computationally intractable task of survival in the open environment. In this sense, mind may be an extra-physical dual aspect of reality, corresponding to unpredictabilities and uncertainties in a physical brain. Such an interpretation is a *dual model of reality* in which mental and physical are fundamental components of the universe. The physical world is manifest only indirectly as a set of stability properties of mind. From the physical perspective the same mental experiences correspond to stability structures in an internal model of reality.

2. Conceptual problems in the mind-brain relationship

2.1. *Defining mind and consciousness*

2.1.1. *Mind* and *consciousness* remain so different from the usual objects of scientific inquiry that it is unclear they conform to the objective criteria usually applied to scientific description. The terms are the subject of such ambiguity that it is essential to review their semantic variations.

Mind is often referred to as the sum of our intellectual faculties, our capacity to think or reason, the *rational mind*, as distinct from sensation. Being *out of one's mind* in a complementary way suggests escape from rational controls into insanity. *Mindless* activity similarly implies unreflecting action. *Minding* carries different emphases of attending — "Mind that step!" or caring — "I don't mind if I do!". Being *mindful* again implies attentiveness. Having *something on one's mind* that of preoccupied thought. *Making up one's mind* that of deciding. *Being of one mind* having the same opinion or intent. Nevertheless, mind as the dual of body embraces the diversity of subjective experience. To avoid such semantic confusion, I will inclusively define *mind*

as: *the envelope of all subjective manifestations of brain-related activity*, including sensation, thought, feeling and states such as dreaming. The essential feature of the *mental* is its *fundamentality*, the fact that all our access to the physical world occurs via the conduit of subjective experience, the one undeniable reality of existence.

Two scientifically controversial attributes of mind are likely to be pivotal to a successful description:

(a) *Consciousness*: subjective manifestation of attentive brain function.
(b) *Free-will*: mental action upon brain function, violating physical determinism.

At a primary level, our *conscious* experiences are our only access to the nature of physical reality. Although we become firmly convinced of the existence of the real world, our access to this world is only by inference from our subjective, conscious experience as observers. The physical universe is manifest entirely as structural stabilities of conscious experience, or as conceptual descriptions we develop from analysis of other forms of conscious observation, such as particle tracks, spectrographs etc. The physical world is thus accessed indirectly as an inferential structure linking our own conscious experiences and those of others into a single stable description. Thus despite believing in the primacy of the world we live in, all of us derive all our knowledge of the universe from our subjective representations of reality (Eccles 1966:315; Blakemore & Greenfield 1987:383; Rose 1973; Margenau 1984:49). Without the direct avenue of subjective awareness, it is unclear that a physical universe would even exist.

This basic and undeniable manifestation of *subjective consciousness* has again a backdrop of other more restrictive concepts. One can refer to another person as *conscious* or *unconscious* depending on whether they appear to be responding to stimuli, or in a state of coma. One can also compare the conscious with the *subconscious* or the *collective unconscious* of Jung, allowing for some attributes of mind to pass subliminally into existence or represent archetypes lying below the level of attentive awareness. Cognitive scientists may dismiss many peripheral aspects of brain processing as being *pre-conscious*, leaving only the major orienting focus of attention as reaching the conscious level. Finally consciousness is viewed as a reflective type of attention process, exemplified by *self-consciousness* in which a person in addition to perceiving is aware of themselves as a subject. As described by Rosenthal (1986:329), "a conscious state is one which has a higher-order accompanying thought which is *about* the state in question". Ironically such self-consciousness has been claimed by Jaynes (1976:216) to be a very recent

and culture-born imposition, however to the contrary, it may be an evolutionary feature of mammalian or even metazoan brains, because distinction of self from world is the fundamental distinction for survival. A central feature of consciousness research is how perception and attention combine to result in action in the brain (and mind).

Consciousness can be defined as the envelope of capacities of the brain to form subjective representations of reality. In this sense, the *brain is conscious of mind.* This is consistent with one of the most popular modern conceptions of the mind as an internal model of reality constructed by the brain, a view consistent with a variety of lines of evidence spanning normal cognition, the nature of optical illusions, dreaming and many pathological states of the brain. *Free-will* on the other hand is the reciprocal action of mind on brain.

2.1.2. *The menagerie of the mind.* The scope of subjective experience can be outlined through a combination of introspection and study of traditional concepts in language. The most undeniable mental experiences are our sensory experiences of the world around us, and physical sensations in our bodies from touch and pain through to the manifestations of emotions such as fear and anger. Along with these come less clearly defined inner images provided by memorization, imagination and thought. While these are less rich than direct sensory experience in usual waking life, probably as a result of competition with direct sensory stimuli accessing the same processing modules, in states of relaxation, sensory-deprival, dreaming, or meditation, internal imagery becomes clearer and less distinguishable in intensity from sensory experience, and may take on a life of its own. Study of the properties of such alternative states has immense potential for consciousness research, because the properties of consciousness are not sensorily tied to the physical world description, thus providing a unique opportunity to test its internal dynamical qualities.

Many mental features, being processes rather than states, cannot be subjected to stable scrutiny without changing their characteristics. While it is easy to understand the meaning of this sentence, it is vastly more difficult to simultaneously perceive the details of how you are able to understand its meaning, and more difficult still to decide to what extent the semantic background of the words is consciously perceived or merely subconsciously controlling the conceptual process. Nevertheless it is accepted English usage that we can choose *to think* and that *thinking* is a structured conscious process, in which a sequence of semantic concepts emerge as a product of directed voluntary attention, a sequential process with semantic direction, which may take the form of narrative, rehearsal or have sensory or abstract properties. To

imagine is again a voluntary process but dealing with imagery generation. By contrast, to have an *idea* is a spontaneous and possibly novel product of the thought process. Such terminology is consistent with a dynamical model in which the attention process generates structural bifurcations, some of which spontaneously generate novel features or concepts. The difficulty of attending to two things at once and the singularity of the stream of consciousness suggests that it represents a global dynamic in the brain. It may be more accurately described as a bundle of related awarenesses, dynamically coupled, but capable of further bifurcation.

Central to our subjective consciousness is the notion of an observer, or self, witnessing a theater of conscious experience through the attention process, having the capacity by an act of will, or intent, to alter the circumstances occurring in the perceived world. Dennett (1991), based on the dictates of a parallel processing model, and various perceptual illusions, asserts that such a 'Cartesian Theater' is non-existent. "What would make this sequence the stream of consciousness? There is no one inside, looking at the wide screen show displayed all over the cortex, even if such a show is discernible by outside observers." (Dennett 1991:101). Nevertheless the construction of the physical world model is derived from our conscious experiences. Although there may be no localized representation of the stream of consciousness in the brain, the self and its intentional relation to the stream of consciousness nevertheless remains our fundamental arena of experiential reality.

2.1.3. *Observer problems in consciousness.* Several features make consciousness uniquely difficult to observe:

(a) Mental observation (introspection) involves a whole-systems observer problem in which the system being observed is also the system doing the observing. "Introspection is one of the many forms consciousness itself can assume, so that it represents a significant part of what we are trying to explain" (Miller 1992:132). The attempt to examine conscious states thus globally alters their phenomenology.

(b) Mental constructs do not satisfy the criteria of objectivity possessed by physical objects and processes, so most aspects of objective observation are rendered invalid. "Although consciousness exists by virtue of some physical property of the brain, just as bioluminescence exists by virtue of some chemical property of specialized cells, it is not as bioluminescence is an observable property of living matter. Nor is it an invisible property [...]. It is detectable to anyone who has it. The difficulty is the method by which

consciousness is detected is logically different from [...] bioluminescence" (Miller 1992:132). Thus *qualia* such as redness remain ill-defined.

(c) As William James (1901:232) originally pointed out "consciousness is not a thing, but a process". Conscious features may thus be rapidly transformed by the very act of observation, leaving only the sensoria as stable observables. *Thought* is an example of such dynamically unstable observation, because the act of thinking results in an evolution of the experience. An *idea* is an unstable bifurcation to a novel thought state.

(d) The boundary between subconscious processing and conscious experience is ill-defined. Consciousness may thus be incomplete as a process. The hidden background of conscious experience, which Dreyfus (1979:189) and Searle (1990a:589) call 'intrinsic intentionality' may contain some of the highest computations.

(e) Crick & Koch (1992:112) note that the problem of consciousness is ill posed, because it is a constructive process, requiring further constraints to provide a unique solution.

(f) The subjective experience of free-will is inconsistent with causal description.

2.2. *Concepts of the brain-mind relationship*

A diverse variety of views of the mind-brain relationship have been advanced, providing pointers to the basis of mind in brain function, while confirming the unresolved state of understanding in this area.

2.2.1. *Complexity*: Consciousness as a property of complex computational systems. One common idea about the emergence of mind is that it is somehow a product of the very complexity of the brain. However neither computer circuits nor artificial neural nets are ascribed to possess the attribute of mind in addition to their functioning at any given level of numerical complexity.

John Searle (1980:417) invented the Chinese room, in which (conscious) operators translate Chinese by symbolic constructs without the system being conscious of the meaning of the translation, to point out that strong AI cannot by itself explain consciousness. Dennett (1991:435) utters the 'systems reply' against this by saying that the brain *is* complex and *is* conscious so it is possible in principle for a parallel virtual machine to become conscious through it's many parallel interactions — "this little bit of brain activity doesn't understand Chinese, and neither does this bigger bit of which it is a part [...] even the activity of the whole brain is insufficient to account for understanding Chinese. Of course the dualists would say "it takes an

immaterial soul to pull off the miracle of understanding". Dennett's (1991:435) critical untested assumption is that the brain is simply a *classical virtual machine*.

Measures of complexity based only on neural net architecture neglect non-trivial properties of the individual neuron. The coelenterate *Hydra* (cf. Fig. 2) displays complex behavior involving a greater variety of locomotion types than the sea snail *Aplysia* and coordinated feeding, despite having an undifferentiated nerve net, which can withstand migratory reintegrations of the ectoderm and endoderm if the organism is turned inside out.

Certain non-linear systems near the chaotic boundary L ~ 1 or in chaotic transition do however display complex bifurcations and the development of novel structure within the system, and for this reason are termed *complex systems* by the Santa Fe school (Jen 1990:XIII). These form good models for neurophysiology, and have the potential when given an adequate quantum foundation also to explain consciousness.

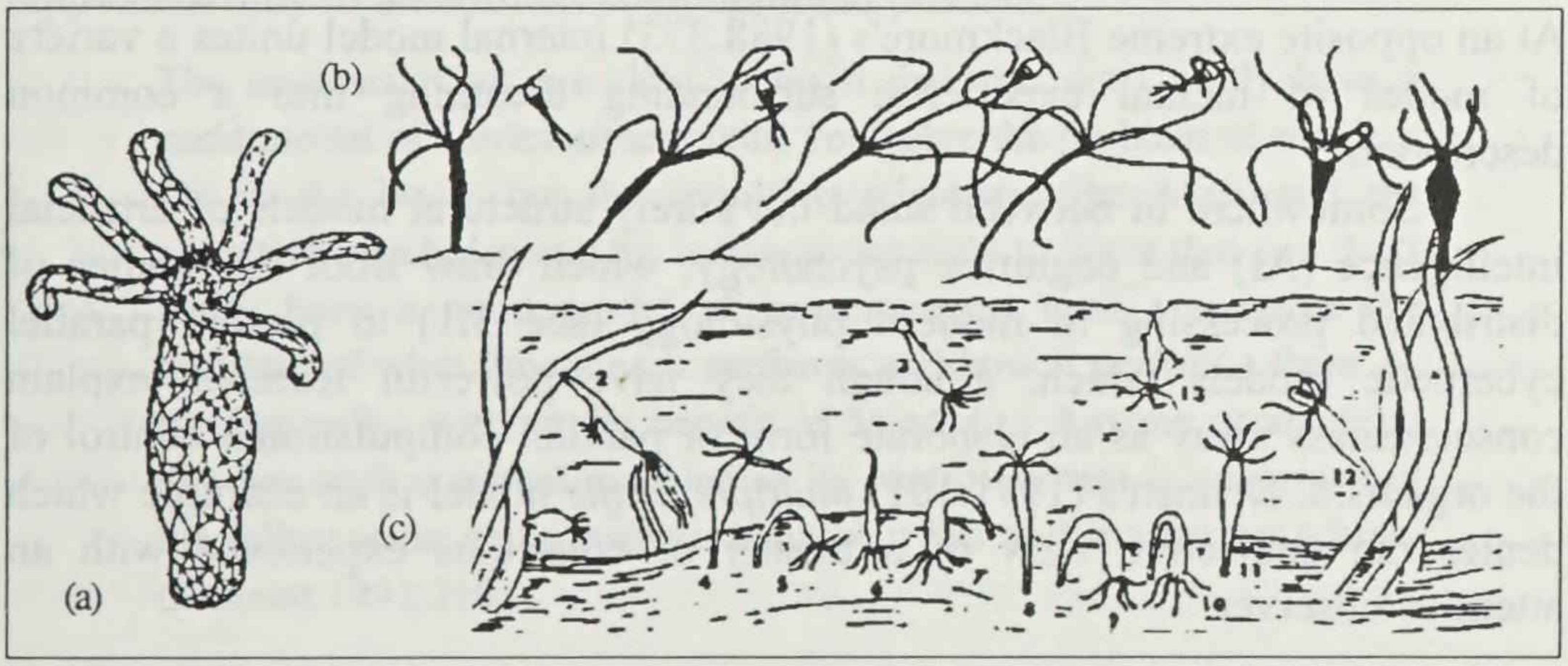


Figure 2: *Hydra poses a dilemma for theories of neural net organization. It can reassemble ectoderm and endoderm if turned inside out and has a disseminated neural net (a) with no global structure, nevertheless it can coordinate eating (b) and possesses more diverse types of locomotion than animals such as molluscs and arthropods which have structured ganglia. These include snail-like sliding, tumbling, inch-worm motion and use of bubbles and surface films.*

2.2.2. *Emergence*: The idea that new properties emerge from the interaction of subsystems, not predicted by the subsystem architecture. In this sense emergence, which is a property of many digital and non-linear systems including molecular assemblies, applies to virtually every system with global feedback, from machines and organisms to the weather, all of which share system attributes which are disrupted by partitioning. Thus while the basis of mind is doubtless also emergent, this does not in itself explain how it 'emerges' from the brain. It is thus necessary to look in detail at the underlying mechanisms of mind for a substantive explanation.

2.2.3. *An internal model of reality* constructed by the brain. The idea of the mind as an internal model of reality has widespread support, both in the modular structures of sensory detectors which respond to features such as line orientation, thus synthesizing a model out of a combined set of features, and in various visual illusions in which these features lead to incomplete or contradictory results. The internal model is also consistent with a role for the mind as a monitoring system for attention. However the precise nature of the model and how the brain uses it to generate mind remain to be elucidated.

On a physiological level, research into modular sensory processing (see 3.3) and the distributed chaos models of Freeman's group (see 4.1.1) illustrate internal models of brain function which share distributed processing features. At an opposite extreme Blackmore's (1988:373) internal model unites a variety of modes of mental experience surrounding dreaming into a common description.

Somewhere in between stand the purely structural models of artificial intelligence (AI) and cognitive psychology, which draw from the studies of distributed processing in modern physiology (see 3.1) to present parallel cybernetic models which, although they have powerful features, explain consciousness away as an elaborate form of parallel computational control of the organism. Dennett's (1991:101) *multiple drafts* model is an example which denies our subjective view of a theater of conscious experience with an attentive observer:

> There is no single definitive 'Stream of Consciousness' because there is no Central Headquarters, no Cartesian Theater where 'it all comes together', for the perusal of the Central Meaner. Instead of such a single stream (however wide), there are multiple channels in which specialist circuits try, in parallel pandemoniums, to do their various things, creating Multiple Drafts as they go. Most of these fragmentary drafts of 'narrative' play short-lived roles in the modulation of current activity but some get promoted to further functional roles, in

> swift succession, by the activity of a virtual machine in the brain. The seriality of this machine (its 'von Neumanesque' character) is not a hard-wired design feature, but rather the upshot of a succession of coalitions of these specialists. (Dennett 1991:101)

The multiple drafts model makes some physiological sense because an asynchronous parallel architecture allows the brain to make optimally rapid, but arbitrarily complex calculations. Such an architecture is consistent with cortical design in which the incoming afferents are associatively connected with the outgoing efferents with no intervening structures, leading to very short computational delays, while the timing delays across the cortex are non-zero. It is also consistent with the attractor dynamical model advanced in this paper in which multiple bifurcations can induce parallel structures in the same dynamic. The general nature of such a distributed internal model also has very interesting time properties (see 8.2), and allows for constructive filling in (blind spot and Fig. 5(c)), editing, and for gaps in the description, such as those caused by visual saccades to be smoothed out (Dennett 1991:234). "Nothing can seem jerky except what is represented as jerky" (Minsky; quoted from Dennett 1991:344).

However Dennett's (1991) description clearly leaves mind a role equivalent only to an abstract computational process:

> The neuroscientists are right to insist that you don't really have a good model of consciousness until you solve the problem of where it fits in the brain, but the cognitive scientists, (the AIers and the cognitive psychologists, for instance) are right to insist that you don't really have a good model of consciousness until you solve the problem of what functions it performs and how it performs them — mechanically, without the benefit of Mind. [...] Anyone or anything that has such a virtual machine as its control system is conscious in the fullest sense and conscious because it has such a virtual machine. (Dennett 1991:210)

"Any scientific theory of mind has to treat it as an automaton" (Johnson-Laird 1983:474). These statements lose the subjective nature of mind completely.

This difficulty arises from dependence on abstract computational ideas as the basis for the models, reducing the functional implementation, and particularly its neurophysiological basis to subordinate roles as in Marr's (1982) three-level analysis of mental phenomena. If the brain uses unusual physical principles in its neurophysiology, such models will fail by the classical trap. Repeated objections have also been mounted on philosophical

grounds. "No connectionist computer could exhibit real mentality" (Searle 1990a:592, 1990b:26). "The subjective features of conscious mental processes — as opposed to their physical causes and effects — cannot be captured by the purified form of thought suitable for dealing with the physical world that underlies the appearances" (Nagel 1986). The current paper addresses this problem by presenting a model in which the biophysical principles are paramount and the computational features are a product of the biophysics.

2.2.4. *Duality*: Mind as a *dual phenomenon* to physical reality. The very great difference between mind and the diversity of physical phenomena suggests that although in a sense paralleling the physical brain, mind may not be a physical attribute as such but a complementary principle, making mind and universe dual aspects of totality. Descartes' homunculus in the pineal gland and his *cogito ergo sum* illustrate two aspects of his dualism, expressed very eloquently in the following passage:

> While I could pretend that I had no body, that there was no world [...]. I could not pretend that I was not [...] from the fact that I thought of doubting the truth of other things [...] it followed I existed [...] from this I recognized that I was a substance whose whole essence or nature is to think and whose being requires no place and depends on no material things. (Descartes 1968:102)

Dualism has been the subject of attack and counter-attack during the 20th century. Gilbert Ryle (1949:17) made a classic critique of dualism, describing it as the 'ghost in the machine', and branding many aspects of mental description as *category mistakes*, promoting Koestler (1967:197) to mount a rebuttal by the same title. An outstanding feature of many of Ryle's descriptions, such as the lemon on the desk, is that they derive from everyday experiences in which the stable physical world model dominates other aspects of conscious perception.

Several researchers have proposed *dualistic* philosophies or even three-aspect brain-mind-knowledge models. Sir John Eccles wrote "we are a combination of two things or entities: our brains on the one hand; and our conscious selves on the other" (Popper & Eccles 1977:100). The brain is a precious "instrument", a "lifelong servant and companion" providing "lines of communication from and to the material world", but we are not it. An act of will, as Eccles sees it is an everyday case of psychokinesis of mind moving bits of matter (Hooper & Teresi 1986:17). He has even gone as far as to propose structured entities *psychons* corresponding to ideas which interact with *dendrons* possibly in the pyramidal tracts. Vendler (1972:190, 1984:113) has

also made a defense of dualism. *Epiphenomenalism* constitutes a weak one-sided form of duality in which world effects mind but not vice versa.

Critics of the artificial intelligence and cognitive psychology schools such as Dennett (1991) describe dualism as forlorn because it undermines the agenda of materialist or operationalist description of both the brain and mind in abstract computational terms: "If mind and body are distinct things or substances, they nevertheless must interact; the bodily sense organs via the brain must inform the mind, [...] and then the mind, having thought things over must direct the body in appropriate action. [...]". "How can mind stuff both elude all physical measurement and control the body?". Such criticisms depend on outmoded classical reasoning: "It is [the] principle of conservation of energy that accounts for the physical impossibility of perpetual motion machines, and the same principle is apparently violated by dualism. This confrontation between quite standard physics and dualism has been endlessly discussed since Descartes's own day, and is widely regarded as the inescapable and fatal flaw of dualism" (Dennett 1991:33). This statement displays a startling lack of understanding of a variety of physical processes from the weather to the behavior of quanta, in which instability and uncertainty fragment classical causality and provide room for a logical loop connecting mind and brain — a central theme of the current paper.

2.2.5. *Sensitive instability*. The internal model is nonlinear, dynamically unstable and undergoes transitions to and from chaos. While some aspects of mind, such as visual processing, have structural stability in their representation of most objects, optical illusions and a variety of mental phenomena from hallucinations to the bizarre subjective realities of dreaming sleep demonstrate that the mind is capable of unstable self-generative behavior. Dynamical arguments dictate that a nervous system which is optimally responsive to sensory conditions must undergo transitions into chaos to provide arbitrary sensitivity and ensure it does not become locked in any stability state or periodic oscillation. Thus while philosophers such as Gilbert Ryle (1949), who rely on stable mental representations of objects, may conclude that mind is not even a well formulated concept, the unstable aspects may be essential to the internal model of reality.

Sensitive dependence is consistent both with representation of the mind as an internal model and with a dualistic interpretation of reality. The form of stability sets such as attractors and their evolution through bifurcation provides the basis for an internal model. The unpredictability of the chaotic regime and its ramifications in terms of quantum uncertainty provide a causal loophole within which to discuss principles complementary to physical processes

occurring above the quantum level, which would support the dualistic perspective without contradiction.

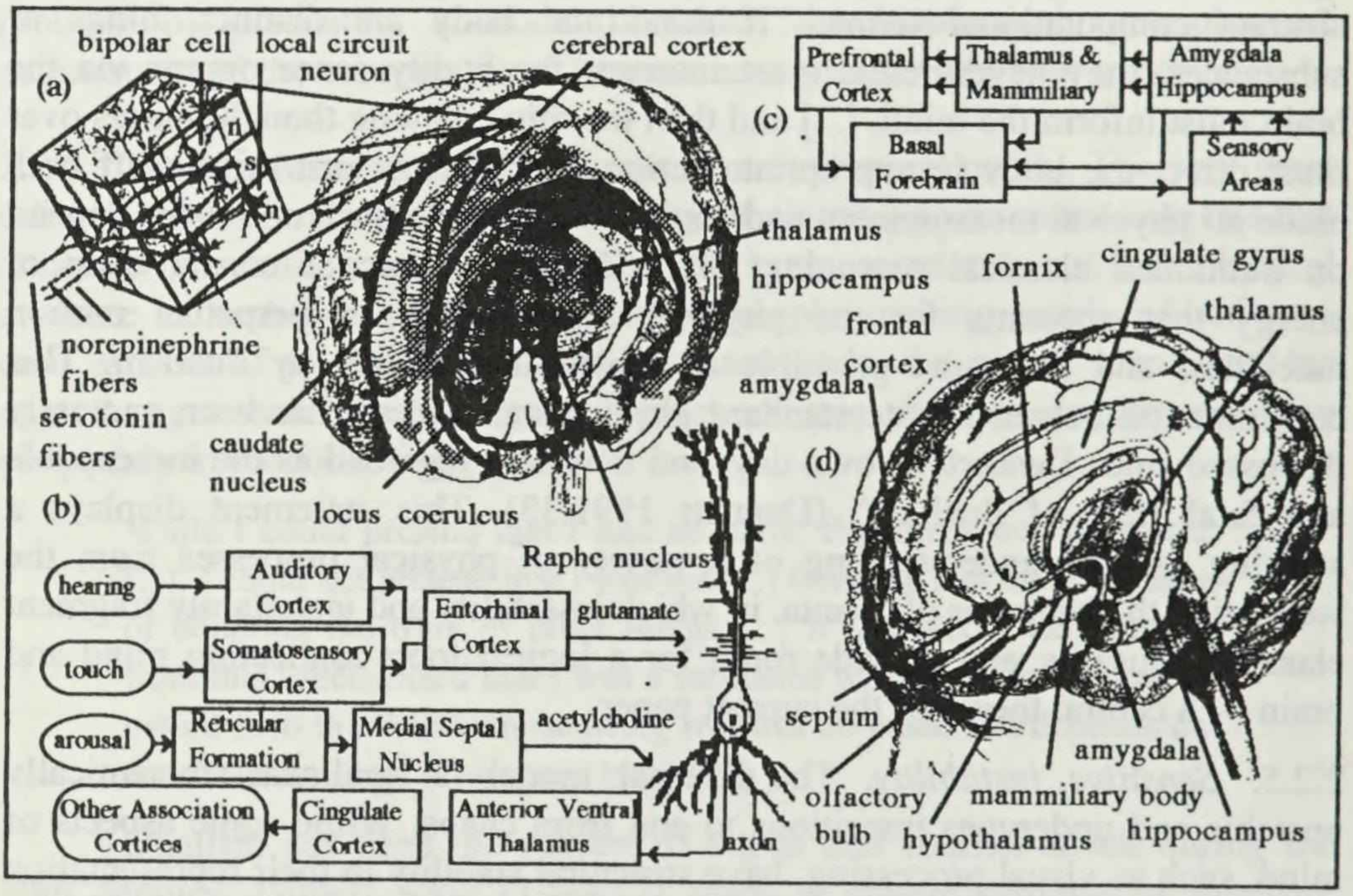


Figure 3: *(a) Nor-epinephrine and serotonin pathways originating from mid-brain centers modulating light and dreaming sleep are distributed across wide areas of the cortex (Bloom* et al. *1985). (b) Inputs from different areas impinge on a single hippocampal CA1 neuron via distinct neurotransmitters, thus mapping neurosystems architecture on to single cells (Alkon 1989). (c) Looping circuits of the limbic system are involved in both affect and memory. (d) Limbic structures and the thalamus in brain section (Bloom* et al. *1985).*

3. The neurophysiological basis of mind

It is obvious that the manifestation of consciousness in the forms we are used to experiencing requires interactive dynamics of the sensitively dependent active brain. What remains more elusive, like the engram of memory, is the neurophysiological basis for conscious states.

3.1. *Local versus distributed generation of mind*

The hypothesis that mind is a consequence of the nature of distributed brain processing has a variety of support, based on the modular architecture of the cortex, modal arousal of the ascending distributed pathways and the impact of limbic circuits which we will investigate below. As all these systems are required for conscious attentiveness, the conclusion that consciousness is a global manifestation of attentive brain function is strongly supported. An alternative strategy for the brain to generate mind would be to have specialized areas dedicated to the generation of the internal model of reality, such as Sir John Eccles' 'liaison brain' (Popper & Eccles 1977:361) or the supplementary motor cortex, which is almost universally active. However damage to a variety of cortical areas reveals only 'graceful degradation' of both function and subjective awareness, rather than 'mind loss' (Blakemore 1991).

Disagreement over the source of major oscillations in the brain such as the alpha and theta rhythms has led to ideas that specific sub-cortical structures such as the thalamus may play a principal role in generating mind, acting as a gating mechanism between the cortex and subcortical sensory centers (Crick 1984:4586; Taylor 1992). It has topographical representations of many cortical modalities and forms an intermediate position between the cortex and the sensoria, thus having the potential to act as a filter releasing only the most relevant stimuli into conscious attention, coinciding with Huxley's (1954) filter theory of consciousness. These roles remain to be proven because the thalamus is difficult to access and the evidence from accidental lesions in humans is not clear. Similarly the ascending pathways of the basal brain are essential to maintain active consciousness, but this appears to be by diffusely activating the entire cortex.

Consciousness could nevertheless involve only a subset of cortical neurons. "Consciousness corresponds to coalitions of cortical neurons dynamically modulated by attention and higher-level expectations [...]. We would expect that only some of the cells in the cortex would be expressing what we see, while others are carrying out unconscious computations, but which cells correspond to consciousness?" (Crick & Koch 1992:112). At an extreme, identifying mind with distributed processing becomes *mind-brain identity* in which all mental states are considered the subjective equivalent of particular brain states. Mind-brain identity has two difficulties. Firstly the structural basis of mind is eliminated rather than explained by identity. Any responsive physical system, such as a computer could equally possess mind by the identity principle. Secondly identity prevents any causal link between the

mind and brain, reducing consciousness and free-will to the status of delusions of the internal model, eliminating any role for the subjective aspect of reality in evolution and hence the need for an 'identity' mind.

3.2. *Ascending distributed pathways*

A very important contribution to the modal nature of conscious activity comes from the distributed pathways ascending from the midbrain centers (see Fig. 3a) responsible for general arousal in the reticular activating system (ROES), and in regulating the major modality shifts of consciousness, light and dreaming sleep. Two pathways lead from the Raphe Nuclei and the Locus Coeruleus to diverse cortical areas and involve the modulating neurotransmitters, serotonin and nor-epinephrine (see Fig. 11). The onset of dreaming sleep is heralded by activity of cells in the Pons and silencing of cells in the Raphe Nuclei and Locus Coeruleus (Bloom *et al.* 1986:173). The latter also show bursts during orientation to novel stimuli. Similar dopamine paths spread out from the Substantia Nigra selectively into the frontal lobes and motor centers. The ascending pathways have been implicated in mental illness, addiction and motor syndromes such as Parkinson's disease (Gilling & Brightwell 1982:119). Dopamine is sometimes associated with pleasure and nor-adrenaline with anxiety.

Dreaming or REM sleep is both one of the most singular phases of conscious activity in which feedback appears to be accentuated at the expense of external input, generating complete subjective realities or 'worlds within'. The nature and function of dreaming consciousness and its wealth of detail remains obscure. The principal hallucinogens are also serotonin and catecholamine analogues see Fig. 11). In addition to cerebral arousal and sleep loss, their action probably triggers fractal waves of cortical excitation through the diffuse connections into interleaved cortical layers shown in Fig. 3(a) inset. Such connectivity gives the hallucinogens the capacity to modulate reflex modular excitability across the entire cortex, giving rise to patterned visions and cross-sensory synesthesias. They have earned a controversial reputation by provoking, alongside dreaming, some of the most remarkable changes in the nature of consciousness discovered by man. For the same reason they represent a key tool for consciousness research.

3.3. *Cortical modularity*

A variety of experiments support the modular (Fodor 1983:49; Mountcastle 1978:36) involvement of cortical centers, both in various sensory-cognitive tasks and their correlates in mental activity. These illustrate how modular cortical processing can be associated with different aspects of conscious experience.

Visual processing is clearly modular, with parallel processing of color and movement in distinct areas (Zeki 1992:43). The primary visual area V1 has 'discrete and segregated' connections through more structured sensors in V2 to V3, V4 and V5 responsible for dynamic form, color form and motion. These areas are each associated with their own lesion syndromes such as achromatopsia (no color) or akinetopsia (no movement). Zeki's studies raise fascinating questions concerning how subjective visual awareness is generated from these modular aspects. Although they have direct reciprocal connections and diffuse connections back to V2 and V1, there is no central arena where their output is sent, suggesting visual awareness is generated either by their modulation back on V1, or somehow by the entire distributed dynamic. Face and mood recognition, written and spoken speech, and music, are all modular features.

The PET scans in Fig. 4(a) illustrate the correspondence between different conscious activities and the activation of specific modular regions of the cortex, including well-known areas such as Wernicke's and Broca's areas of linguistic interpretation and articulation and the supplementary motor cortex, as well as highlighting less well understood areas in the frontal lobes. Listening to ambiguous structured signals (time reversed recordings) can activate just about the entire cortex (Friberg 1992) suggesting that activation is at least partially a product of chaotic instabilities in the process of forming a stable representation. Dreaming states provide interesting PET scans in which the cortex is perceptually activated in a manner consistent with the similar EEG to the waking state (see Fig. 4b,c), and the intensity of dream experiences. One feature different in dreams is the lower activity of the inferior frontal cortex, which may reflect the uncontrolled nature of dreams (Madsen *et al*. 1991:502). Such studies support a modular distributed internal model, which may also be *holographic* in its use of distributed phase fronts and wave transforms. The holographic aspect, popularized by Pribram (1991), arises naturally from the many to many nature of synaptic connections, the simultaneity of Hebbian synaptic response and from the decomposition of sensoria into features such as line orientation and ocular dominance, forming a parallel representation in

which each memory or experience is registered across the cortex as in terms of its attributes. What is less clear is how attributes such as color motion, edges and filled regions coordinate with the primary sensory areas to resynthesize the complete conscious view.

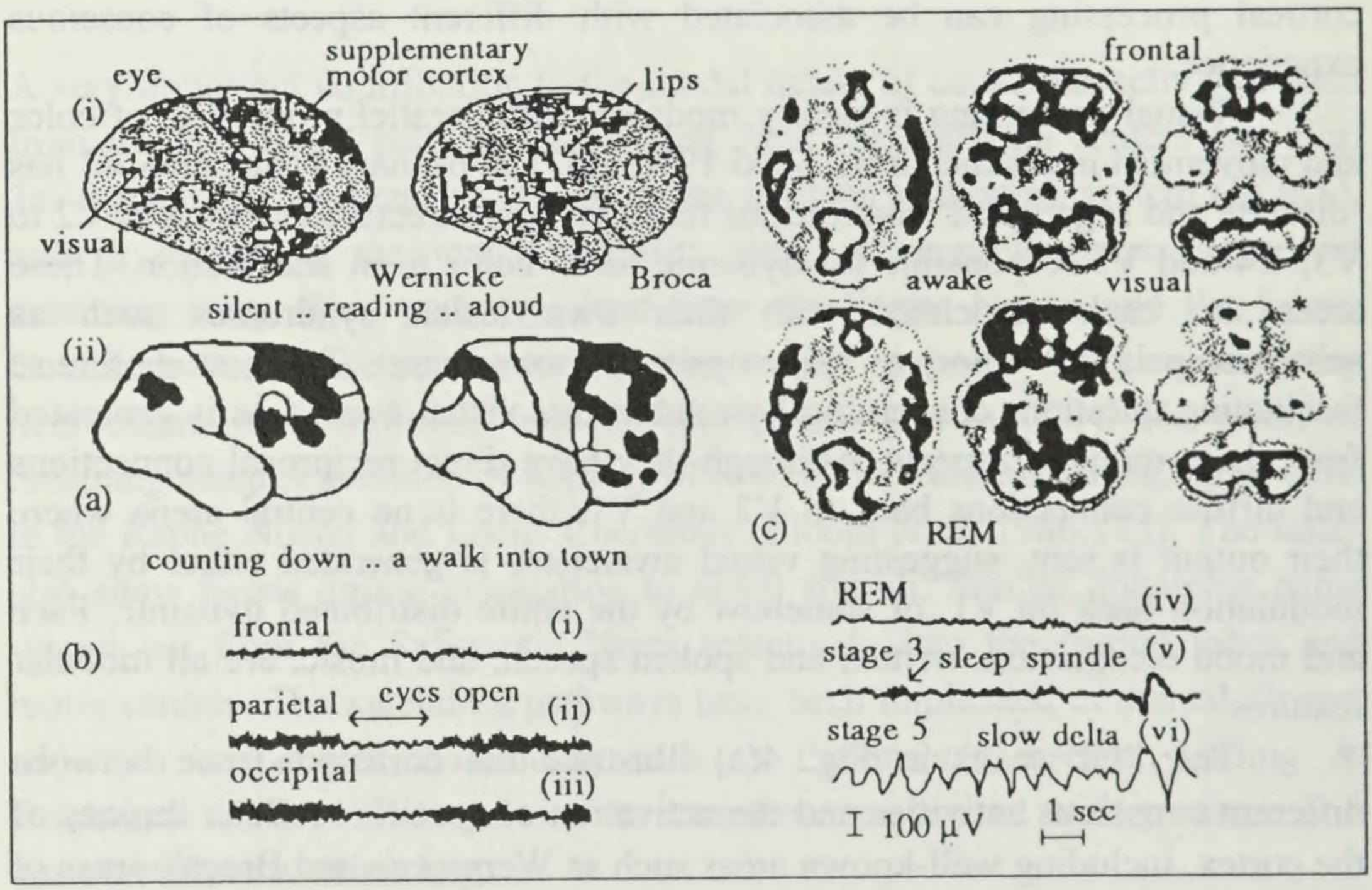


Figure 4: *(a) Cortical modularity in PET scans. (i) Silent reading is contrasted with reading aloud, in which there is wider cortical involvement, including motor and somatosensory lips areas. (ii) Counting down is contrasted with visualizing a walk into town, stimulating a variety of frontal areas as well as the parietal cortex (P. Roland after Blakemore 1991). The supplementary motor cortex is activated in all four views. (b) Similarity of the REM sleep EEG (iv) to the alert state [(i)-(iii) eyes open]. (c) REM sleep PET scan parallels the awake brain in activation of visual cortex and frontal lobes (dark), except for reduced REM inferior frontal activity (*), consistent with the lack of control in dream sequences (after Madsen* et al. *1991).*

3.4. *The split-brain and sex*

Study of split-brain patients reveals how difficult it is to pinpoint the structures supporting sentient consciousness. When the left and right cerebral hemispheres are severed by cutting the corpus callosum, replies to experimental questions center around the content of the dominant hemisphere, because it is uniquely able to articulate verbal responses. If a composite image is shown separately to the left and right half eye fields of the split-brain subject,

they will describe the image their dominant hemisphere sees, and will be unable to refer descriptively to stimuli presented exclusively to their recessive hemisphere, unless it also retains linguistic ability. For example a nude in the left field will elicit a laugh and the indirect comment "That funny machine". The person thus behaves verbally, but not emotionally, as if the experiences of the non-dominant hemisphere are unavailable. However if asked merely to point to the picture seen, the recessive hemisphere, which is specialized at non-verbal pattern recognition, can assume control. The subject appears to retain an integrated personality and displays only minor conflicts of behavior, because the midbrain structures involving emotion and arousal are still intact, although the hemispheres appear a little like Siamese twin minds which can express distinct desires and aims. One patient's hemispheres for instance had the distinct aims of being draftsman and racing driver (Bloom *et al.* 1985:228). Consciousness, even in the intact brain, may be a bundle of coupled awarenesses (Bloom *et al.* 1985:29; Parfitt 1987:19; Dennett 1991:101) rather than a single dynamical entity.

Sexual differences in the brain provide a further intriguing dimension of variation in human consciousness (Kimura 1992). At least three types of difference have been noted, enlargement of a specific hypothalamic nucleus in men, and differences both in lateralization and relative function of frontal and parietal areas. Women appear to have less linguistic lateralization, despite displaying superior verbal abilities (Bloom *et al.* 1985:226), and are several times more likely to have aphasia or apraxia from frontal than parietal strokes. Men have corresponding parietal and lateral dominance, leading to the possibility that male and female brains have global differences of organization similar to the plasticity seen in sensory processing.

3.5. *Attention and memory: The limbic system and frontal areas*

The limbic system (see Fig. 3e) (cf. Mishkin *et al.* 1988:62; Alkon 1989:26) also forms a particularly interesting set of looping pathways combining sensoria, emotional states and episodic long-term memory (Fig. 3c,d). The hippocampus, which has an older three-layered structure than the six-layer neocortex has a pivotal role in establishing long-term memory, possibly by transferring experiences into associative memory over a matter of weeks. It has projections from diverse sensory areas via the entorhinal cortex and feeds back into the thalamus and subsequently to cortical areas including prefrontal, cingulate gyrus, and basal forebrain. The amygdala has similar looping circuits linking diverse sense modes and connecting to the thalamus and deeper

emotional centers in the hypothalamus. Phase decoherence occurs in the hippocampus during orientation to unfamiliar stimuli. The limbic system thus forms a bridge between emotion, memory and a distributed representation of time action and self in the frontal lobes. This is consistent with the emotional and motivational side-effects of frontal lobotomy and with studies on time-delayed learning in damaged hippocampi. It also gives a graphic portrayal of the link between extremes of emotional experience from fear to exaltation, the central themes of survival, attention, and the establishment of long-term memory.

The limbic system may also be linked to both the ascending pathways and the cortex in processing waking memories in the REM phase of sleep (Winsen 1990:45). In several mammalian species, theta rhythms, which are generated in the brain stem and pass both to the Septum in the forebrain and to synchronous generators in the hippocampus, can act as phase locking signals for long-term potentiation, in association with orientation to key survival activities. Spatially selective CA1 cells, which signal an animal's location in the waking state, are selectively active in subsequent REM phases, suggesting REM functions in memory processing in the sleep cycle. The role of emotion in the limbic system as a monitor of and driving force for survival, may thus underlie the archetypal intensity of dream content. However, because we dream about past experiences, it is also likely that hippocampal cells will revisit locationary states. Notably, we can also remember our dreams. It is difficult to see how this is possible at the same time as memory reconsolidation.

A second active type of short-term memory often called working memory (Goldman-Rakic 1992:73) complements (long-term) associative memory by providing short-term storage of symbolic information as well as permitting the manipulation of that information. It appears to be centered on the prefrontal cortex with reciprocal connections with both the parietal cortex and the limbic system. Prefrontal damage effects use of knowledge to guide behavior in everyday situations, including predictive tracking, e.g., of projectile movements. When a monkey is trained to look at where a target has disappeared after a delay selected cells in the prefrontal cortex fire, on target disappearing, others fire during the delay and others on the motor act. Such eye movement also involves feedback loops to the basal brain (from pyramidal cells to the striatum, the substantia nigra, mediodorsal thalamus and back to pyramidal cells). Prefrontal action is modular with spatial and compound attributes active in different loci. A model linking the frontal and limbic structures in a representation of space-time is developed in 8.2.

3.6. *Global dynamics: Mind states and brain states*

Examination of the contributions to consciousness by the major dynamical structures of the brain confirms that consciousness is a collective product of the ascending pathways, the cortex and limbic system. The dynamical activation of the cortex by ascending distributed pathways appears essential for consciousness, while all sensory areas and most of the associative areas of the cortex can be seen to contribute in a modular manner to the envelope of conscious experience, dynamically modified by the looping circuits of the limbic system.

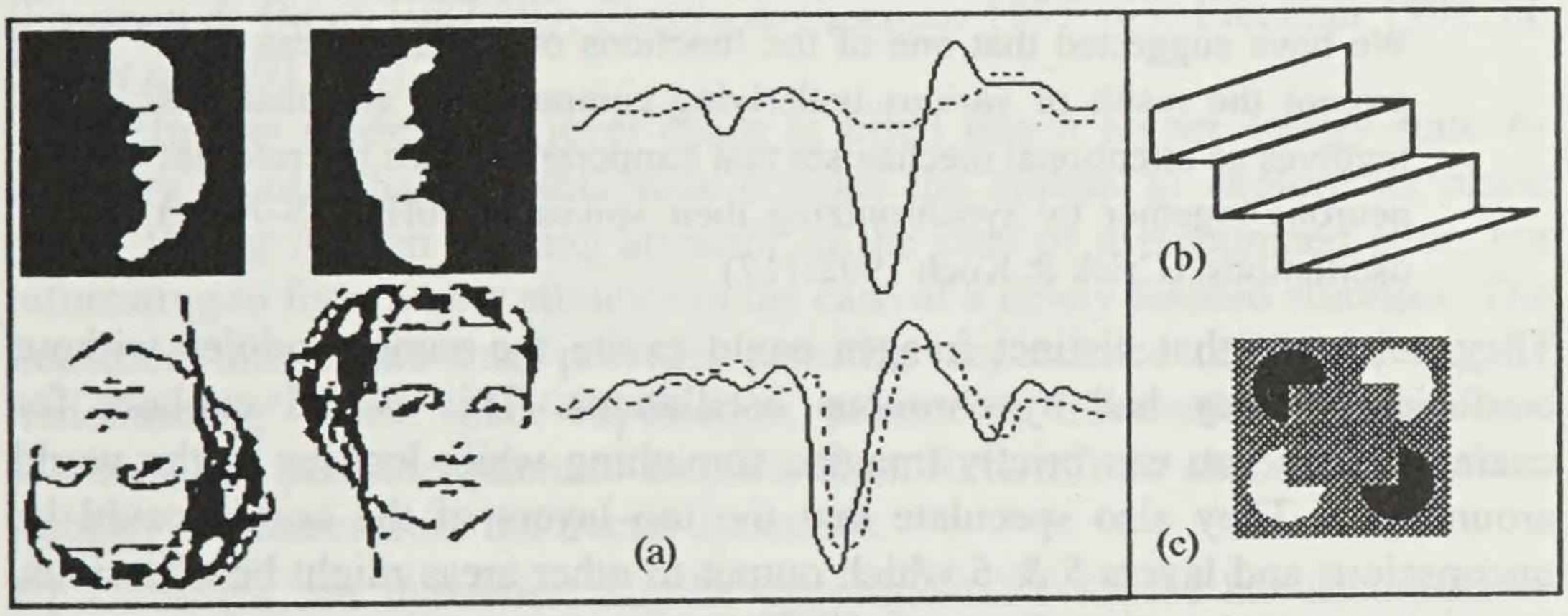


Figure 5: *Optical illusions illustrate the close linkage between mind state and brain state, and support a dynamical bifurcation model of conscious imaging. (a) The lower face, which is easy to recognize in either orientation gives similar evoked potentials, while the upper one which is difficult to recognize inverted does not (Jeffreys after Blakemore 1991). Optical illusions illustrate two features of visual processing consistent with attractor dynamics: (b) alternating percepts of a diagram which is ambiguous in 3D, (c) construction of a geometrical figure from incomplete information.*

Conscious experience is thus subject to much of the global dynamical variation for which the brain is capable, from anesthesia, through waking, resting, dreaming, and hallucination. Only in deep sleep, seizure and coma

when the global dynamics are profoundly altered do we see a loss of conscious function. In Fig. 5(a) the close correspondence between conscious recognition and brain states is illustrated. In Fig. 5(b) two optical illusions illustrate the way in which perception displays both oscillatory compensations in the presence of ambiguous 3D information, and attractor-like constructs which complete partial visual information with perceived lines and regions. This can be seen as a possible example of linkages between edge detectors in V2 and higher areas and is also consistent with an attractor-bifurcation basis for the internal model of reality.

Crick & Koch (1990, 1992) have explored a variety of hypotheses as to where and how consciousness might be generated in the cortex. One structured hypothesis is that it is associated with a specific frequency mode:

> We have suggested that one of the functions of consciousness is to present the result of various underlying computations and that this involves an attentional mechanism that temporarily binds the relevant neurons together by synchronizing their spikes in 40Hz (35-70Hz) oscillations. (Crick & Koch 1992:117)

They point out that distinct images could excite the same modules without confusion if they had synchronous oscillations. This would explain, for example, how you can briefly imagine something while looking at the world around you. They also speculate that the top layers of the cortex could be unconscious and layers 5 & 6 which output to other areas might be conscious. A minimum processing time of 60-70ms for a conscious percept can be deduced from the display of rapid images (20ms red + 20ms green = yellow) or tones.

4. Non-linear dynamics in the central nervous system

Physical evidence for attractor dynamics in a variety of aspects of central nervous system function and development has become abundant in recent years. Chaotic regimes have been demonstrated, both at the neurosystems level and in the dynamics of single excitable cells, and fractal dynamics has been proposed for ion channels (King 1991:298)

4.1. *Electrodynamics*

4.1.1. *Neurosystems dynamics*. At the neurosystems level, experimental evidence has accumulated for chaos in the EEG's of at least some phases of

cortical activity, including sleep, resting wakefulness and pathological states such as epilepsy (Babloyantz 1985:122, 1989:126; Basar 1990:1). The low correlation dimensions of several of these states is consistent with collective chaotic dynamics in neuron populations, rather than stochastic or independently programmed behavior. Evoked potentials also show desynchronizations during orientation, consistent with phase relations being pivotal in recognition and orientation (Basar *et al.* 1989:56; Hoke *et al.* 1989:93), supporting a holographic model. The model of burst dynamics in the olfactory bulb advanced by Walter Freeman (see Fig. 6e,f) combines these two aspects into a model with bifurcations of spatially distributed waves into chaotic temporal dynamics which both follow the neurophysiology and also permit real tests of pattern discrimination of neural nets displaying comparable dynamics (Freeman & Baird 1987:393; Skarda & Freeman 1987:165; Freeman 1991:38; Yao *et al.* 1991:103).

In this model, low level chaos is lifted into a higher energy state by olfactory input. Chaos in this state enables the system to explore its phase space, falling into an existing attractor in the case of a recognized odor, but bifurcating to form a new attractor in the case of a newly learned stimulus. The transition into chaos thus provides sensitive dependence on input, ergodic 'randomizing' phase space exploration, parametric bifurcation to form new symbols, and possible quantum amplification. Return from chaos in turn fixes stability structures from the fractal dynamics.

4.1.2. *Single cell dynamics.* Similar experimental evidence has accumulated for chaos in a variety of excitable cell types, supported by the chaotic models of Chay & Rinzel (1985:357) (see Fig. 7a,b,c). These extend the Hodgkin-Huxley (1952) equations to take account of calcium ion pumping, thus displaying a variety of dynamical features, including period doubling bifurcations, chaos and period three oscillations characteristic of the chaotic regime. These dynamics model well the chaotic excitations of pancreas cells and *Nitella* internodal cells. Similar models have been advanced for excitations in neurons and heart pacemaker cells. The irregular behavior of controlling cells in small ganglia such as in *Aplysia* studies is also consistent with sensitive dependence and chaos, by contrast with the more regular beating of subordinate neurons.

4.1.3. *Fractal ion-channel kinetics.* A Markov model is commonly used for ion channel kinetics, in which an open state is linked to one or more closed states. However the likelihood that a closed channel will open behaves fractally with increasing time scales according to Fig. 7(d) (Liebovitch *et al.* 1987a:173, 1987b:979, 1991:243). This is consistent with bio-molecular structures

behaving fractally, not only in a geometrical sense, but also dynamically as shown for myoglobin in Fig. 7(e) (Ansari *et al.* 1985:1000). The dynamics of many important biological molecules may be fractal in this way, which involves the linkage between a variety of quantum excitations of differing energies, and feedback between tertiary structures and active sites.

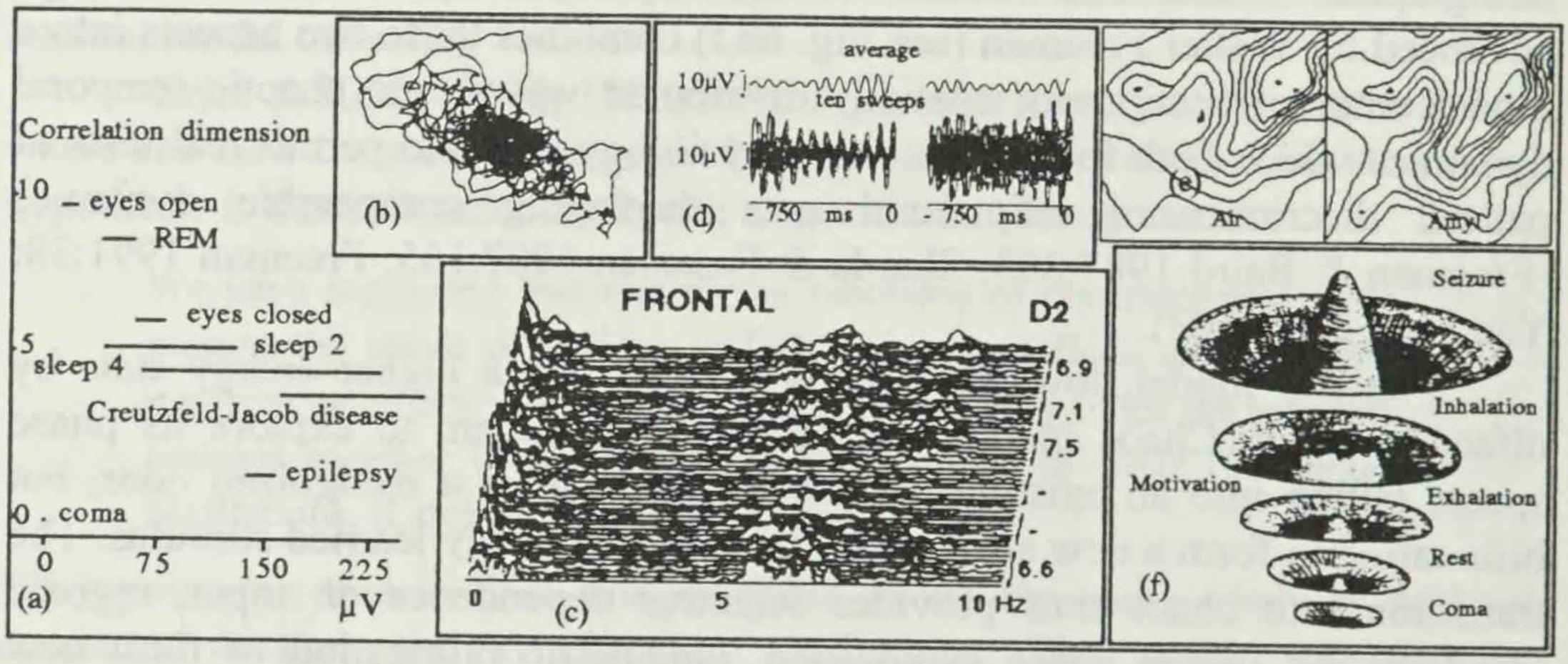


Figure 6: *Chaotic neurosystems dynamics are illustrated by: (a) the low correlation dimensions of a variety of brain states; (b) phase portrait of an EEG recording (Babloyantz & Salazar 1985); (c) time evolving Fourier spectrum and associated correlation dimensions. (d) Phase decoherence in novel or unexpected stimuli is consistent with a distributed model of processing based on oscillatory phase, similar to a hologram. (e, f) Chaotic and distributed processing is combined in Walter Freeman's model of olfactory bulb processing. Recognition of a given odor by the bulb arises from the distributed pattern of activity, occurring in bursts phased with inhalation. The time-dependent dynamics supporting this consists of bifurcation from low-level chaos to higher level activity which settles into an existing attractor (recognition) or develops a new one (learning) after exploring phase space in higher level chaos. Chaotic neural nets based on neuroanatomy can perform pattern discrimination tasks competitively with other neural net designs (Skarda & Freeman 1987).*

4.2. *Long-term adaptation*

Many aspects of the long-term structure of sensory areas of the cortex are consistent with their inheriting an attractor structure derived from particular sensory innervation and stimulation patterns. On a short time scale are the reported spatial distributions corresponding to olfactory stimuli (see Fig. 6e)

which on a longer time scale adopt new forms on relearning the same stimulus a second time, and phase desynchronization of cortical evoked potentials. On a longer time scale plasticity of sensory structure (cf. Fig. 8) from the somatosensory barrels of the rodent (b), through to visual ocular dominance and orientation patterns induced by training regimes (a) indicate major sensory structures arise as a dynamical system induced through bifurcation.

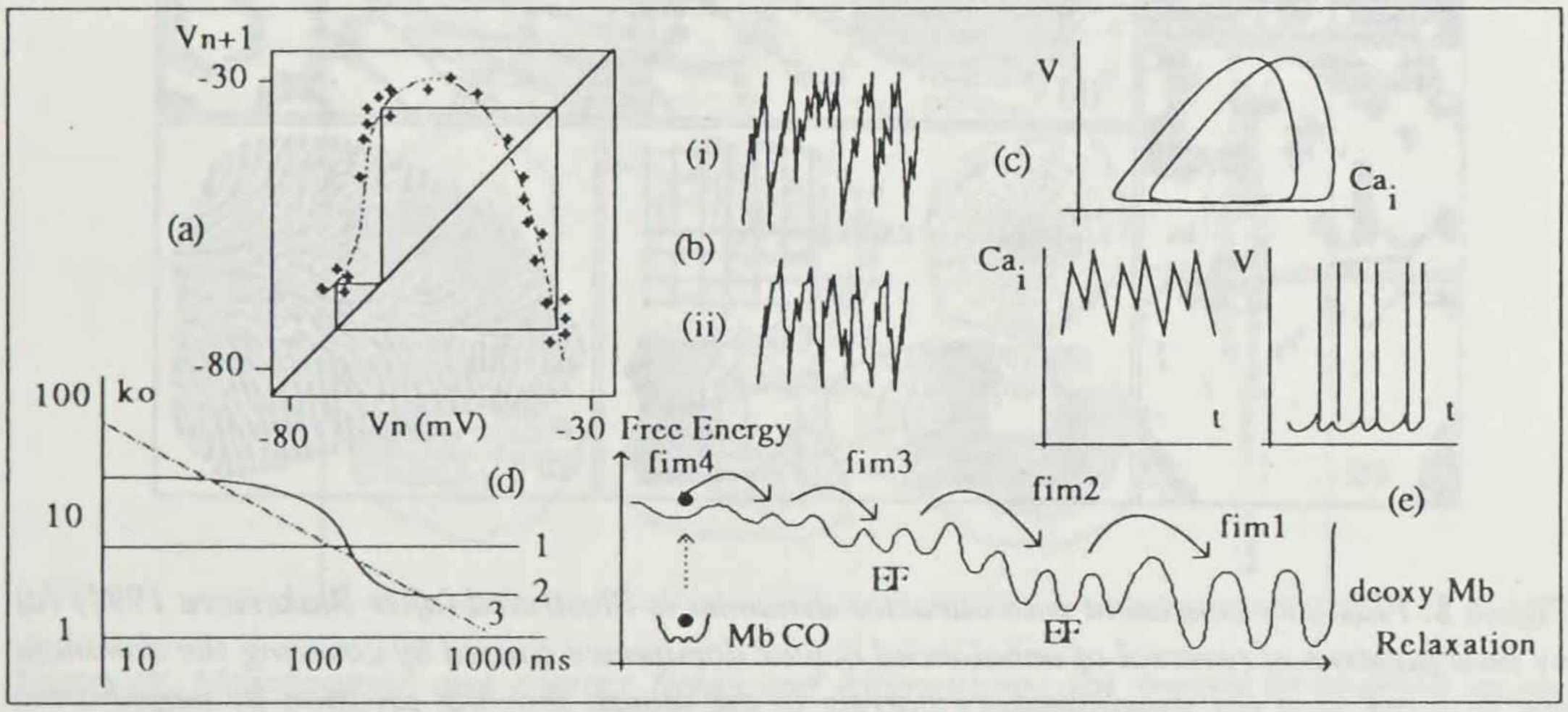


Figure 7: *(a) Period 3 oscillations in Nitella indicate dynamics within the chaotic regime. Chay-Rinzel model (1985), (b) output is comparable with experimental recordings, (c) period doubling bifurcation in model. (d) Experimental behavior of voltage gated K^+-channel is consistent with a fractal model (3) rather than a one, or two step Markov chain (1,2) (Liebovitch* et al. *1987a, 1987b). (e) Fractal dynamics in relation of excited myoglobin is illustrated in terms of functionally important movements and equilibrium fluctuations involving a variety of quantum transitions on differing scales.*

4.3. *Neurogenesis*

The raw numbers game of neurogenesis suggests attractor dynamics may form an essential bridge between central nervous genotype and phenotype. The 50,000 genes governing central nervous system development (around 60% of human genes) cannot informationally specify the connections for 10^{11} neurons and 10^{15} synapses. Generalizing principles are thus required to complement the informational specificity of developmental genes such as the homeotic genes, thus providing both genetic efficiency and plasticity. The form of early embryogenesis is a series of bifurcations induced by morphogen gradients leading to the differentiation of major brain structures (see Fig. 9a). Further

general principles playing a dynamical role in central nervous organization include cell surface interactions enabling migration up the glial scaffold (b), selection of tissue layer, or target cell synapse type, and parallel growth (Blakemore 1991).

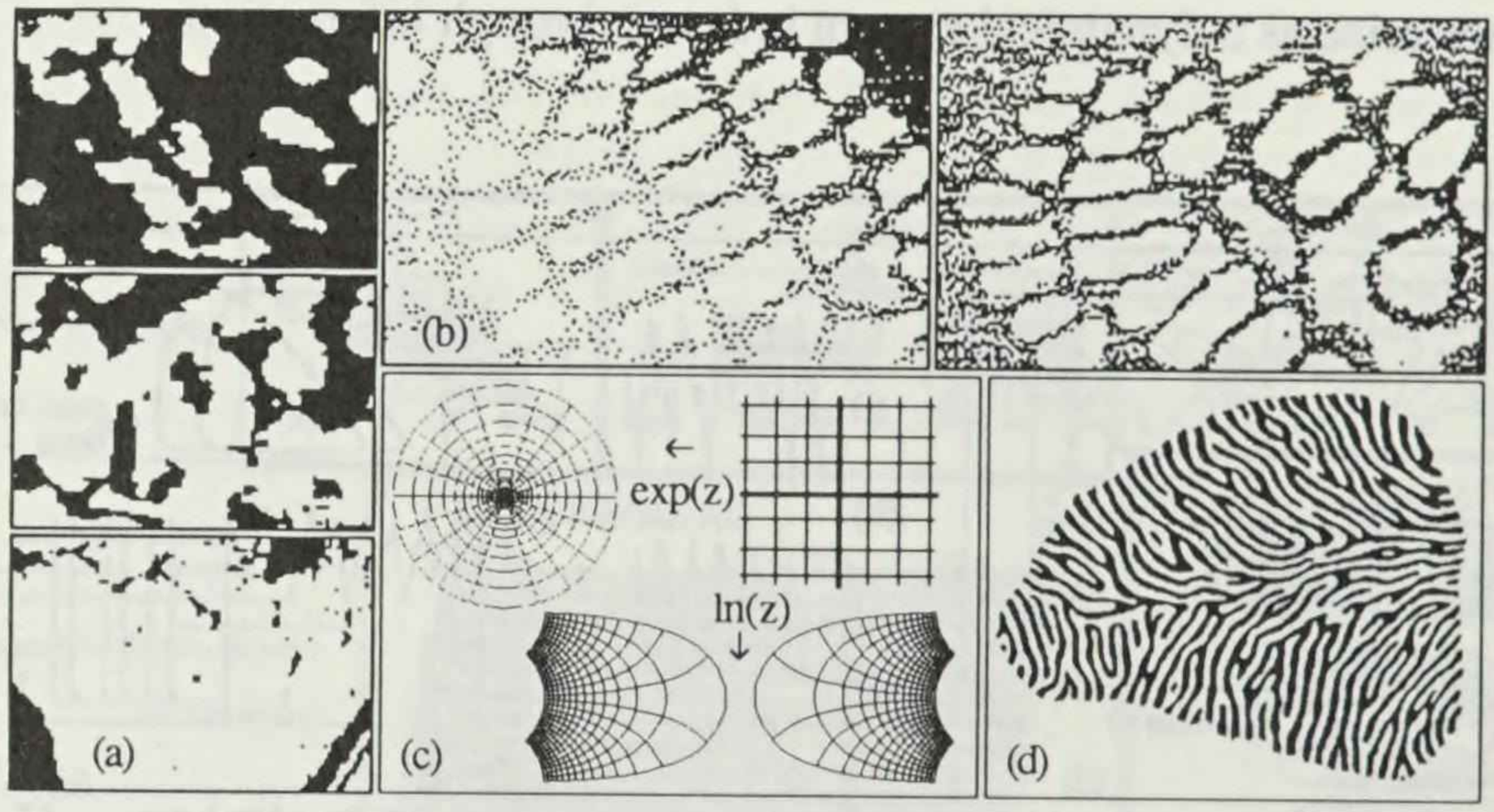


Figure 8: *Plasticity consistent with attractor dynamics is illustrated (after Blakemore 1991) (a) by field patterns of reversal of imbalanced ocular dominance caused by covering the dominant eye in a cat, and (b) somatosensory barrels in the mouse showing invasion by neighboring nuclei on removal of a whisker. (c) The visual field on the cortex is distorted by a non-area-conserving map similar to a complex logarithm, which gives greater sensitivity to the center but does not match the geometry of the perceived world (Cowan & Sharp 1988). (d) Ocular dominance displays a bifurcation of the 2D field in terms of the 1D parameter of dominance (Hubel & Wiesel 1989).*

The neurogenic picture is thus consistent with genetic selection up to target cell type but the development of specific synaptic connections and the organization of thalamic and cortical layers, ocular dominance columns, barrels etc. through dynamical excitation driven by the afferent sense organs, culminating in the sensory experiences of the newborn (Kalil 1989). This is consistent with the plasticity of sensory structures already described, with tissue culture experiments (c), and with the waves of excitation seen on the prenatal retina (1/10-1/100 action potential speed), which stop just before the onset of visual activity. These waves appear to result in both geniculate layering and subsequent organization in the visual cortex (Shats 1992:35), by competitive input, in which synchronous inputs cause Hebbian enhancement, while asynchronous inputs from distinct eyes cause synaptic separation, consistent with the sequential organization of (1) the retina via early firing in

ganglion cells, (2) subsequent layering of the geniculate after retinal wave input, and finally (3) organization of ocular dominance and other features in the visual cortex.

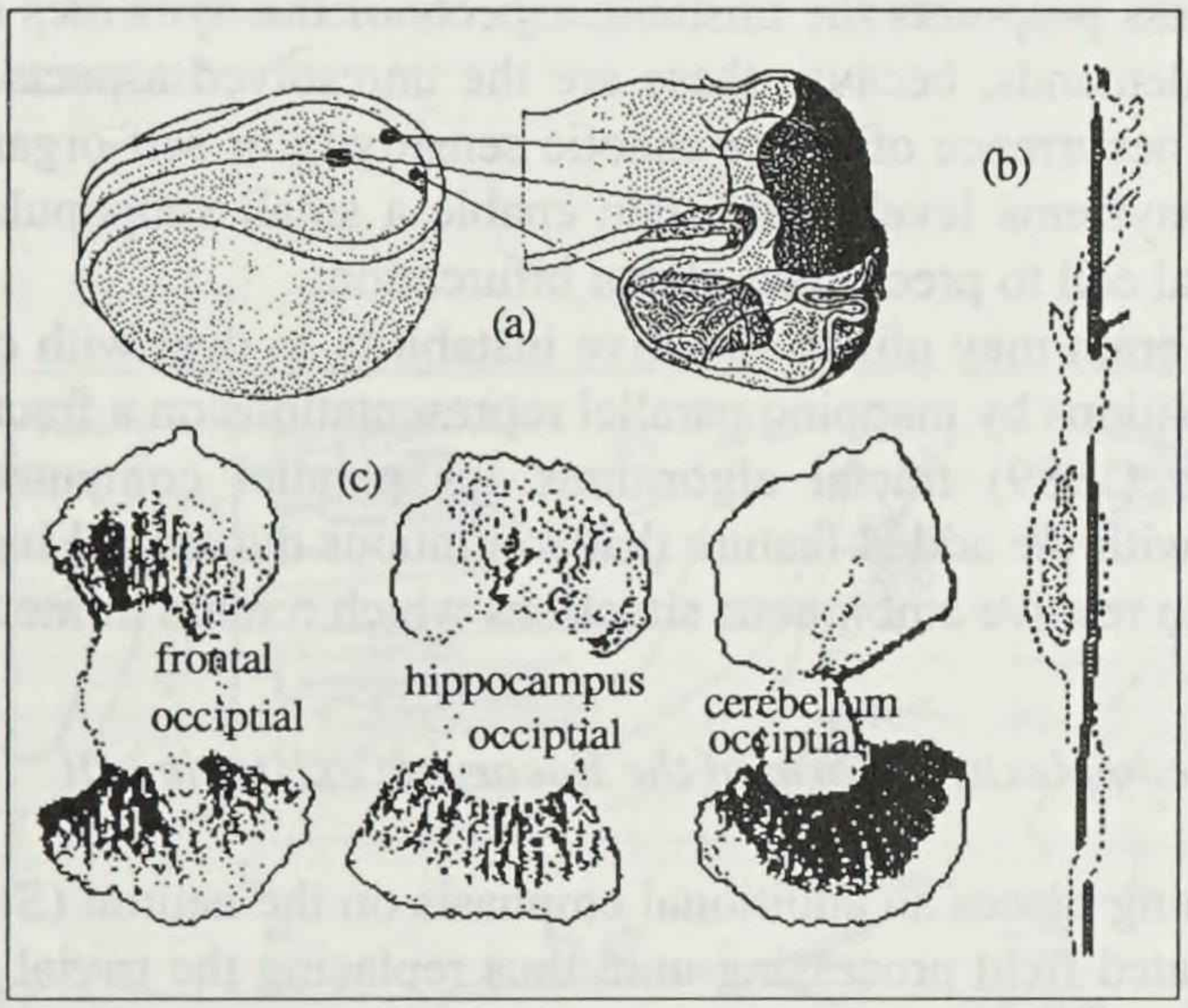


Figure 9: *Morphogenic and contact fields and bifurcations: (a) impact of position within primary morphogenic tissue bifurcations on the development of brain regions, (b) cell-adhesion properties of proteins such as CAMs enable migration of specific neuron types, both along the glial scaffold and to specific cell layers or target types, (c) Specificity of ascending optic fibres may be limited to a general affinity for cortex suggesting the form of cortical sensory architecture may be organized by input from sense organs and stimulation in early life, rather than genetic specificity alone (after Blakemore 1991).*

5. The fractal link between chaos and quantum mechanics

5.1. *The scale link between neurosystems and cellular dynamics*

The occurrence of chaos in neurosystem dynamics suggests that the brain may also utilize the fractal aspect of chaos as an intrinsic aspect of its processing, in combination with the natural scale transformations from organism to cell to molecule. The architecture of the central nervous system includes specific linkages between the level of whole neurosystems and the single cell. One is illustrated in Fig. 3(d) where a single hippocampal CA1 pyramidal cell has inputs from distinct brain regions, the sensoria and the reticular activating system via distinct neurotransmitters and distinct anatomical regions of the cell.

Such architecture permits a two-way interaction between large-scale neurosystems dynamics and that of single cells, which both enables large-scale bifurcations to alter the stability of single cells and for single cells to precipitate bifurcations at the neurosystems level. The utilization of instability to provide responsiveness pinpoints the unstable aspects of the dynamics at the center of processing demands, because these are the unresolved aspects of the internal model. The occurrence of either chaotic sensitivity or self-organized criticality at the neurosystems level could then enable a small subpopulation or even a single critical cell to precipitate global bifurcation.

The brain may utilize sensitive instability to deal with computationally difficult situations by mapping parallel representations on a fractal basis similar to Penrose's (1989) fractal algorithms for parallel computation (Dewdney 1989:141), with the added feature that continuous dynamical instability is used in addition to resolve ambiguous situations which remain intractable digitally.

5.2. *The complexity of form of the Eucaryote excitable cell*

Such reasoning places an additional emphasis on the neuron (Stevens 1989:17) as an integrated field processing unit, thus replacing the trivial formal neurons of McCulloch-Pitts, or optimizing analogue models such as the Hopfield net (Tank & Hopfield 1987:62) with a sophisticated integrated unit capable of chaos and unstable bifurcations. This is supported by the obvious complexity of typical central nervous neurons, with up to 100,000 synaptic junctions having a variety of anatomical forms (see Fig. 10c), unstable bifurcations across threshold, and other nonlinear features (Fig. 10a). On a descending series of scales, the cell is itself a physical fractal both structurally and functionally in terms of its dendritic and axonic trees, (b) and in terms of subcellular processing both across dendrites (d) and synapto-synaptic junctions (e). Despite the approximate conformity to linearity of neuronal conduction over a restricted range above threshold (a), the neuron also has pivotal features of self-organized criticality in the form of tuning to its threshold, sigmoid limit-cycle bifurcation at threshold, and chaotic dynamics as depicted by the Chay-Rinzel model. The sensitivity of sensory modules such as pressure organelles also displays nonlinear (quadratic) dynamics.

The fractal nature of dendritic and axonal trees provides the neuron with its second outstanding complex systems feature, which is that of a *fractal integral transform*. The capacity of the neuron to use its fractal structure to form many-to-many synaptic contacts lies at the foundation of its traditional role as a summation module. When organized in layers this permits a global

integral transform, leading to the formation of complex fields from simple ones in sensory processing. The combination of this architecture with oscillatory signals could generate a Fourier-type invertible transform which would permit the retrieval of previous structures in a form comparable to a hologram, consistent with phase decoherence dynamics in experimental studies of the cortex and hippocampus.

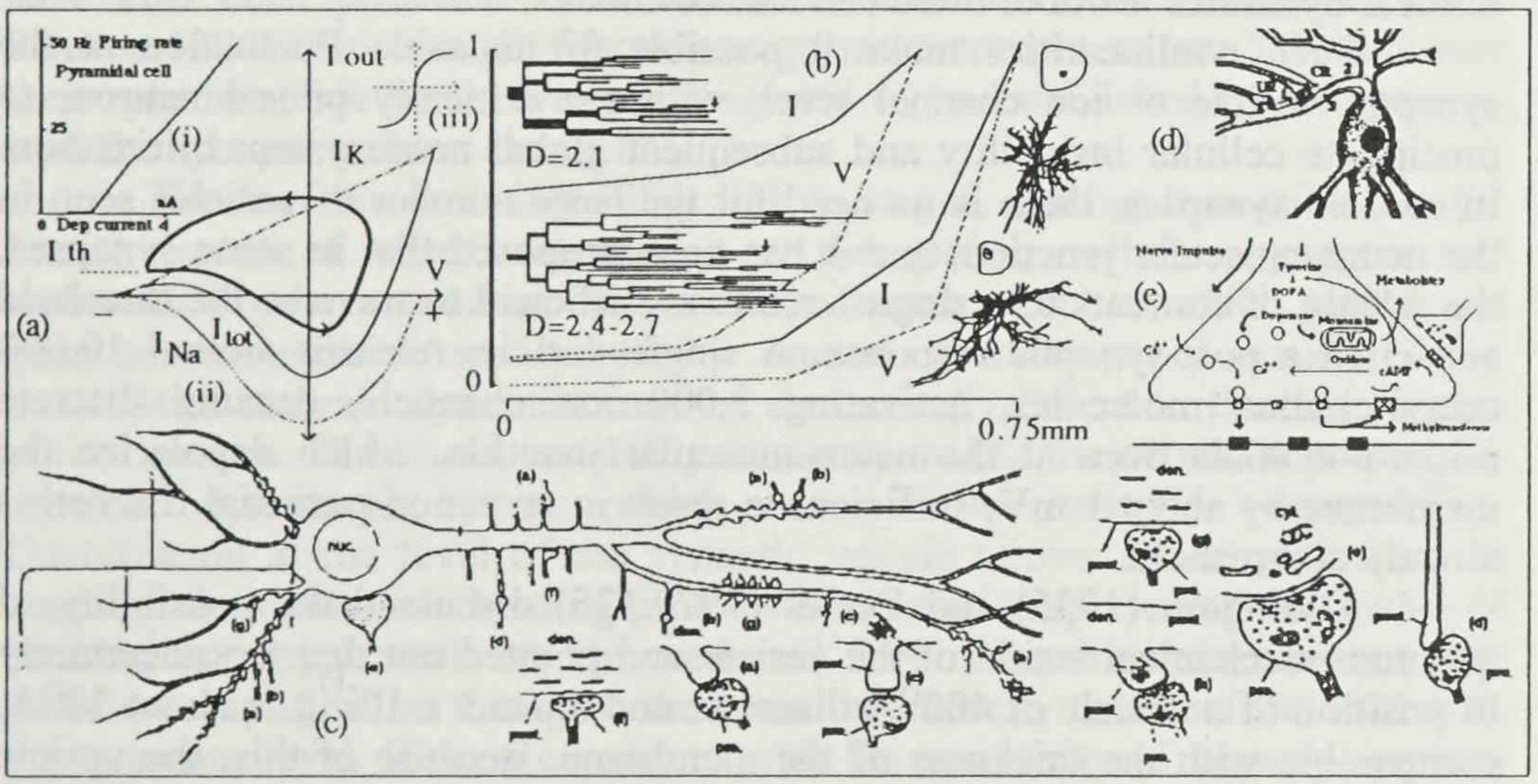


Figure 10: *Non-linear and fractal aspects of the neuron. (a) Non-linearities occur in formation of a limit cycle and excitation threshold (ii), despite approximate linear relation between depolarization current and firing rate in a limited range (i). Sigmoid transmission curve (iii) and mechanoreceptive bulbs also have a non-linear response. (b) Fractal structures of dendrites of two cell types and their electrodynamics (Schierwagen 1986). (c) The anatomical complexity of the neuron is illustrated by the structural variety of synaptic junctions, which also utilize distinct neurotransmitters. (d) Dendritic microcircuits and synapto-synaptic junctions (e) place the level of net organization one or two levels below the neuron. Synaptic conduction involves many feedbacks (e), some of which, including the two-molecule activation of the acetyl-choline ion channel have quadratic rather than linear concentration dynamics.*

Two characteristics of the neuron pivotal to a reassessment of its function are thus:

(a) Chaos and threshold self-organized criticality in non-linear dynamics;
(b) The *fractal integral transform*.

5.3. *The nonlinear synapse*

The fractal geometry of the neuron leads to an examination of the way cell organelles can provide a similar bridge between cellular and molecular dynamics. A variety of cell organelles provide a nonlinear basis for sub-cellular dynamics. The concentration dynamics of the synapse (see Fig. 10e) involves a rich diversity of feedbacks with nonlinear characteristics. Concentration dynamics is linear only for single molecule interactions, but critical ion channels such as the acetyl-choline channel require two molecules for activation, thus having quadratic dynamics. Synapto-synaptic junctions display bilinear dynamics. Both of these can lead to chaos.

Such nonlinearities make it possible for unstable fluctuation at the synaptic vesicle or ion channel level, within a critically poised neuron, to precipitate cellular instability and subsequent global neurosystem bifurcation. In cortical synapses, there is no need for the large number of vesicles seen in the neuro-muscular junction, and it has been proposed that in some synapses, the release of contents of a single vesicle is sufficient to traverse the threshold and elicit a post-synaptic response. A single vesicle, releases around 10,000 acetyl-choline molecules, activating 2,000 ion channels, causing discrete micro-potentials even at the neuro-muscular junction, which depolarize the membrane by about 1 mV, sufficient to result in an action potential if a cell is already at threshold.

Eddington (1935) and Eccles (1970:125) discussed the possibility of quantum-mechanical action of the vesicle and pointed out that the uncertainty of position of a vesicle of 400°A diameter and mass 3×10^{-17}g is about 30°A, comparable with the thickness of the membrane. Because of this, the vesicle can be regarded as a quantum object, which is at the same time capable of triggering cellular and hence global instability. The topological closure of the vesicle membrane results in the amplification of quantal instabilities from the level of the molecule to the larger level of the vesicle. The kinetics of vesicle association with the pre-synaptic membrane is determined by binding to one, or a few proteins, making vesicle release a function of the kinetics of one or a few molecules. The precise mechanism of vesicle exocytosis is not yet elucidated, but may involve the vesicle membrane protein synapsin I.

5.4. *The molecular level*

Activation of a single ion channel requires one or two neurotransmitter molecules. While the ion flux resulting from a single open ion channel will not generally elicit an action potential, if the channel happens to command a critical site on the two-dimensional dendritic surface, for example close to the cell body where the action potential begins, and the cell is at or near threshold,

then the single quantal encounter of a neurotransmitter binding to an ion channel could be capable of evoking an action potential. The fractal nature of ion channel kinetics finally allows for the interaction of molecular quantum excitations on a variety of fractal scales, constituting the quantum chaotic level of expression. Long-term potentiation associated with a receptor-kinase-membrane feedback (Alkon 1989:26; Winson 1990:42) is another kinetic process at the molecular level which permits a molecular change to trigger a distinct global history, however the determinate nature of memory makes it one of the less likely aspects of brain function to be subject to quantum instability. Membrane dynamics also involve piezo-electric interactions. Microtubules have also been proposed as molecular cellular automata (Hameroff 1987; Penrose 1994), which might function as quantum computers (see 7.5), however their role in active brain dynamics remains to be established by comparison with the synapse and ion channel.

The four levels of instability link in stages, making it possible for the fractal aspect of chaotic dynamics at the global, cellular, synaptic and molecular levels to combine to provide a fractal model in which global and quantum instabilities are linked by mutual interactions of scale. Global instabilities in brain dynamics may be dynamically-linked to fluctuation of a critical neuron. Threshold instability similarly makes the neuron a potentially unstable dynamical system which is open to synaptic perturbations. Quantization at the level of the synaptic vesicle allows for amplification of quantum fluctuations in binding proteins into vesicle rupture that is capable of eliciting micropotentials at the neuronal level. Sensitive dependence and quantum amplification thus give the brain the capacity to detect fluctuation at the quantum level. This is consistent with the sensitivity of sensory apparati which are all capable of detections at or close to the level of single quanta (see 7.1).

6. The evolutionary origins of fractal processing

It is one thing to establish the possibility that fluctuations at the quantum level could in principle become amplified into global instabilities in the brain, but quite another thing to explain why the brain should find it advantageous to allow such disordered processes to intervene in its functioning. Normally noise in a system is regarded as the anathema of computational precision, so an explanation is in order.

6.1. *The computational intractability of survival in the open environment*

The principal task of the brain of is to compute the survival strategy most likely to enable the organism to evade death and produce viable offspring. A

computational problem is intractable if the number of computational steps required grows super-exponentially with the complexity of the problem. The *traveling salesman* problem (Bern & Graham 1989:66), finding the shortest route round n cities illustrates this, growing with *(n-1)*! A problem may also be formally undecidable in the sense of Gödel. Many adaption-survival problems in the open environment share the characteristics of intractable problems, because each strategy tends to be matched by a competing strategy in another organism and the number of options rapidly exponentiates. An active organism must also complete a processing task within 0.1-1 second if it is going to have survival utility, regardless of its complexity. Such arguments make it clear why parallel processing is an integral feature of vertebrate nervous systems.

The fractal algorithm (Penrose 1989; Dewdney 1989:140), which in addition to parallelism, features fractal task assignment, shares significant features with biological processing. Including attractor dynamics with chaotic regimes in such a scheme provides additional features of sensitive dependence, phase space exploration, continuous resolution of instabilities, and the capacity to form new symbolic structures through bifurcation. It also provides a dynamic model for cognition in which bifurcation generates a series of symbolic structures, which become stable representations forming the successfully-modeled aspects of a problem. The complementary unstable component may continue to hunt through chaotic states, either bifurcating to stability, or forming a fractal instability which could in turn be perturbed by quantum instabilities.

6.2. *Chaotic excitability as a founding Eucaryote characteristic*

Chaotic excitability may originate deeper in evolutionary history, representing one of the oldest features of eucaryote cells (King 1978:27, 1990:16). The piezo-electric nature and high voltage gradient of the excitable membrane provides an excitable single cell with a generalized sense organ. Sensitive dependence would enable such a cell to gain feedback about the external environment, rather than becoming locked in a particular oscillatory mode. Excitation could be perturbed mechanically and chemically through acoustic or molecular interaction, and electromagnetically through photon absorption and the perturbations of the fluctuating fields generated by the excitations themselves. Such excitability would predate the computational role of neural nets, making chaos fundamental to the evolution of neuronal computing rather than vice versa. The chemical modifiers may have been precursors of the amine-based neurotransmitters which span acetyl-choline, serotonin,

catecholamines and the amino acids such as glutamate and GABA, several of which have a primal status chemically. The use of positive amines may have chemically complemented the negatively charged phosphate-based lipids (see Fig. 11) in modulating membrane excitability without requiring complex proteins. It is thus possible that chaotic excitation dates from as early a period as the genetic code itself and that the first eucaryote cells may have been excitable via direct electrochemical transfer from light energy, before enzyme-based metabolic pathways had developed.

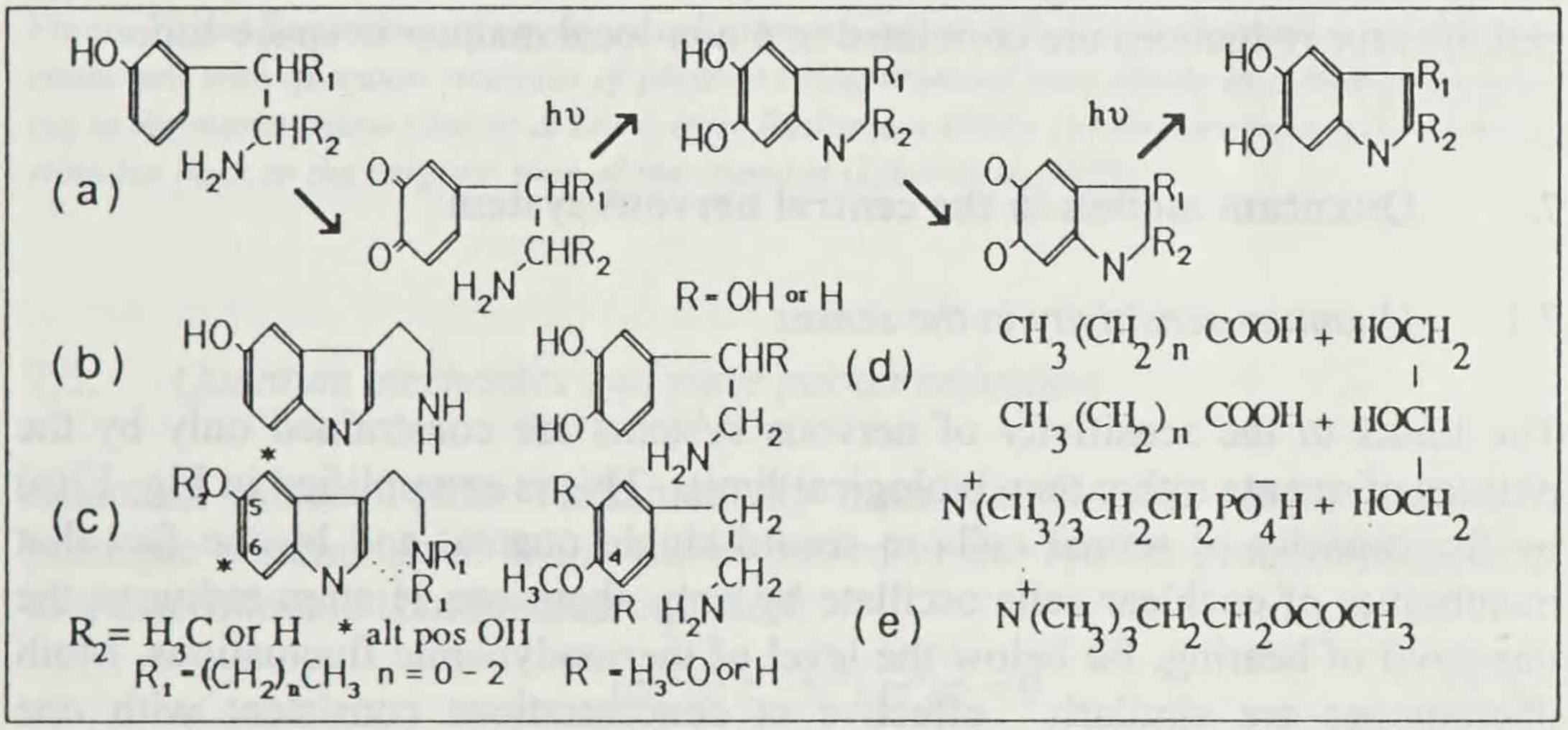


Figure 11: *Primal chemical aspects of neurotransmitters. (a) Primal uv-bridge between catecholamines and indoles. (b) Serotonin, Nor-adrenalin (R=OH) & Dopamine (R=H) and (c) their psychoactive variants are monoamines. (d) Acetyl-choline and (e) phosphatidyl-choline demonstrate a common tertiary amine involvement.*

6.3. *Consciousness as an evolutionary manifestation of chaotic neurodynamics*

From this perspective it is natural to postulate that, far from being an epiphenomenon, consciousness is a feature which as been elaborated and conserved by nervous systems because it has had unique survival value for the organism. We are thus led to an examination of how chaotic excitation may have evolved from single-celled animals through the early stages represented by *Hydra* to the complex nervous systems of metazoa. We have seen how chaotic excitation provides for exploration of phase space and sensitivity to internal and external fluctuations. However the conservation of consciousness

may also involve features expressed only by chaotic systems which are fractal to the quantum level.

It is a logical conclusion that the conscious brain has been selected by evolution because its biophysical properties provide access to an additional principle of predictivity not possessed by formal computational systems. One of the key strategies of survival is *anticipation* and *prediction* of events (King 1978:10; Llinàs (1987:339). Computational systems achieve this by a combination of deductive logic and heuristic calculation of contingent probabilities. However quantum non-locality may also provide another avenue for anticipation which might be effective even across the membrane of a single cell, if wave reductions are correlated in a non-local manner in space-time.

7. Quantum models in the central nervous system

7.1 *Quantum sensitivity in the senses*

The limits to the sensitivity of nervous systems are constrained only by the physics of quanta rather than biological limits. This is exemplified in Fig. 12(a) by the capacity of retinal cells to record single quanta, and by the fact that membranes of cochlear cells oscillate by only about one H atom radius at the threshold of hearing, far below the level of thermodynamic fluctuations. Moth pheromones are similarly effective at concentrations consistent with one molecule being active, as are the sensitivities of some olfactory mammals. The quantum uncertainty of the vesicle in relation to the membrane has also been noted above as a source of sensitivity of the synapse to quantum fluctuation.

7.2. *Sense modes as quantum modes*

The very distinct qualitative differences between vision, hearing, touch and smell do not appear to be paralleled in the similar patterns of electrical excitation evoked in their cortical areas. It is thus hard to see how the internal model of reality generates such different subjective modalities as the experiences of vision, smell and hearing from common electrochemical dynamics. One possibility is that the senses are generated in the internal model by the same quantum modes of sensory excitation, namely photons, phonons, membrane solitons and weak bonding interactions. If all these excitations can occur simultaneously in the membrane, its quantum-chaotic excitation could represent a form of cellular *synesthesia*, which is subsequently specialized in representing each individual sense mode.

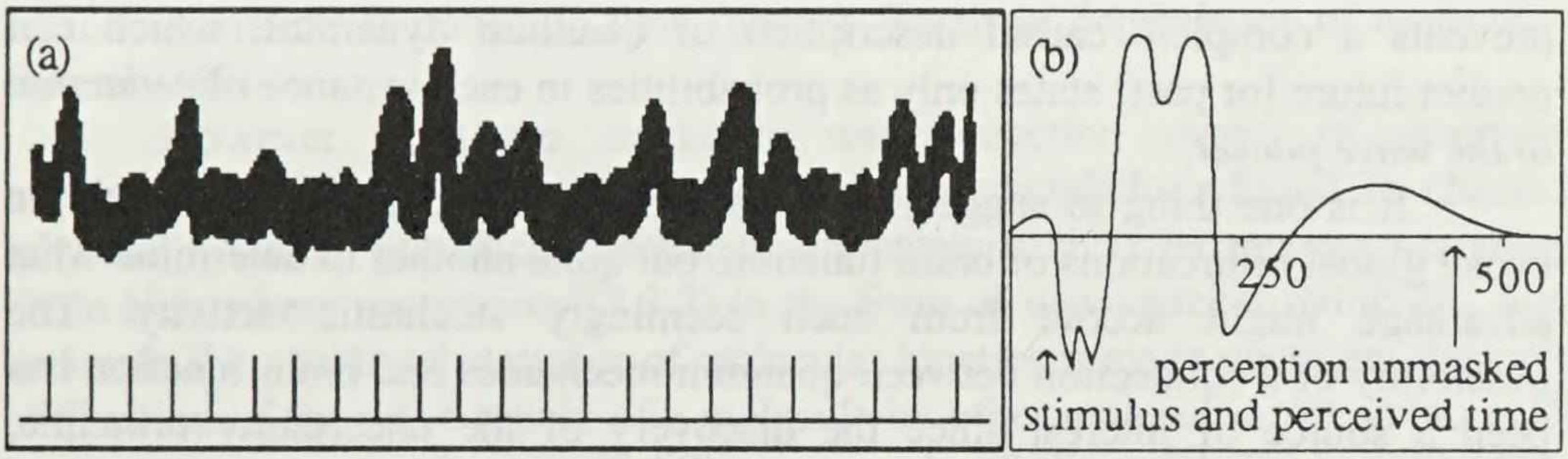


Figure 12: *(a) Excitations of single rod cells shows peaks with 0, 1, or 2 photons being registered, consistent with quantum statistics of photons being released very slowly at a rate corresponding to the marks below (Bailer & Lamb after Blakemore 1991). (b) Dereferencing of a perceived stimulus back to the original time of the stimulus (Libet* et al. *1979).*

7.3. *Quantum mechanics and wave packet reduction*

Quantum systems differ fundamentally from the classical case, which is in principle deterministic. While the evolution of the system proceeds according to a deterministic Hamiltonian equation:

$$(\partial^2/\partial t^2 - \nabla^2 + m^2)\varphi = 0 \qquad [7.3.1]$$

the measurement process, results in causality violations in which the probability interpretation

$$P = \varphi^* . \varphi \qquad [7.3.2]$$

constitutes the limits on our knowledge of the system. This results in a stochastic-causal model, in which measurement collapses the wave function from a superposition of possible states into one of these states. While quantum-mechanics predicts each event only as a probability, the universe appears to have a means to resolve each reduction of the wave-packet uniquely, which I will call the principle of choice. This is the subject of Schrödinger's famous cat paradox, in which quantum mechanics predicts a cat killed as a result of a quantum fluctuation is both alive and dead with certain probabilities, while we find it is only one: alive, or dead! The *stochastic-causal* processes of quantum mechanics violate causality because Heisenberg uncertainty

$$\Delta E \cdot \Delta t \sim \frac{h}{2\pi} \quad \Delta p_x \cdot \Delta x \sim \frac{h}{2\pi} \qquad [7.3.3]$$

prevents a complete causal description of quantum dynamics, which can predict future [or past] states only as probabilities in each instance of *reduction of the wave packet*.

It is one thing to suggest that quantum fluctuations could in principle evoke global bifurcations of brain function, but quite another to determine what advantage might accrue from such seemingly stochastic activity. The possibility of a connection between quantum mechanics and brain function has been a source of interest since the discovery of the uncertainty principle, because of its implications for consciousness and free-will, and several interesting models have been developed. The connection between the observer's mind and quantum mechanics is pivotal in some interpretations of wave function collapse.

7.4. *Quantum chaos versus uncertainty as substrates for classical chaos*

Repeated attempts to model a variety of quantum analogues of classical chaotic systems have revealed significant differences which may prevent the full display of chaotic dynamics in the quantum analogues. Two theoretical approaches have been mounted on a variety of transition systems. In the semi-classical approach (see Fig. 13b) point particles are replaced by wave packets whose trajectories are calculated to provide a simulation of the wave function (Tomsovic & Heller 1991:664). Complementing this are quantum wave function approaches, such as quenched quantum mechanics, and studies of the so-called *scarring* of some chaotic wave functions around the periodic orbits (Gutzwiller 1992:78), which are necessarily embedded in any chaotic system (a). A variety of systems have been explored experimentally from hydrogen atom in a magnetic field to particles such as electrons traversing a molecule or molecular medium (c).

The spreading of wave fronts results in some smoothing of the classical picture of chaotic mixing, including tunneling between trajectories, non-diffusive or time reversible dynamics, and the level repulsion between eigenvalues characteristic of the many-body dynamics of atomic nuclei. At the time of writing, verdicts on the capacity of quantum systems to fully exhibit chaos is still in flux, with some quantum systems, including magnetically excited atoms and electrons traversing molecular media appearing to display key features of chaos (Schuster 1986:209; Casati 1986:2437; Giesel 1989:2883; Wintgen & Honig 1989:1467; Zhang *et al.* 1990:3646; Peterson 1991:282; Uzer 1991:42). The electron traversing a molecule (Gutzwiller 1992:78) gives a simplified picture of chaos in molecular dynamics displaying

chaotic variation in transition time (phase). Sensitive dependence of molecular kinetics follows.

However it is the stochastic wave-reduction aspect of quantum mechanics which ultimately underpins the unpredictabilities found in chaotic physical systems. Statistical mechanics ultimately derives its random variation from Heisenberg uncertainty [7.3.3] in the form of wave-packet reduction. For example the positional statistics of molecular kinetics is made uncertain through diffraction of the wave aspect of a molecule by other molecules. An amino acid at room temperature has a self-diffraction angle of about 5° (King 1989:145), contributing initial condition uncertainty to each successive chaotic encounter (see Fig. 13c) when traversing a molecular medium. One of the important roles of classical chaos may thus be the amplification of quantum uncertainty into macroscopic indeterminacy. Sensitive-dependence in physical systems may thus result in *quantum inflation*, the amplification of quantum fluctuation into global perturbations of the dynamic. The distributed nature of wave reduction over the eigenspace may thus link to the ergodicity of chaotic systems.

7.5. *Quantum concepts in brain function*

Bohm's work on the Einstein-Podolsky-Rosen conjecture, Bell's theorem and the Aspect experiments (Clauser & Shimony 1978; Aspect *et al.* 1982) which display spin-correlations between a split photon pair over space-like intervals have demonstrated that hidden variable theories cannot be locally causal, leading several researchers to postulate the idea of non-local states correlating the activity of various parts of the brain (Penrose 1987).

Interest in quantum concepts in brain function has had a considerable history starting from Eddington (1935), and continuing with Eccles (1970:125). Basar (1983) has suggested matrix theory and Feynman diagram approaches (Stowell *et al.* 1989:482) to resonances at the neurosystems level. Eccles (1970:125) and Margenau (1984:72) have also discussed the possibility of quantum reduction being dependent on the mind of the observer, leading to the paradox of Wigner's friend in which an observer's friend splits the wave function, and reports on the result. Multiple minds thus lead to ambiguities of splitting. One way around this paradox is to require mind to be a unity rather than a multiplicity removing the ambiguity of the reduction point, another is that the first conscious observer in the chain collapses the wave function. Recent studies using down-converters demonstrate that the possibility of gaining information about a photon's path collapses the wave function and that such knowledge can be erased to regenerate a coherent wave (Horgan 1992:94).

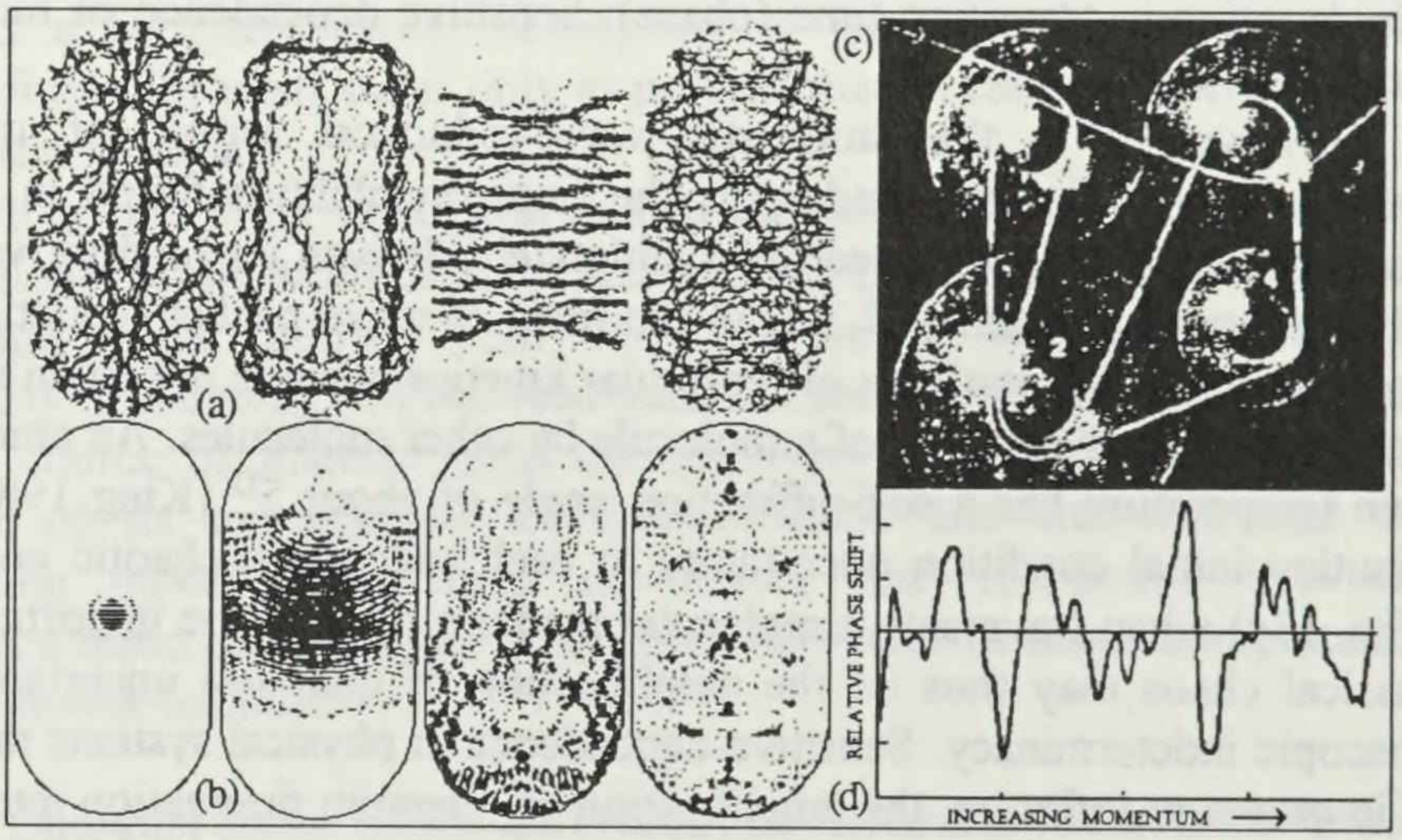


Figure 13: *The quantum stadium represented (a) by quantum wave functions displays scarring of several wave functions around embedded periodic solutions (Gutzwiller 1992), (b) semi-classical approach provides a close approximation using a finite number of periodic solutions at least for some stages (Tomsovic & Heller 1991), (c) electron traversing a molecule has continuous variation of time (phase) with chaotic irregularity (Gutzwiller 1992).*

Deutsch (1985:97) has analyzed the potentialities of a quantum computer, which has a fuzzy logic representing quantum superposition of states to form a probability function in the interval [0,1] in place of the usual {0,1} = {T,F} of formal logic. Although the algorithmic capacity of such a quantum computer does not extend the class of functions computable by a conventional Turing machine, several specific instances have been given in which a quantum computer might solve special tasks more efficiently (Lockwood 1989:240). These do not appear to provide significant advantages over parallel distributed processing.[1] Both these authors adhere to the Everett many-worlds interpretation of quantum mechanics in which the collapse of the wave function never occurs, and all histories having a non-zero probability under the quantum prediction are presumed to co-exist as parallel aspects of a cosmic wave function. This bypasses the Schrödinger cat paradox, however it contradicts the evidence of our conscious sensory processes, which in common with physical measuring apparati, experience a single historical process. Collapse of the wave function also appears to be the aspect of quantum mechanics which underlies the indeterminacy of chaotic systems.

The mathematician Roger Penrose (1986, 1989, 1994) has also studied the relation between the conscious brain and quantum physics and attempted to combine quantum theoretic and relativistic ideas. He has suggested that collapse of the wave function may be a deterministic process based on the interaction of the superimposed wave function with the gravitational field, thus having parallels to decoherence theories (Zurek 1991:36).

7.6. *The supercausal model*

A final model (King 1989), which also combines quantum theory and relativity, develops a supercausal hidden-variable theory which is consistent with conventional quantum mechanics, but allows for correlations between quantum events over both space and time, replacing the stochasticity of the quantum model with a transcausal description, which is non-local in space-time. The temporal ordering of causal events is thus violated below the quantum level by space-time symmetric interactions. This description prevents determination of a system from initial conditions, because the non-local correlations include future states of the system. It is based on the transactional interpretation of special-relativistic quantum mechanics.

The relativistic energy-momentum equation

$$E^2 = p^2 + m^2 \qquad [7.6.1]$$

has dual energy solutions

$$E^2 = \pm\sqrt{p^2 + m^2} \qquad [7.6.2]$$

in which the negative energy solution has reversed temporal behavior in space-time.

This is consistent with Feynman diagrams in which a particle traveling in the usual (*retarded*) direction can be equated with its anti-particle in the time-reversed (*advanced*) state. This fact allowed Dirac to predict the existence of the positron from the negative energy solutions to the electron wave equation.

As a simple example, the Hamiltonian equation [7.3.1] for a zero spin particle with mass m has elementary solutions:

$$\varphi_{+,k} = (2\pi)^{-3/2}\ e^{i(k.x - \omega t)} \qquad [7.6.3a]$$

$$\varphi_{-,k} = (2\pi)^{-3/2}\ e^{i(k.x-\omega t)} \qquad [7.6.3b]$$

where

$$\omega = (k^2 + m^2)^{1/2} \qquad [7.6.4]$$

One solution travels in each direction in space-time, forming distinct retarded and advanced solutions. For a photon which is its own anti-particle, these reduce to the offer and confirmation waves of the emission and absorption foci. In the Feynman diagram Fig. 14(a), the force between electrons is determined by integrating all possible virtual photon and higher-order interactions (b). The photon is virtual because it exists only for an interval consistent with the uncertainty relations [7.3.3], and is detected only by its secondary effects in the electric field. While in virtual exchange, all possible exchanged photons are summed, in the case of a real exchanged photon, the boundary condition that only one real photon is exchanged, forces reduction of the packet of all possible such exchanges to one real exchange. Time reversal is standard in Feynman diagrams, a time-reversed electron being equivalent to a positron (d).

Such time-reversal is used in the transactional interpretation of quantum mechanics (Cramer 1986:647) (see Fig. 14c), a mutual encounter between emitter and absorber is modeled by the release of crossed-phase advanced and retarded waves, each having zero-energy, the *offer* wave of the emitter and the *confirmation* wave of the absorber. While the retarded offer wave travels with elapsing time in the usual manner, the advanced confirmation wave, back-propagates in a time-reversing manner from the absorber to the earlier emission event. The mutual interference of these advanced and retarded waves produces a real superposition (the photon) between the emission and absorption events in space-time.

Modeling reduction of the wave packet now depends on the mutual interaction of all contingent emitters and absorbers as in (e), on the basis that a photon can only be created linking the two events and cannot simply disappear into space, following Feynman's absorber theory (Davies 1974:130). This means that the probability distribution is determined by boundary conditions which include all contingent absorbers which could have alternatively participated in the emission event (f). However, because these include future states which have not been causally determined, a logical regress results, leading to paradox in terms of temporal determinism. Transactions can also link contingent foci across both time-like and space-like intervals by linking confirmation waves at any particular emission vertex, regardless of the proper time interval to the contingent absorbers, e.g., cA1 and cA2 in Fig. 14(e), explaining the pair-splitting experiments of Aspect *et al*. (1982:1804).

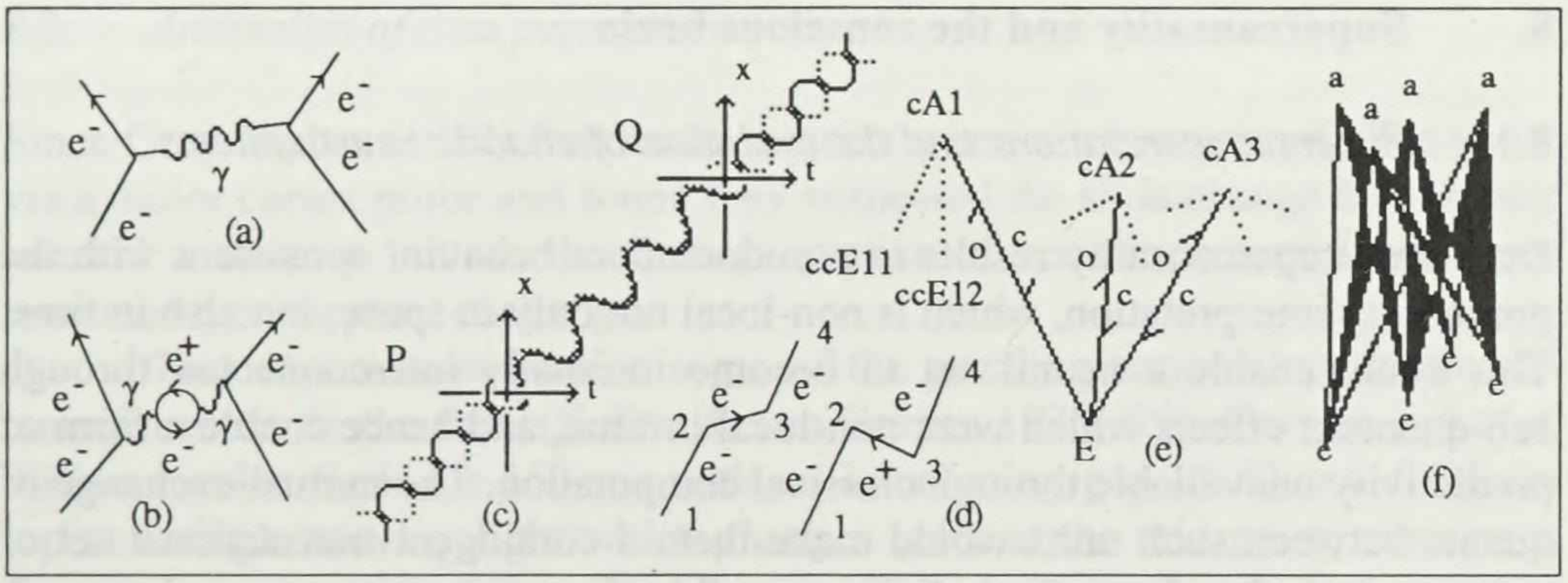


Figure 14: *(a) Feynman diagram of exchange of a photon (b) higher-order diagram. (c) One-photon transaction involves interfering offer and confirmation waves. (d) Electron deflection and positron creation and annihilation. The time-reversed electron is a positron. (e) Contingent emitters and absorbers as boundary of collapse. (f) Spliced reduction interactions.*

One way of modeling transactional collapse is via a bifurcation of a nonlinear interaction between all contingent foci, however the time parameter in any such bifurcation has to be handled very carefully. Whether or not collapse results from a nonlinearity in gravitation as suggested by Penrose (1989, 1994), the space-time boundary constraints are inconsistent with the usual idea of temporal causality defined by initial conditions and Laplacian determinism.

Transactional collapse is also consistent with quantum decoherence models, which include incidental collapse caused by field and thermal excitations (Zurek 1991:36). Although decoherence has the effect of breaking a transactional contingent set into a class of smaller sets linked by emission and absorption foci, similar to higher-order Feynman diagrams, it does not alter the supercausal properties of transactional reduction, enfolding the 'implicate order' (Bohm 1980) of quantum non-locality without disruption. Thus similar space-time properties apply to kinetic molecular systems with many thermodynamic and other quantum interactions between production of an intermediate and its reaction.

8. Supercausality and the conscious brain

8.1. *Superset correlations and the evolution of chaotic neurosystems*

Dual-time supercausality results in pseudorandom behavior consistent with the probability interpretation, which is non-local not only in space, but also in time. This could enable a neural net to become internally interconnected through sub-quantum effects which were non-local in time, and hence enable a form of predictivity unavailable through classical computation. The mutual exchange of quanta between such units would make them a contingent transactional set of emitters and absorbers. Such linkage could arise via excitons, or photon or phonon exchange. The cell membrane topology forms a global link between its quanta of excitability, making such linkages possible also in the single cell. A variety of excitons, including the major oscillations of the EEG could also form a basis for neurosystems linkage in the brain. The many-to-many transform nature of the neuron may provide a basis for this effect through the connection of any given state to a large population of neurons in the cortex.

An excitable cell or neurosystem which evolved initially to achieve constrained optimization through chaotic fluctuation, could thus also display a new type of predictive modeling through non-local quantum interactions. Predictive optimization may thus have driven the evolution of the excitable cell and subsequently a structurally-unstable chaotic brain in which consciousness and free-will become direct manifestations of the quantum non-locality underlying membrane and brain-function.

This view combines a *reductionist* approach, in which biological phenomena are reduced to chemical and finally physical models, with a new emphasis on quantum physics as the limit of a fractal process. A component of *panpsychism* is included in the physical description, in which consciousness can be associated with a real quantum by virtue of the uncertainty arising from its wave-particle duality. *Sentience* is the capacity of the emitter to utilize the confirmation waves of contingent absorbers in wave-packet reduction, while *free-will or intent* is the uniqueness implied by the *principle of choice*. *Emergentism*, the capacity of a system to be more than the sum of its parts, is also present, because the time-symmetric subquantum associations in the model are developed as a result of the large number of units in a parallel net which can become transactionally related as mutual conditional emitters and absorbers. This gives the brain a degree of cooperative uncertainty which is lacking in a single quantum. *Free-will* raises possibilities that the mind can at least in some ways alter the future states of the universe. The limits of such possibilities remain to be established.

8.2. *Anomalies of time perception*

Since Grey-Walter (1962) first made subjects witness movement of slide show via a motor cortex probe and found they witnessed the slide change *before* they pressed a dummy button, the time properties of conscious experience have remained a conceptual challenge.

Two experiments outline some of the puzzling temporal properties of consciousness. In the first, (Kolers & von Grunau 1976:329) alternate lights of different color flash for 150 ms with an intervening gap of 50 ms. Subjects report a single moving light which changes color at the mid point, even on a first exposure, or random color change. This creates an apparent paradox because the color change apparently occurs *before* the second light has come on.

In a second class of experiment (Libet *et al*. 1979:193), which has been the subject of repeated discussion (Libet 1985a:529, 1985b:563, 1987:783, 1989:183; Churchland 1981a:165, 1981b:492; Honderich 1984:115; Snyder 1988:253) involves the subjective timing of stimulation of one hand (say the left, which excites the right somatosensory area) at the same time as direct stimulation of the opposite (left) finger somatosensory area. The genuine hand-tingle is perceived *before* the cortically induced one even if it actually occurred afterwards. Because of the considerable delay for the development of neuronal adequacy for the conscious experience (200-500ms) the time of the experience appears to be referred back to the primary evoked potential (10-20ms after stimulus) (see Fig. 12b).

Although this referral can be explained as a construct of the internal model, similar to spatial representations which are subjectively 'out there', temporal projection comes close to causal paradox. Libet (1979:193) suggests "a dissociation between the timings of the corresponding 'mental' and 'physical' events would seem to raise serious though not insurmountable difficulties for the [...] theory of psychoneural identity". Penrose (1989) "suggested that a materialistic explanation of Libet's phenomena would require a revolution in fundamental physics" (Dennett 1991:156). "This antedating procedure does not seem to be explicable by any neurophysiological process [...] [but is] attributable to the ability of the self-conscious mind to make slight temporal adjustments, i.e., to play tricks with time." (Dennett 1991:156).

Dennett (1991:139) explains such features by looping of the subjective time sequence out of the physical sequence. The order of consciously perceived events does not have to be coincident with the physical or apparent physiological order when parallel processing builds up a global model of a time sequence. The order in which constructs become established may be arbitrary, within the space-time constraints of a large parallel device, but the completed

construct will nevertheless represent the sequence of the original, perhaps modified by simplifying assumptions of the internal model. This approach suggests however that the completed representation cannot be formed until *after* the sequence ends, (e.g., until both the red and green lights have flashed and not half-way across), and may require editing of the partial constructs of the model either prior or subsequently to their registration.

Further experiments are required. The supercausal model was constructed to deal with the causal paradox of free-will but could apply also to these examples. Observational difficulties make the issue similar to the problems of quantum measurement. One difficulty is pinpointing the time of subconscious origin of a response which results in a button press or a verbal signal. Another is that comparing the absolute times of stimuli and neurophysiological events with those of perceived conscious events ('it happened when the hand was at 2') involves comparing the 'representing and represented' states (Dennett 1991).

8.3. *Supercausality and the representation of time in the cortex*

One particularly interesting idea is that time is represented in the same distributed and holographic manner that other modalities are. The relationship between the frontal lobes and the rest of the cortex appears to involve representations of activities integrating future states (intentions) into time-directed actions based on past experiences (memories). The frontal lobes generalize motor acts into associations in a similar manner to the sensory association areas in the rest of the cortex. Thus the frontal cortex may generate a spatially distributed representation of time in terms of the organization of both remembered and planned actions spanning the past and future, utilizing oscillatory phase relations as seen in EEG and evoked potential studies, possibly in the 40Hz mode suggested by Crick & Koch (1990). Coherent oscillations would link by Hebbian coincidentality. Both short-term working memory and the long-term consolidation of the limbic system may thus form part of a transform representation of time.

Subjective time may thus be an internal model whose basis is quite different from mechanical notions of linear time, partly because it requires integrated representation of past memorizations and learning with future plans and survival strategies. It is easy to see that visual perception constructs an external spatial reality but more difficult to accept the possibility that time is similarly an internal construct. What may be even more difficult to accept is that the subjective notion of free-will or intent arises because the function of consciousness is to *anticipate*, forming an 'ill posed' problem in time.

A holographic representation of time generated by the frontal cortex and limbic system thus provides a possible realization of the supercausal model. The central task of the brain is the representation of the activity of the organism in terms of both past and future temporal dynamics. While the past is based predominantly on memory, the future, representing the organism's survival strategy, may be based on complementary principles of computation and predictivity, utilizing both attractor-based computation and access to quantum non-locality. The modal oscillations in such a holographic representation are time-symmetric in the sense that the beats of phase coherence measure only a circular phase-shift and not a direction. This is exactly the same act that is required in quantum measurement to determine the uncertainty relations, since counting beats to determine frequency and wavelength requires a time or distance determined by the uncertainty relations [7.3.3]. It thus raises the rather odd specter that cortical oscillations and their corresponding mental states may be inflated quanta reverberating through the brain. It also suggests that the subjective notion of the present may be an extended *quantum of the present*, forming a reverberating envelope of past and future states.

Solving the problem of temporal representation is central to understanding the nature of attention, consciousness, and will, both because of the causal paradox implied by will, and because the problem of the 'ghost in the machine' is essentially a problem of how the temporal dynamics of attention are organized. Enclosing this ghost of attention within the quantum of the present carries the paradox into the causality-violating arena of sub-quantum physics.

8.4. *The experiencing totality*

Although normal waking experience has a reasonable correspondence to our concept of physical reality, the experiences of dreaming and other reflexive states such as hypnogogic and meditative trance, psychotropic hallucinations and near-death experiences, which transcend correspondence to the physical world, raise fundamental questions concerning the relation between the mind and the physical world. Dreaming is one of the most outstanding of these non-collective conscious states. It is one which we are all aware of, and one whose intensity, in cases of good recollection, parallels, or even exceeds that of sense experience of the 'real world'. Dreaming has definite correlates in central nervous activity in the REM phases of sleep, originally called *paradoxical* because of the appearance of internal waking arousal, illustrated in the EEG's

and PET scans of Fig. 4, contrasting with the slow wave activity of deep sleep. The unusual properties of such states suggest that the more esoteric aspects of mind, which I will term *dreaming*, may contain deeper clues to its underlying nature beyond physical correspondence. In such a dual model, mind is more fundamental to reality than merely a physical internal model, a complementary principle to physical reality, emerging physically through indeterminacy.

The concept of a dual totality in which mind and universe are primary components raises further deep issues. While it may not be possible to describe mind from the point of view of physical world constructs alone, it *is* possible to describe the physical world as stability properties of conscious experience. Similarly, although our model of the physical world is inferential, our conscious experience from birth to death is direct and undeniable. It is thus possible to mount an alternative description of reality in which mind is primary and fundamental and the physical world is merely a stability structure of mind, as is central to the Indian philosophy of mind. The link between chance, living organisms and consciousness is also central to the Chinese oracle *I Ching* (Wilhelm 1951:263) in which these three are regarded as joint manifestations of a unifying predictive cosmic principle.

The status of such reflexive conscious states as dreaming may thus represent one of the greatest enigmas of scientific inquiry, because it is here that the temporal paradoxes described enter into unstable self-feedback without direct input from the external world. Dreaming is traditionally viewed as an illusory or hallucinatory invention of the mind, functioning either in the release of psychological tensions, or as a subjective manifestation of neural processing during sleep, possibly in the consolidation of long-term memories (Koukkou & Lehmann 1983:225; Winson 1990:42), or even to forget as Francis Crick has suggested. Although true REM sleep appears to be a mammalian trait, there is evidence for a paralysis phase of sleep in animals spanning the arthropods and vertebrates. Although dreams presumably do serve a physiological function, as evidenced by metabolic compensation after periods of deprivation, the origin of the content of dreaming remains obscure.

Complementing physiological studies of dreaming is a parallel stream of literature addressing the possibility that dreaming has unusual space-time properties, associated as much with future as with past experiences (Dunne 1935). Although the significance of dreaming in Western culture has concentrated on the symbolism of dreaming as an expression of fears and aspirations in daily life and its analysis as a means of therapy, reference to dreaming in other cultures, such as Australian aborigines, and the *Senoi* of Malaysia includes the use of dreams to anticipate future problems and events,

and is based on the concept that the dreaming state is another level of conscious reality, which is not an illusory representation of the 'real world', but is rather a mode of conscious existence in its own right. I have had many personal dreaming experiences which attest to such temporal properties of dreaming, including having a double dream of being stung, reporting the dream to my wife and an hour later being stung wide awake in bed.

Similar accounts occur in societies, such as the *Huichols* and *Mazatecs* of Mexico and the Amazonian *Cashinahua*, *Shipibo*, *Jivaro*, etc., where plants or fungi are taken to induce hallucinatory trance states during shamanic rites. Five aspects of these states have been noted by anthropologists: geometrical illusions, visions of animals and demons, the separation of the mind from the physical body, clairvoyant visions of distant places, and divination of past or future events (Harner 1973). "On the day following one *ayahuasca* party, six of nine men informed me of seeing the death of my 'chai', my mother's father. This occurred two days before I was informed by radio of his death" (Harner 1973:12).[2]

The apparent capacity of people, in near-death experiences to have perceptions of their surroundings from another physical position (out of their body) invites further questions concerning the physical location of consciousness, particularly when they (occasionally) report accurate details they could not have witnessed from their physical position, such as the patient who correctly perceived a discarded shoe on a ledge three floors above the room where she had cardiac arrest (Groff 1988).

In what I would loosely describe the *Sorcerer's Explanation*, the *dreaming* aspect of reality underlies the physical so that the waking experience of the physical world is just one manifestation of a wider *dreaming totality*, rather than *vice versa*. Castaneda (1976) in his many allegories, discusses the *technique of dreaming* in which the dreaming and waking state are connected by *intent* so that dreamer can gain control. The technique involves picking some simple action that the dreamer will perform as an act of volition to assume temporary command of their will, and check the onrush of dreaming attention. For example the act of looking at the backs of one's hands while in the dream. This technique is paralleled in Stephen LaBerge's (1985, 1990:78) research into *lucid dreaming* (Blackmore 1990:373), in which the subject learns to make a variety of reality tests of the dreaming state by combining waking practice tests with setting intent during the sleep phase. These are complemented by waking techniques such as looking for the gaps (see 1.4.3) in conscious experience, *stopping the internal dialogue and stalking* (Abelar 1992:XIII).

The empirical investigation of such reflexive conscious states constitutes the best hope we have for discovering the foundations of the mind-

brain relationship. While research is dominated by clinical tinkering with the brain from outside, a comprehensive description will continue to elude society. Thus balancing the pictures gained by brain lesions, EEG studies and PET scans should be an emphasis on pure consciousness research, combining scientific techniques with the traditional means used by societies throughout history, namely meditative and shamanic trance, the use of power plants and dreaming techniques. Several of these have been largely ignored as unscientific, or prohibited as dangerous to consumer society because of their very capacity to induce fractal or chaotic conscious states, thus setting back by decades society's development of an understanding of the mind-brain relationship. Complementing such traditional techniques are new devices emerging from brain research laboratories. One valuable such device is the *Dream Light* developed by LaBerge (1990:78) from research studies on dreaming EEGs, which detects REM periods and alerts the subject by a flashing light or acoustic signal. Such devices can help to bring the relatively uncharted and inaccessible realms of consciousness into the scientific arena.

9. The cosmological perspective

The brain may be one of the few places where the *supercausal* aspect of wave-packet reduction can be clearly manifest, as a result of its unique capacity to utilize correlations in its dynamics. Although other unstable systems such as the weather may also display such features of non-locality, it is difficult to think of a physical experiment which could in any way match the brain as a detector of correlations within the stochastic model of quantum mechanics. In this respect it should be noted that cosmology is not simply a matter of vast energies, but also quantum rules. The diversity of wave-particles resulting from symmetry-breaking of the fundamental forces finds its final interactional complexity, in which all forces have a common asymmetric mode of expression, in complex molecular systems. It is thus natural that fundamental principles of their quantum interaction may be ultimately realized in the most delicate and complex molecular systems known — those of brain dynamics.

10. Conclusion

The importance of developing a model of brain function which gives a consistent description of mind, consciousness and free-will, is profound. The model described links the structural instability of brain dynamics, quantum uncertainty and the dual-time model. The quantum-physical brain may thus be more than just an interface between sensory input and decision-making. It may

in fact be a doorway between complementary aspects of the physical universe, the time-directed nature of real-particle symmetry-breaking and the time-symmetric aspect of the sub-quantum domain (King 1989:128). If so, the role of consciousness and mind-brain duality may be central to cosmology.

Notes

1. An interesting new application of quantum computing to cryptography has recently been announced by Shor (cf. *New Scientist*, September 24, 1994).

2. The mushroom shamaness Maria Sabina avowed:

> The more you go inside the world of *teonanacatl* the more things are seen. And you also see our past and our future, which are there together as a single thing already achieved, already happened [...]. Millions of things I saw and knew. I knew and saw God: an immense clock that ticks, the spheres that go slowly around, and inside the stars, the earth, the entire universe, the day and the night, the cry and the smile, the happiness and the pain. He who knows to the end the secret of *teonanacatl* can even see that infinite clockwork. (Schultes 1979; Guzman *et al.* 1991:93)

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The Fractal Maximum-Power Evolution of Brain, Consciousness, and Mind

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1. A fractal interpretation of Einstein's concept of thinking

Albert Einstein believed that the whole of science and mathematics was "nothing more than the refinement of everyday thinking" (Einstein 1954:290). Einstein knew that an understanding of the nature of everyday thought patterns was absolutely fundamental to the scientific development of the physical world-picture. Early in his *Autobiographical Notes* (Einstein 1949) he felt compelled to bring up the topic, and to describe introspectively the flow or unfolding of thought processes he felt were central to his own accomplishments as a scientist:

> What, precisely, is 'thinking'? When at the reception of sense-impressions, memory-pictures emerge, this is not yet 'thinking'. And when such pictures form series, each member of which calls forth another, this, too, is not yet 'thinking'. When, however, a certain picture turns up in many such series, then — precisely through such return — it becomes an ordering element for such series, in that it connects series which in themselves are unconnected. Such an element becomes an instrument, a concept. I think that the transition from free association or 'dreaming' to thinking is characterized by the more or less dominating role which the 'concept' plays in it. It is by no means necessary that a concept must be connected with a sensorily cognizable and reproducible sign (word); but when this is the case thinking becomes by means of that fact communicable. (Einstein 1949:7)

Einstein felt that the key dynamic in *thinking* was the recurrence of a connecting picture or concept that brings order to our sensory experience. For simplicity we might visualize Einstein's account as follows: First, there are several strips of motion-picture film with self-similar frames each calling forth the next frame, but he says, this is not yet thinking. Next, a particular frame turns up in many of the strips, thus connecting them all in the formation of a concept; *this*, he says, is thinking.

Einstein's description of his own thought process has many things in common with the features of fractals, for example, fractal self-similarity, recursion, and self-referentiality are clearly evident. In reading through Einstein's account, we can easily imagine a motion-picture film of a computer generated journey through the complex plane of the widely familiar Mandelbrot fractal set (see, for example, Dewdney 1985). Figure 1 shows a portion of the Mandelbrot set with the parent, snowman-like "Mandelbrot" in the center, and self-similar (not self-same) miniature Mandelbrots sprouting everywhere.

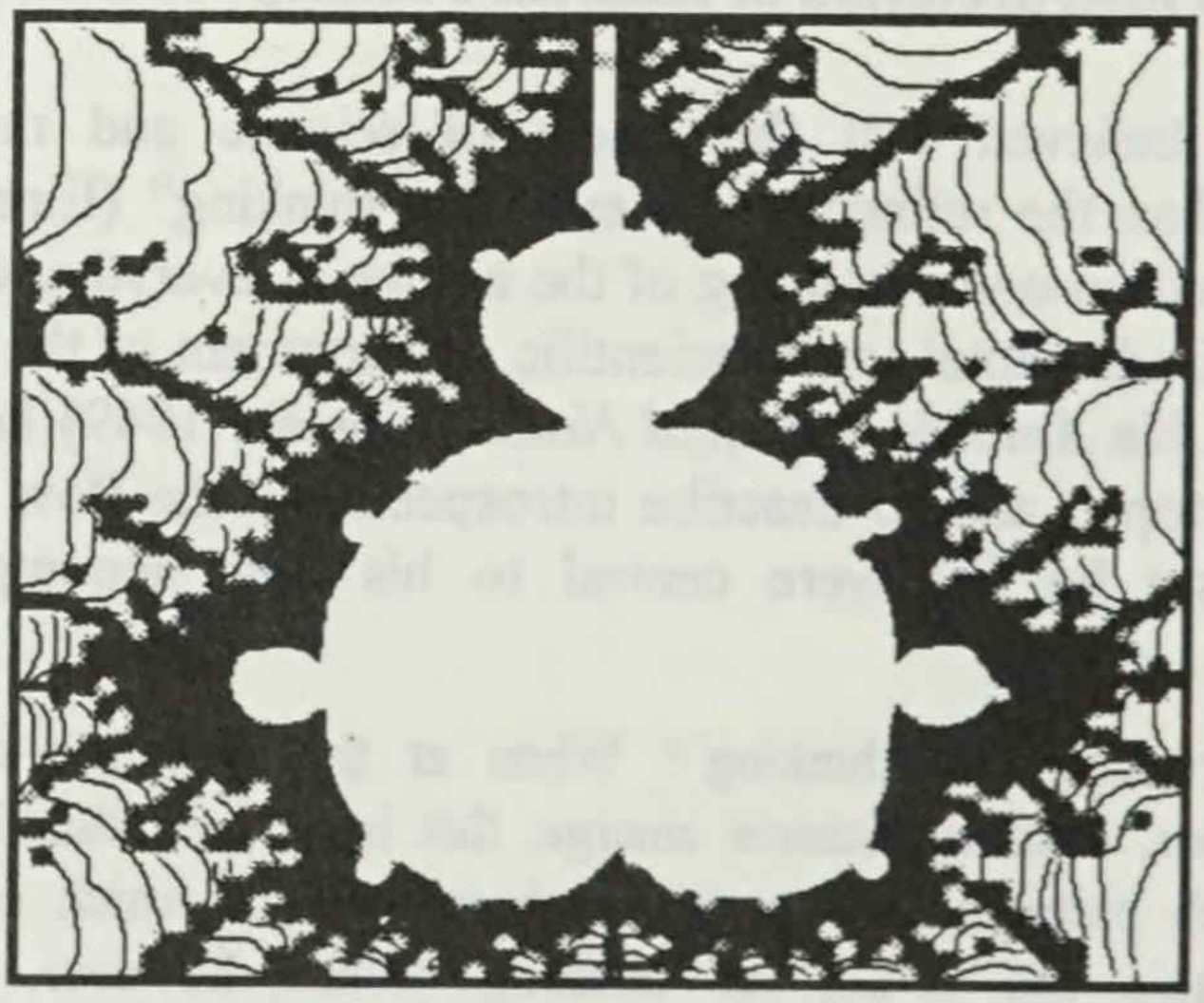


Figure 1: *Portrait of portion of Mandelbrot fractal set depicting a parent snowman-like 'Mandelbrot' with miniature Mandelbrots sprouting everywhere. This portrait is an abstract fractal object inhabiting a time-space (phase space). Compare with the living fractal structure in Figure 5.*

The recurrence of the self-similar Mandelbrots takes on the role of Einstein's 'certain picture' that turns up in many series connecting them together. When applied to brain processes the unfolding of nonlinear fractal

sets such as this helps explain why a certain picture would recur in the brain *at all*. Einstein would not have known in his day that *all* of the elements in his series might be connected by fine filaments, as are the parent and miniature Mandelbrots, thus actually allowing his connections to come into being in his mind. Einstein also may not have noticed that the organizing picture that turns up is, like the rest of the elements in the Series, *itself* only *self-similar* (not exactly the same image) upon each of its recurrences or recursions. At any rate we can liken the snowman-like Mandelbrot to the concept or 'certain picture' that Einstein says turns up, thus connecting everything and coming to play the dominating role in thinking.

Is the 'certain picture' actually the *same*, as one might interpret Einstein to have meant, each time it returns? Did Einstein really mean that the different series of mental images are *unconnected* before thought connects them? To help peer deeper into what Einstein may have really meant let me propose that we wed Einstein's introspective account of the thought process to another equally classic introspective account of the *flow* of thought — that of William James.

2. A fractal interpretation of James' stream of consciousness

James is famous among psychologists for his extremely detailed, clearly stated, and powerfully argued description of "The Stream of Consciousness" that appeared as a chapter in his textbook, *The Principles of Psychology* (James 1890). James' text historically was the first general textbook of psychology. Only small portions from James' lengthy description of the stream of consciousness or thought are required to fill in Einstein's account and give it an interpretative feel for a truly fractal flow. James (1905) provided extensive argumentative examples for each of the following summary conclusions about the flow of consciousness:

> *Consciousness is in constant change* [...]. What I wish to lay stress on is this, that *no state* [of mind] *once gone can recur and be identical with what it was before* [...]. For an identical sensation to recur it would have to occur the second time *in an unmodified brain*. But as this, strictly speaking, is a physiological impossibility, so is an unmodified feeling an impossibility; for every brain-modification, however small, we suppose that there must correspond a change of equal amount in the consciousness which the brain subserves [...].

> If the assumption of 'simple sensations' recurring in immutable shape is so easily shown to be baseless, how much more baseless is the assumption of immutability in the larger masses of our thought!
>
> For it is obvious and palpable that our state of mind is never precisely the same. *Every thought we have of a given fact is, strictly speaking, unique, and only bears a resemblance of kind with our other thoughts of the same fact* [italics added]. When the identical fact recurs, we *must* think of it in a fresh manner, see it under a somewhat different angle, apprehend it in different relations from those in which it last appeared [...]. *A permanently existing 'Idea'* [in a given mind] *which makes its appearance before the footlights of consciousness at periodical intervals is as mythological an entity as the Jack of Spades.* (James 1905:154-157)

Using examples from everyday experience, James argued convincingly that *no image or thought ever recurs to us in an identical fashion.* He went to great length to describe exactly why recurring thoughts only *seemed* to be identical. The snowman-like Mandelbrots that appear in the unfolding flow of the Mandelbrot set *seem* also to be the same, but upon close scrutiny they, too, never are. Einstein's account of recurring pictures coupled with James' flow of thought provides a way to "zoom in" on a more accurate description of an entirely *self-similar* flow of mental pictures in our thoughts. It is as if each of our mental lives can be thought of as a great journey through many ever-changing fractal sets like the Mandelbrot, all the while manifest in this or that fractal percept. James treats *connectedness* within this 'fractal stream of consciousness' as follows:

> *Within each personal consciousness, thought is sensibly continuous.* Consciousness [...] does not appear to itself chopped up in bits. Such words as 'chain' or 'train' do not describe it fitly as it presents itself in the first instance. It is nothing jointed; it flows. A 'river' or a 'stream' are the metaphors by which it is most naturally described. *In talking of it hereafter, let us call it the stream of thought, of consciousness, or of subjective life. The object before the mind always has a 'fringe'.* The traditional psychology [reductionistic sensationalism] talks like one who should say a river consists of nothing but pailsful, spoonsful, quartpotsful, barrelsful, and other moulded forms of water. Even were the pails and the pots all actually standing in the stream, still between them the free water would continue to flow. It is just this free water of consciousness that

psychologists routinely overlook. Every definite image in the mind is steeped and dyed in the free water that flows around it. With it goes the sense of its relations, near and remote, the dying echo of whence it came to us, the dawning sense of whither it is to lead. The significance, the value, of the image is all in this halo or penumbra that surrounds and escorts it, — or rather that is fused into one with it and has become bone of its bone and flesh of its flesh; leaving it, it is true, an image of the same *thing* it was before, but making it an image of that thing newly taken and freshly understood. *Let us call the consciousness of this halo or relations around the image by the name of 'psychic overtones' or 'fringe'.* (James 1905:157-166)

James saw thought flowing like a stream; every image in this stream having a fringe or halo that connected it with everything near and remote. He provided a figure illustrating how the fringe could be symbolized in terms of brain-action occurring over time (James 1905:166). Figure 2 is an updated and more detailed version of James' figure that shows the dynamical life of each image in the mind is depicted as a curve that rises and falls in intensity, but that *always* overlaps with the dynamical curves of other images.

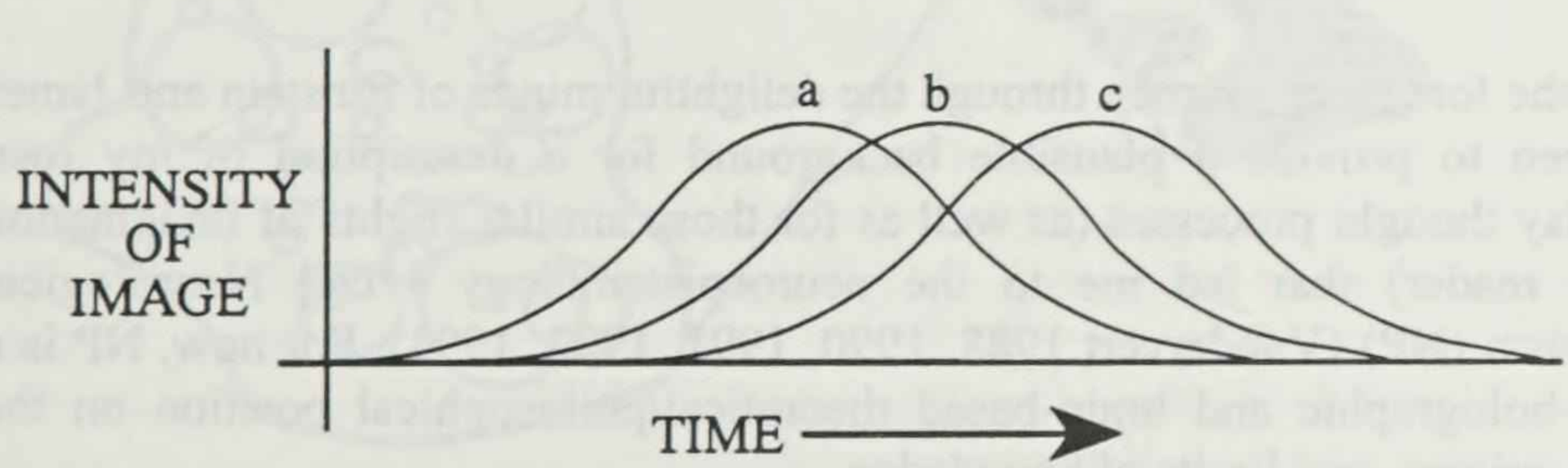


Figure 2: *Images in the brain to some degree overlap with one another. These curves should be thought of as normal bell-shaped curves whose tails ever approach, but never reach the baseline.*

Now, of course, Figure 2 is purposely simplified to convey the idea of connectedness in the flow of thought on a small scale. If we simply let these curves be the normal, bell-shaped curves with which everyone is familiar, the tails of the curves in Figure 2 would continue ad infinitum in both directions, and there would not be three of them, but millions upon millions going every which way extending infinitely on the plane. This means that through the fringe every image everywhere is to some degree connected with everything else — even though the connections may be as remote as far-flung potential iterations

through the Mandelbrot set, which appear, too, to be infinite. In the Mandelbrot set, miniature Mandelbrots, see Figure 1, may appear to be free-floating, but are always connected to the parent by filaments.

With James' description of the fringe that surrounds all images in the mind, it seems reasonable to believe that Einstein's 'certain picture' that turns up was not actually connecting *unconnected* series of images, but series that only *seemed* unconnected due to their remoteness from one another. James' description of the fringe helps us understand how such remote connections, that have often been convincingly proposed to be basic to creativity (e.g., Koestler 1964; Mednick & Mednick 1967), could propel an Einstein ever toward the formulation of a holistic world-picture *that works in the real world.* To Einstein in his day, the great connecting leaps he made to axioms of science were a mystery.

It is unfortunate that Einstein and James could not today collaborate on the question Einstein posed, "What, precisely, is thinking?" Perhaps, together, they would come to some of the same conclusions about the 'fractal mind of Albert Einstein' that have been rather speculatively proposed.

3. Pots and pans, and soap bubbles

All of the foregoing journey through the delightful minds of Einstein and James has been to provide a plausible background for a description of my own everyday thought processes (as well as for those similar flights of imagination of the reader) that led me to the neuroepistemology I call Neurological Positivism (NP) (Vandervert 1988, 1990, 1991, 1992, 1993). For now, NP is a fractal-holographic and brain-based theoretical/philosophical position on the nature, origins, and limits of knowledge.

3.1. *The fractal mind: The first hints*

When I was a boy of thirteen or fourteen years I, like many other boys and girls my age, washed and dried a lot of family dishes, and pots and pans. (This was in the days before nearly anybody had automatic dishwashers.) I can vividly remember peering time and time again at the amazingly complicated patterns of soap bubbles. The bubbles would swirl around, especially in the pots and pans, making endless intricate patterns, all the while suddenly joining and parting in mysterious ways. I can remember thinking to myself, "Gee, just think, scientists and mathematicians must know just what is happening with all

these amazing, ever-changing patterns of soap bubbles. They can probably predict just when these beautiful and complicated patterns will form, and then suddenly change with the motion of the water." (As a youth, little did I know their actual limitations.) One day, while totally perplexed by the behavior of

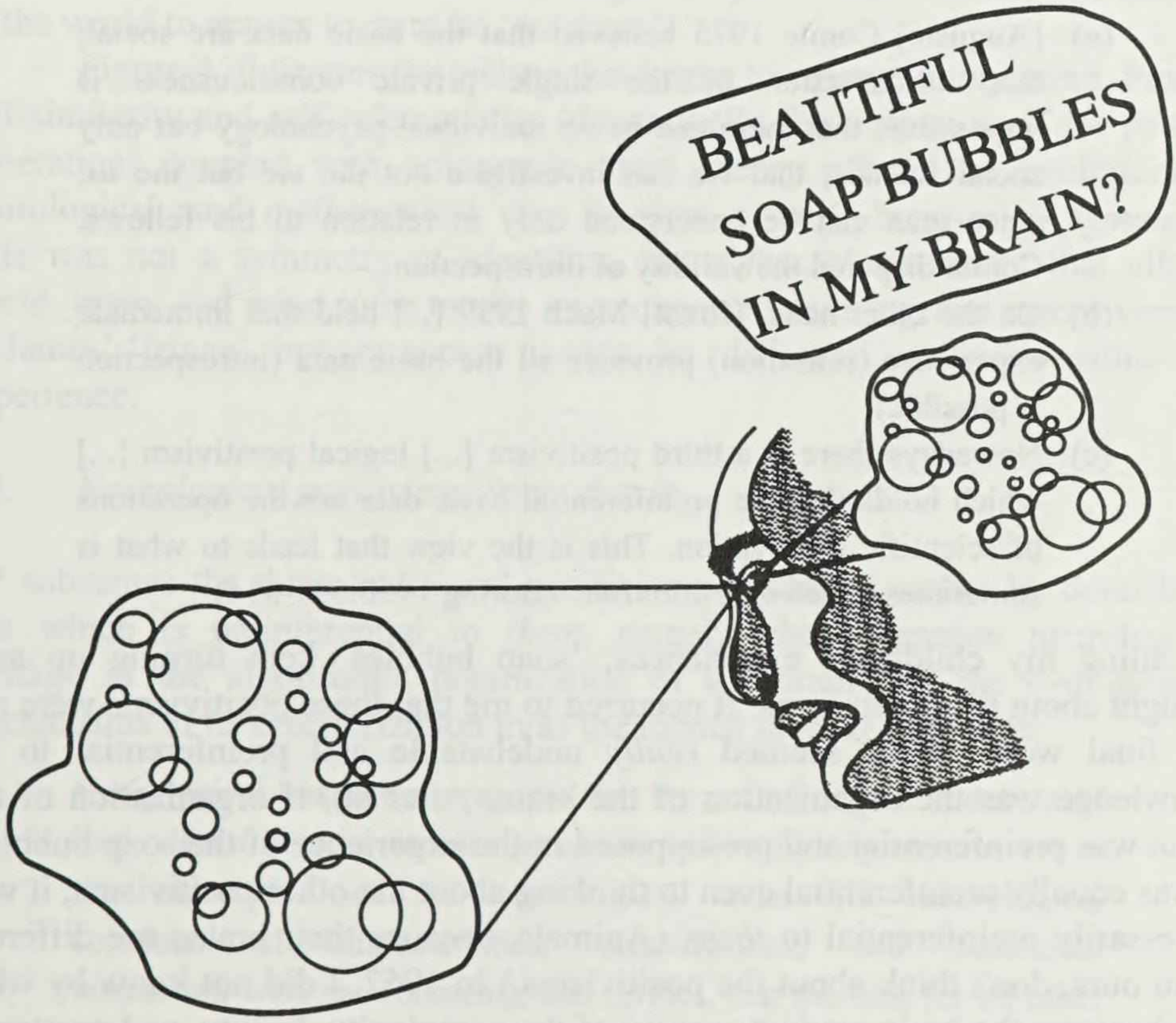


Figure 3: *The childhood moment of realization that complex world dynamics must have a self-similar dynamical counterpart in the brain.*

the soap bubbles, and trying very hard top understand the mysteries that governed them on my own, a picture, somewhat like Einstein's certain picture, flashed in my mind. I saw the soap bubbles swirling around *inside* my head. It suddenly occurred to me that no matter what was going on with the soap bubbles, no matter how complicated, beautiful, and mysterious; *it was all going on also inside my head*! There must be, I thought, processes 'like' in the swirling water and soap bubbles going on inside my brain. Well, at the time, this revelation didn't help much. Now I had two versions of the same mystery to deal with — one in the kitchen sink, and the other in my brain.

Many years later when I was in graduate school in psychology, like most other students of psychology, I came across the philosophical *positivisms*. These positivisms were philosophical positions on what was basic, undebatable, and preinferential to all knowledge. Boring (1950) described the three traditional positivisms succinctly:

> (a) [Auguste] Comte 1975 believed that the basic data are social, that introspection of the single private consciousness is impossible, that there can be no individual psychology but only social science, that we can investigate not the *me* but the *us*, since man can be understood only in relation to his fellows. Comte disputed the validity of introspection.
>
> (b) On the other hand, [Ernst] Mach 1959 [...] held that immediate experience (sensation) provides all the basic data (introspection is possible).
>
> (c) Nowadays there is a third positivism [...] logical positivism [...] which holds that the preinferential basic data are the operations of scientific observation. This is the view that leads to what is sometimes called *operationism*. (Boring 1950:633-634)

Recalling my childhood experiences, 'soap bubbles' kept turning up as I thought about the positivisms. It occurred to me that these positivisms were not the final word. What seemed *really* undebatable and preinferential to all knowledge was the organization of the brain. After all, if organization of the brain was preinferential and presupposed in the experience of the soap bubbles; it was equally preinferential even to thinking about the other positivisms; it was necessarily preinferential to *them*. (Animals, because their brains are different from ours, don't think about the positivisms.) In 1967, I did not know by what mechanisms the brain made its copies of the complexity, beauty, and mysteries of the world, or by what strange mechanism it made the soap bubbles 'appear' to be 'out there' in the pots and pans. However, I was now convinced that such brain mechanisms had to exist. Sommerer & Ott (1993) have recently demonstrated fractal patterns on the surface of a moving fluid that can be seen 'by eye' very much like my soap bubble experience!

3.2. *Neurological positivism*

Over the next two decades a new knowledge base began to materialize that would help us understand the brain mechanisms that lie behind the soap bubbles, and ultimately everything else. This new knowledge base included the fractal geometry of Benoit Mandelbrot (1977); chaos theory, for example, Gleick's

(1987) overview; and Karl Pribram's (1971, 1991) holographic/holonomic brain theory. Fractal geometry (the geometry of chaos), and chaos theory (chaotic attractors are fractals) applied to neurological activity began to explain how and why copies might be made in the brain, and holographic/holonomic brain theory described how the brain might 'project' soap bubbles, and the rest of the world to appear to us to be 'out there'.

Figure 4 illustrates the picture that began to emerge in my mind. Fractal self-similarity and self-referentiality (dynamically feeds upon itself for pattern generation) coupled with holonomic brain theory offered an evolutionary, neurological, and mathematical way to view a world-brain-mind *symmetry*. This was not a symmetry of identities, but a *fractal* symmetry that allows world, brain, and mind to be totally interconnected as in a grand macro version of James' 'fringe', but yet appear to us to be 'different' categories within our experience.

3.3. *Neurological positivism: Some details*

NP subsumes the three traditional positivisms described earlier by describing that which is preinferential to *them*, namely, their common neurological heritage in the algorithmic organization of the brain and the evolutionary mechanisms of its exteriorization in/as the mental models of culture:[1]

> Neurological positivism proposes that the preinferential, undebatable basic data and order for all that can be known by any creature are in the algorithms of its neurological order (its neurological computational characteristics, organizations, and functional interaction with environment); and further, that the data for all other positivisms (social, experiential, and logical) exist as high-level homological [having common descent] *transformations* of the neurological order. (Vandervert 1988:314)[2]

Within the framework of NP, the algorithmic organization of the human brain has been described as the outcome of fractal maximum-power evolution selection dynamics (see Appendix) operating in space and time that gradually became encapsulated (literally, placed in a protective container) in the skull and the rest of the nervous system (Vandervert 1991, 1992). In addition to the encapsulation of the algorithmic *organization* of space and time (described in Vandervert 1992:257-259), the self-referential, self-organizing (autocatalytic) *dynamics* of fractal maximum-power evolution are likewise thought to have been encapsulated as the driving features and forces behind the processes of

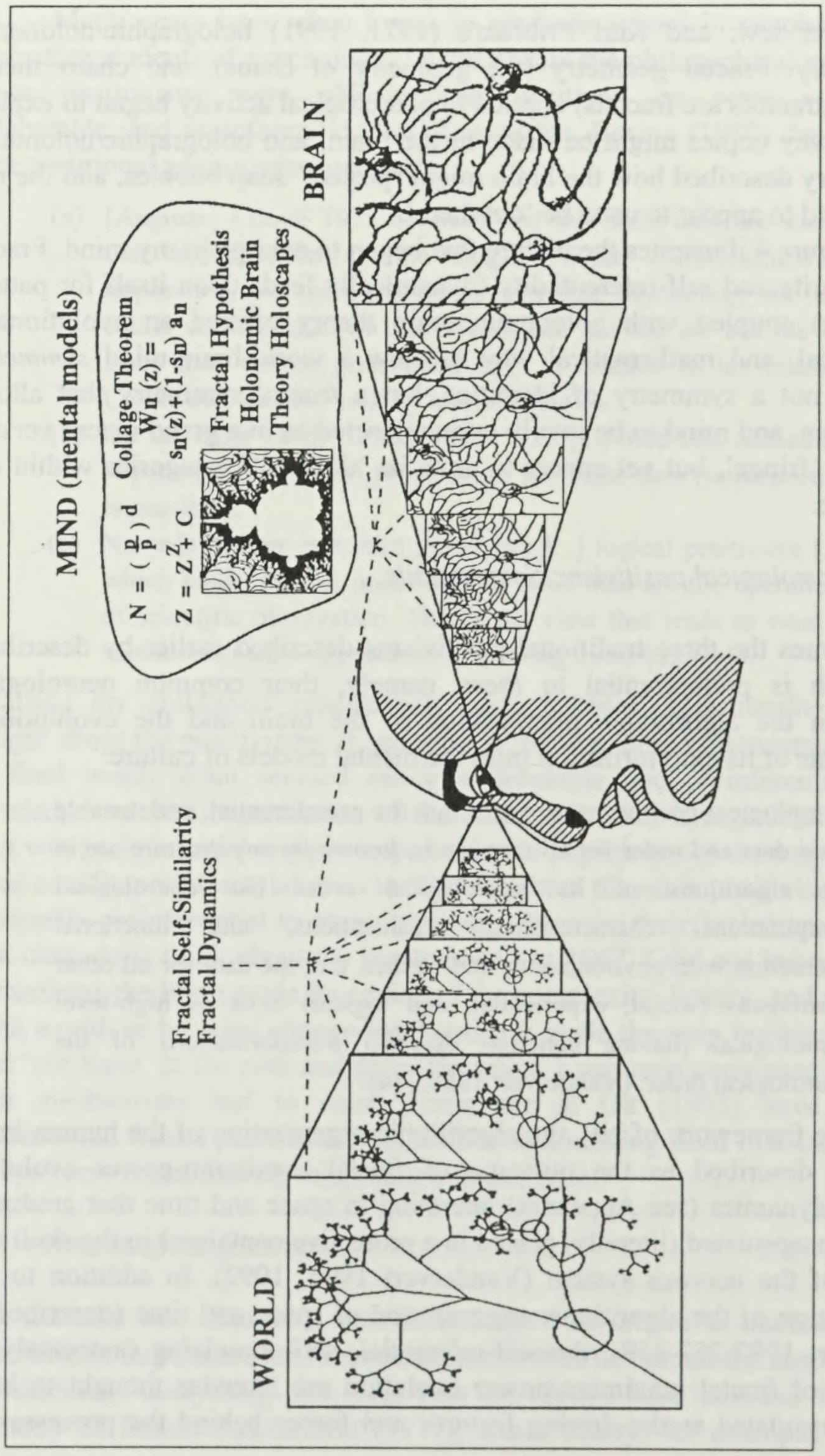


Figure 4: *A picture begins to emerge of a fractal symmetry among world, brain, and mind. In each category of experience, fractal structure and function dominate. In addition, the dynamical mechanism that permits algorithmic movement among them is proposed to be fractal.*

perception, cognition, and behavior, and, subsequently, mind *in* space-time (Vandervert 1991:211-214).

The general evolutionary and neurological arguments that undergird fractal descriptions in NP are based respectively upon the fractal maximum-power principle (see Appendix), and the *fractal hypothesis*. The *fractal hypothesis* (Golberber, Bhargava, West & Mandell 1985) proposes an allied fractal dynamical relationship between fractal structure and fractal function in living systems:

> What is the significance of fractal structure and what are the links between fractal structure and physiological function? From a developmental viewpoint, fractals provide a new morphogenetic principle underlying the construction of many apparently unrelated, highly complex, irregular structures by means of a simple code. The basis of this code is self-similarity, so that a complex, branching structure like the bronchial tree or His-Purkinje [neural] system can be generated by adding the same structure on progressively smaller scales. Such a fractal algorithm will also serve to minimize constructional error, since it relies primarily on a self-similar iterative mechanism. (Goldberger & West 1987:426)

At the same time the development of the fractal structures described above serve as the substrate for fractal dynamical impulse patterns.

> The effect of the self-similar, irregular [structural] network will be to 'shatter' a cardiac impulse starting at the His bundle into myriad stimuli, cascading down the His-Purkinje system toward the myocardium. (Goldberger & West 1987:430)

The mathematician is encouraged to consult Goldberger, Bhargava, West & Mandell (1985), and the general reader is encouraged to consult West & Goldberger (1987) for more complete understandings of the *fractal hypothesis*.

Figure 5 depicts a natural living fractal system that illustrates in a simple way the features of the fractal hypothesis. The fractal hypothesis is supported by many neurological studies, for example, see MacLean's (1990, 1991) fractal interpretation of brain microgenesis; and Vandervert (1990, 1992) for overviews.

This chapter has three dynamically interrelated purposes: (a) to illustrate the evolutionary instantiation of fractal space-time in the brain; (b) to describe how the culturally shareable mental models of *mind* arise and exteriorize as fractal variants of the space-time organization of the brain; and (c) to describe fundamental mental model exteriorizations of Immanuel Kant, and Albert Einstein.

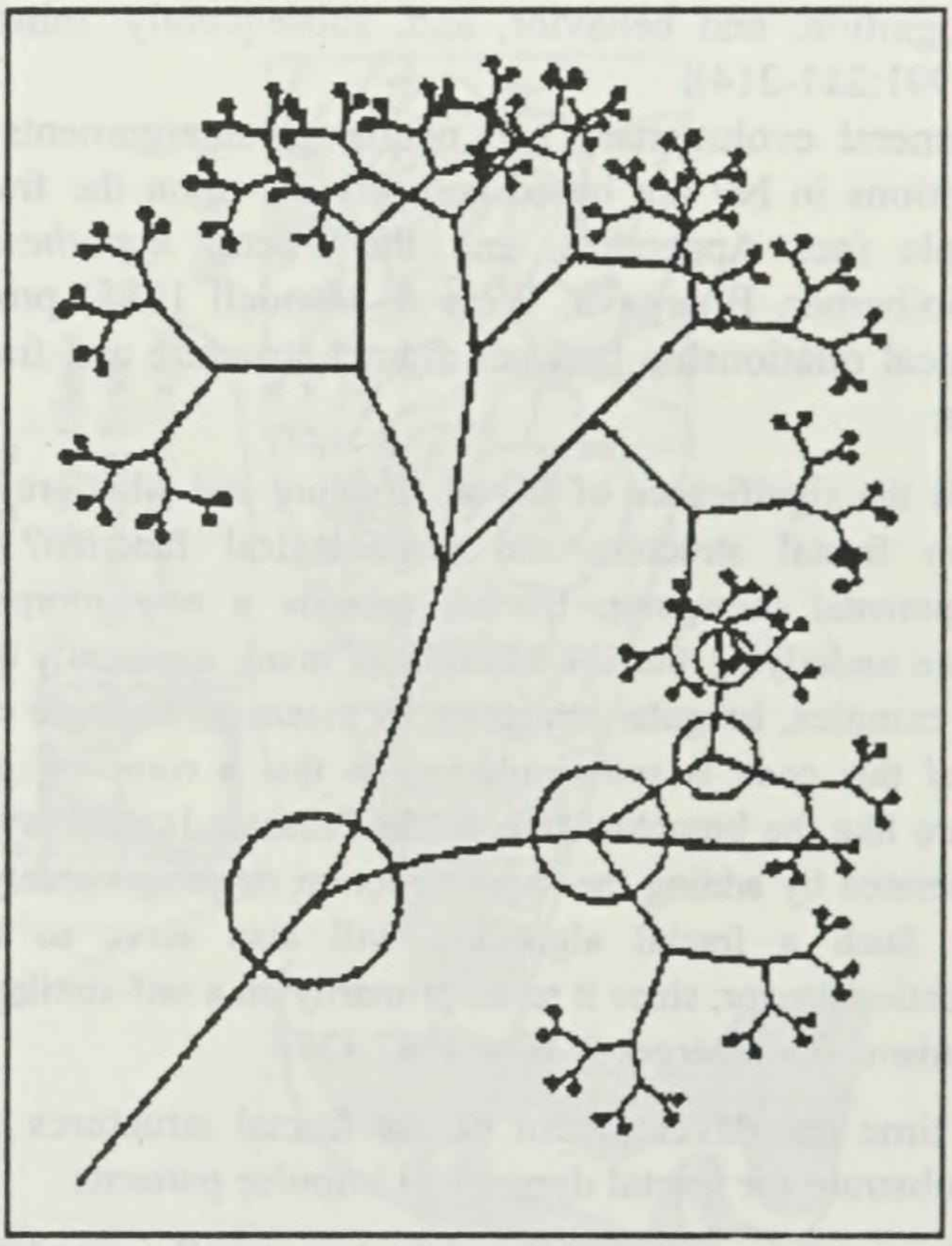


Figure 5: *Fractal self-similarity in a biological system. As the plant (baby's breath) is generated (grows), the fractal pattern is copied recursively. The structure within each circle is a fractal copy of the preceding one. Compare with the purely mathematical growth of fractal structure depicted in Figure 1.*

4. The fractal maximum-power instantiation of the space-time

4.1. *Activity framework of consciousness*

Consciousness, like everything else in nature, can be understood as an outcome of dynamic energy principles — the principles of thermodynamics (see Atkins 1984 for a sophisticated, yet easy to follow introduction). Viewed from its energy framework, the evolutionary struggle for existence is always the struggle for energy capture within the two fundamental conditions of organic existence, *space and time* (see Boltzmann 1905, 1974; Lotka 1922, 1945;

Odum 1988; Odum & Odum 1981). In NP the evolution of brain algorithms, or brain energy patterns of *space and time* and those of *consciousness* are inseparable. A definition of consciousness as the activity of the space-time algorithms of the brain will be provided shortly.

The common basic design of brains and nervous systems across phyla illustrates that the evolution of algorithms that deal with space and time contingencies, for example, those of the brain's hippocampus, the evolutionary floor of the cerebral cortex (O'Keefe 1985; O'Keefe & Nadel 1978), extends back in time over hundreds of millions of years. Thus, consciousness as a category of nervous activity is very old, and the human brain can be viewed as carrying in it a triune paleontology of consciousness that involves that of reptiles, prehominid mammals, and humans (MacLean 1975, 1990). (See Appendix: *Fractal Autocatalysis*.)

From where did consciousness come? From what general dynamical conditions was it constructed and encapsulated in the brains of creatures? Lotka (1945:179) provided a rather straight forward universal way of understanding the manner in which brain algorithmic patterns of energy flow might be selected and retained from (constructed from) space and time activity on the parts of '*the dynamics of systems of energy transformers*' (the dynamics of systems of energy creatures). We can adapt the scenario provided by Lotka to help understand the evolutionary and dynamical instantiation and encapsulation of the algorithms of consciousness as the pure or generalized form of this space-time *activity*. It might be helpful in the following example to imagine, for example, the 'pursuer' as a fox, and the 'pursued' as a rabbit:

> An admittedly primitive illustration of the mode of approach to the problem [for our purposes the problem of describing the dynamic selection of the algorithmic organization of consciousness in the brains of creatures in terms of the maximum-power principle] is the case of a "pursuing" transformer [a creature] of velocity v_1 seeking encounter with a "pursued" transformer of velocity v_2 while the latter flees in a straight line [or any other pathway for our purposes here] toward a refuge of safety. The pursuer, constantly directed toward the pursued, then follows a so-called "curve of pursuit" [or ensemble of curves]. Whether capture occurs or not depends on the relative position of the pursuer and the pursued at the *time* [italics added] when the first stage of the pursuit, the "stalk", begins (that is, when the pursuer first directs his course toward the pursued); and depends further on the *time* [italics added] when the second stage begins, namely when the pursued first reacts by "flight" to the "attack" of the

> pursuer. [These two stages combined describe a dependency on initial conditions, much as sensitivity to initial conditions is a feature of the behavior of chaotic systems.] The problem [see opening line of this quote] thus conventionalized resolves itself to a problem of geometry. [More accurately described, we now know by *fractal* geometry, the geometry of chaos, and nonlinear flight and pursuit paths.] Capture certainly occurs [receptor-effector neural circuitry of pursuer is selected], or does not occur [receptor-effector neural circuitry of pursuer is not selected], according as a certain circle[s] and ellipse intersect, capture occurs for some initial positions [initial conditions] and does not occur for others. In this conventionalized case we can, for example, discuss the influence upon the probability of capture, or variations in the velocities v_1 and v_2 or in the degrees of perfection of the receptors, etc. Carrying this model somewhat further, the influence of the density of the distribution of refuges in the territory may be discussed [for the mathematical treatment see Lotka 1932:183]. (Lotka 1945:179)

In sum, through countless iterations of Lotka's scenario (extended to the time scale across phyla) and its space-time representation that appears in Figure 6, isomorphic energy transforms of the space, time, and sense modalities of evolving creature activity involving the pursuer/pursued *relationship* become encapsulated (literally, placed in a protective "container") in a fractal algorithmic organization of the nervous systems and their bodies of each generalized species. The Lotka scenario may be looked upon as a fractal maximum-power equivalent of the *fractal hypothesis*. As Crutchfield, Farmer, Packard & Shaw (1986) suggested, the chaotic/fractal nervous system that has been selected has met the demands of the chaotic/fractal possibilities of an ever-changing environment:

> Chaos is often seen in terms of the limitations it implies, such as lack of predictability. Nature may, however, employ chaos constructively. Through amplification of small fluctuations it can provide natural systems with access to novelty. A prey escaping a predator's attack could use chaotic flight control as an element of surprise to evade capture. Biological evolution demands genetic variability; chaos provides a means of structuring random changes, thereby providing the possibility of putting variability under evolutionary control. (Crutchfield, Farmer, Packard & Shaw 1986:56-57)[3]

In NP the maximum-power evolution of a space-time neuromatrix in creatures constitutes the basis of their self-referential and autocatalytic (see Appendix) *consciousness*. It is to such a description and definition of consciousness we now turn.

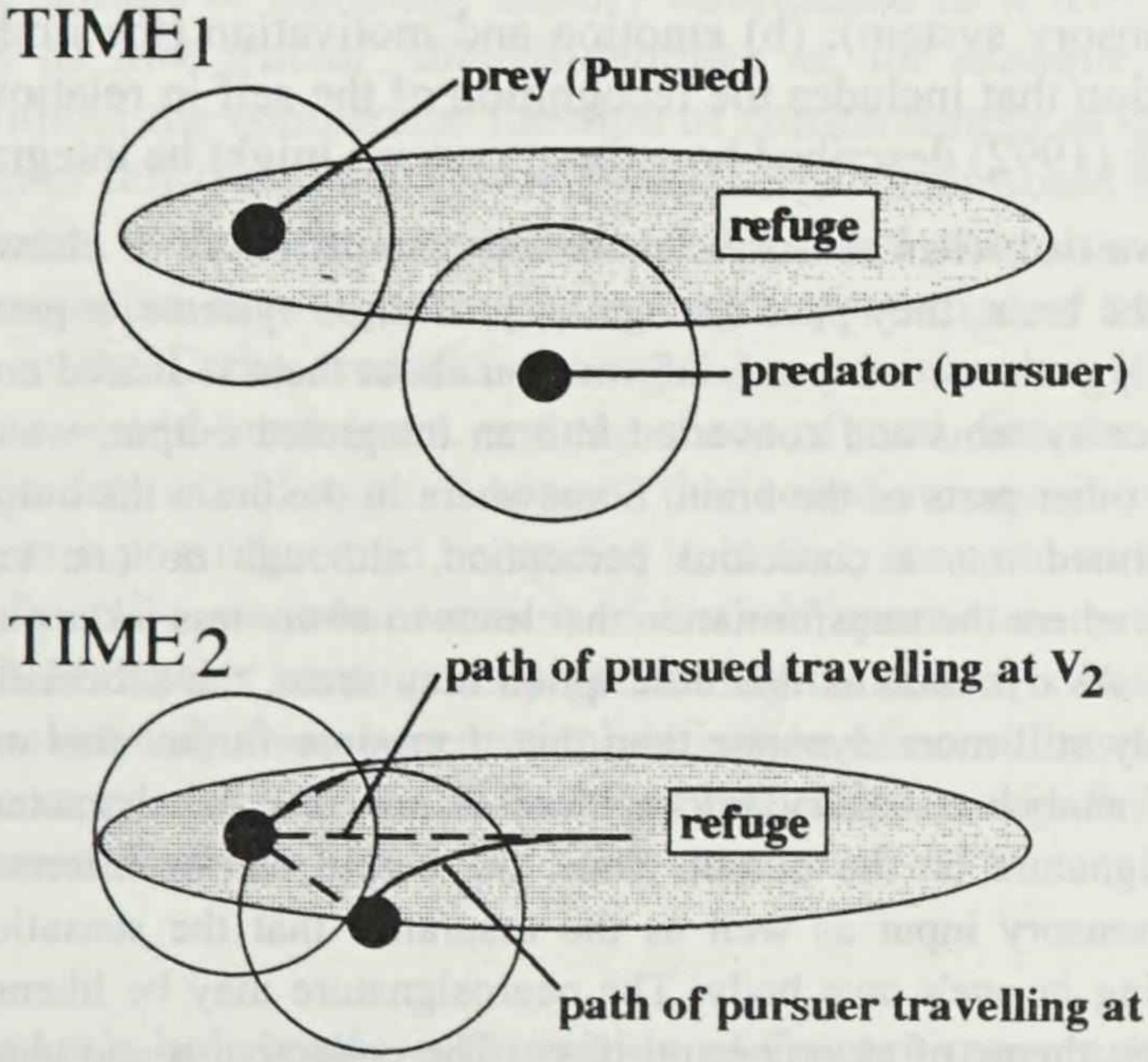


Figure 6: *Countless milennia of iterations of selective processes in this generalized prey-predator scenario resulted in the encapsulation of space-time algorithms in the brain. Algorithms are patters of energy pathways (methods of work) that solve problems.*

4.2. *The definition of consciousness*

The hardwired space-time cognitive mapping functions of the brain's hippocampus have been described in some detail by O'Keefe (1985), and O'Keefe & Nadel (1978). However, there is a deeper question. Is there evidence for a hardwired space-time neuromatrix in the brain that could translate into the experience of consciousness? Melzack (1992) has developed a pervasive model

to account for the diversity of phantom limb experiences that involves circuitry throughout the brain, and that fits our everyday experience of an active 'stream of consciousness'. To explain vivid phantom limb experiences among people born without the particular limbs in question, Melzack has proposed a largely hardwired neuromatrix dispersed over three major brain circuits. The functions of these brain circuits include: (a) the sensation of the body and its movements (the somatosensory system); (b) emotion and motivation (the limbic system); and (c) cognition that includes the recognition of the self in relation to sensory input. Melzack (1992) described how these systems might be integrated:

> I believe that when sensory signals from the periphery or elsewhere reach the brain, they pass through each of these systems in parallel. As the signals are analyzed, information about them is shared among the three systems and converted into an integrated output, which is sent to other parts of the brain. Somewhere in the brain the output is transformed into a conscious perception, although no one knows exactly where the transformation that leads to awareness takes place.
>
> As dynamic as this description may seem, the processing is probably still more dynamic than that. I propose further that as the matrix analyzes sensory information, it imprints its characteristic neurosignature on the output. Thus, the output carries information about sensory input as well as the assurance that the sensation is occurring in one's own body. The neurosignature may be likened to the basic theme of an orchestral piece. The collective sound changes when different instruments play their parts (the input), but the product is continually shaped by the underlying theme (the neurosignature), which provides the continuity for the work, even as the details of its rendition change. (Melzack 1992:123-124)

The integrated activity of these circuits *continuously generates* a pattern of impulses that indicates "that the body is intact and unequivocally one's own" (Melzack 1992:123). These largely hardwired patterns of impulses are closely in line with Melzack's interpretation to represent a continuously-generated *feedforward* template of the *active* 'body universe'. That this continuously-generated pattern of impulses represents a fractal-holographic space-time template for the body is evidenced by the fact that the missing body part *even if congenital* is experienced as extended in space and time. Thus, the phantom limb experience, somewhat surprisingly perhaps, is a(the) vital clue as to the origin and nature of the stream of consciousness we all experience. While Melzack did not connect his model with a definition of consciousness *per se*, conscious experience *may be* the continuously-generated entirety of the activity

of the fractal space-time neurosignature of the *body in the brain* — it feeds forward the integrity and 'whereabouts' of the genetically-derived template of the body universe. Consciousness continuously constructs this model of space-time in the brain as a comparator system by which the brain can movement-by-movement, moment-by-moment differentiate itself from, and make sense of, the constant barrage of incoming sensory information *as it itself continuously reconfigures its own fractal dimensionalities* as, for example, in the Lotka scenario. Without the comparator function of consciousness as described here, the evolution of self-contained, self-referential organisms would not seem to be possible. That is, without the continuously fed forward parameters of the space-time of the organism moving through the larger space-time of its surroundings as depicted in the Lotka scenario, the organism-environment (figure-ground) differentiation would breakdown, and the chaos of total disorder that preceded the cosmos (order) would reign. It appears that consciousness is as fundamental to our being as it possibly could be, and as it, in fact, *seems* to us to be.

The fractally amended version of Lotka's space-time activity scenario coupled with Melzack's continuously generating neuromatrix has provided the basis for a preliminary fractal-theoretical definition of consciousness. However, the complete story of fractal space-time lies embedded within Pribram's (1991) holonomic brain theory.

5. Pribram's holonomic composition of fractal space and time in the brain

In NP it is proposed that *fractal-holographic* space and time have been encapsulated in the brain through countless millennia of iterations of maximum-power principle energy flow refinements via the struggle for survival (energy capture) among creatures as depicted in the Lotka scenario and Figure 6 (Vandervert 1991, 1993). In this section the specific question that will be addressed is as follows: What neurological structures and related dynamics have evolved to represent holographically projected space and time in the brain's neuromatrix that give rise to the perception of an 'out there' (and the holographic apparitions of phantoms)?

Within Pribram's (1991) *holonomic* brain theory (as differentiated from his earlier purely 'holographic' brain theory; see Pribram 1991:26-29) holoscapes are described as organizations of dendritic microprocessing wherein space and time, and spectra (sensory modality and form information) are embedded. Holoscapes are the fundamental units of dendritic microprocessing

and are comprised of ensembles of frequency, amplitude, and phase activity — the coordinated information necessary to project a hologram. Networks of holoscapes are therefore transformable in the brain into our everyday holographic-like experiences of perception and cognition (including dream states) *in* a ground of fractal space-time consciousness, and all composed within the skull. Holoscapes are by definition algorithmic (see footnote 2) in guiding energy/information flow compositions toward optimization (minimum entropy or disorder/maximum information) both in phylogenesis and ontogenesis. This entropy/information aspect of processing in holoscapes connects their evolution with the complementary thermodynamic principles of fractal maximum-power evolution (as modified by Vandervert 1991) which drive living systems progressively toward higher qualities of energy flow and entropy minimization.

We can now describe in terms of fractal maximum-power evolution how holonomic networks have come to provide just an essential fit of characteristics and tremendously refinable processing in motor-perceptual-cognitive systems that, in order to survive, must master a fractal environment cluttered with prey and predators, and a myriad of other objects and events in constant flux. D'Arcy Thompson (1917) long ago anticipated the dynamical evolution of whole systems such as networks of holoscapes that compose the adapted world inside the skull:

> The form, then, of any portion of matter, whether it be living or dead, and the changes of form which are apparent in its movements and in its growth, may in all cases alike be described as due to the action of force. In short, the form of an object [including its detailed internal structure] is a 'diagram of forces', in this sense, at least, that from it we can judge of or deduce the forces that are acting or *have acted upon it* [italics added]. (D'Arcy Thompson 1917:11)

Like the fish's fin that reflects the hydrodynamic properties of water (Lorenz 1977:6), then, the holonomic organization of the brain represents a 'diagram of forces' that mirrors its own evolutionary history of the complex energetic necessities of survival.

Below is a description of the features of the diagram of forces (as Thompson would have put it) of holonomic processing:

(1) The projection of experience away from its locus of processing — the world composed inside the skull appears to consist of objects and events 'out there'. It is difficult to imagine any workable evolutionary prey-predator scenario without such holographic-type exteriorizing projection.

In NP this automatic projection of experience away from its actual locus in the brain is referred to as *primordial perceptual constancy*, which is thought to provide the ground and process of consciousness for all other constancies, for example, the color, size, and shape constancies. (See Vandervert 1990:9-11 for discussion concerning the primordial constancy, and how it has influenced the development of science.)

(2) The enfoldment and storage of multiple 'hidden' nested orders among networks of holoscapes which may be activated by attentional and intentional processes. And, the immediate recognition of any minute portion of a figure as the entire figure *even if never before consciously perceived in that particular fraction*. The tip of a predator's ear, a muffled sound displaced in space and time, or an olfactory nuance is immediately recognizable as the presence of the entire figure. (Many images may be recorded in a single hologram, and any portion of a hologram contains the entire hologram.) Melzack's hardwired neuromatrix seems fractal-holographic.

(3) Tremendous storage capacity, rapid retrieval, and practically instantaneous cross- and auto-correlation in computing power for processing 1 and 2 above.

In summary of this section, the space-time, and spectral, holonomic features of the algorithmic organization of the brain provide a better picture of the body neuromatrix or 'diagram of forces' that reflects the overall dynamics of the Lotka scenario. Pribram's holonomic model is absolutely critical, it seems, in that it allows us to understand the generation of holographic-like spatial and temporal experience of phantom limbs; it allows us also to extend Melzack's neuromatrix conception to aspects of the sense modalities to understand holographic-like phantom seeing and phantom hearing experiences (see Melzack 1992:123) among those so impaired. In NP, consciousness *is* the continuously generated entirety of the fractal-holonomic body in the brain — a continuously active body universe of space-time, and spectra, including the constancy mechanisms. Consciousness is this fractal-holonomic world of awareness composed within the skull. In the next section the emergence of the exteriorization of symbol systems (including mathematics) and mental models will be described as a natural evolutionary extension of these features—form autocatalytically arising from pre-existing autocatalytic form. The fractal space-time, spectra algorithmic patterns of conscious in the brain will thus be connected to the fractal space-time, spectra of *mental models* including those of the mathematics of fractals and chaos and holography — collectively, *mind*.

6. UNFOLDMENT: How and why the algorithmic organization of the conscious brain exteriorizes in the form(alisms) of mental models

In NP, mind and its definition are derived directly from the dynamics of brain evolution, and from the algorithmic properties of consciousness described above. Mind consists of patterns of brain subcircuitry that are selected from those of the algorithmic organization of the brain in accordance with the fractal maximum-power principle (see Appendix). Mind is palpable in two forms: (a) as patterns of subcircuitry erected and nested in a self-similar, self-referential fashion in the fractal-holonomic brain; and (b) as exteriorizable (culturally shareable) mental models.[4] More than 20 years of sophisticated global electroencephalographic studies that monitor circuitry-specific modeling activity in the brain are completely consistent with this idea (Gevins 1989). *Mind* is defined as one's collection of culturally shareable mental-model circuitry configurations in the brain. Mind thus began with cultural evolution, perhaps with *Homo habilis* some two million years ago, and continues to evolve in both its composition and nature. (Lower animals are conscious, but since they do not have culture they likewise do not have appreciable 'minds'.)

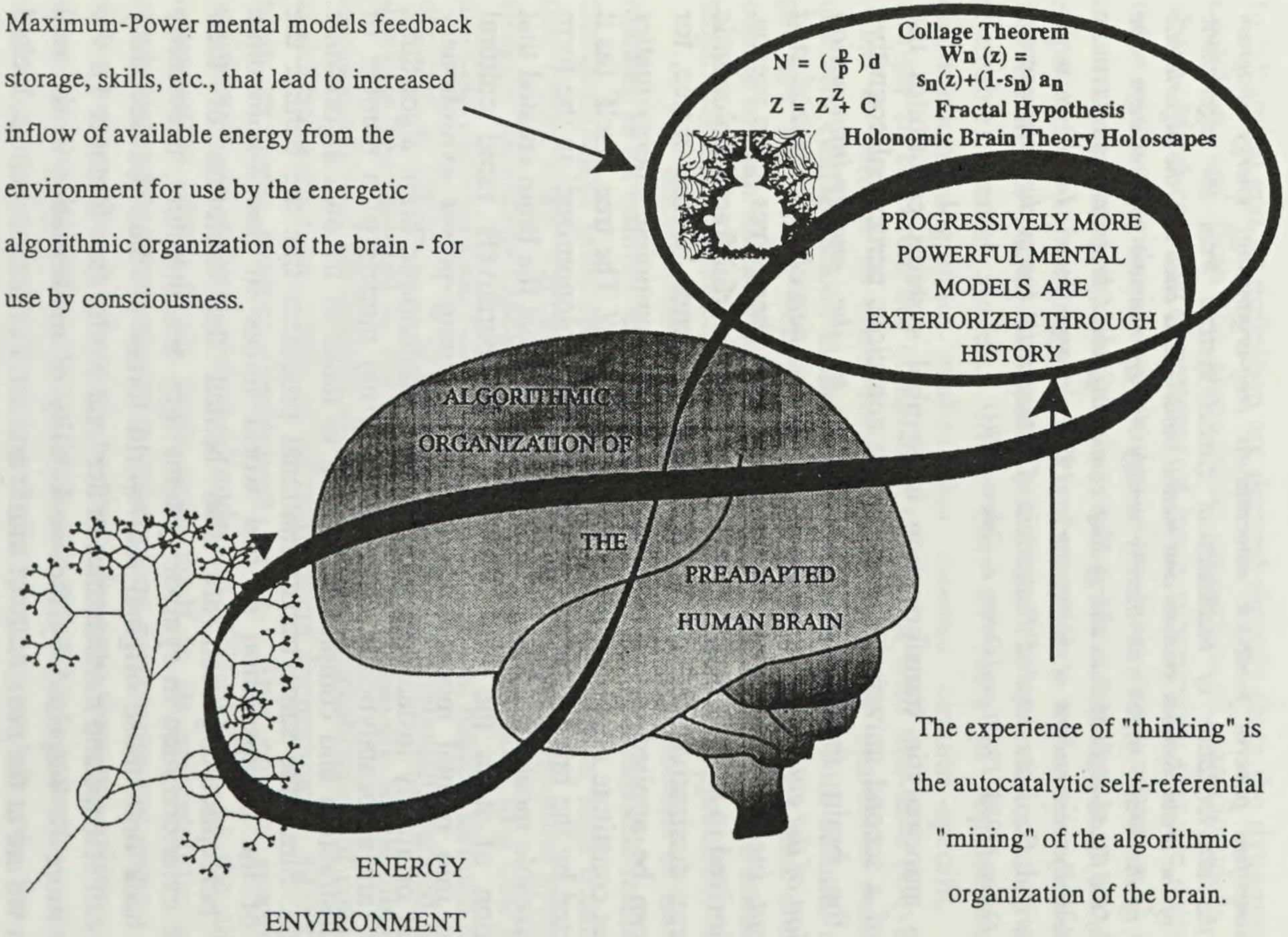
The fractal maximum-power autocatalytic production of mind in this manner is an entirely natural energetic affair that follows self-referential and thermodynamic principles in making progressively more high quality energy (see Odum 1988; Vandervert 1991) available to the brain-mind system — the struggle for energy capture depicted in Figure 6 extended to a new level. The autocatalytic evolution and exteriorization of mental models through *thinking* is depicted in Figure 7. It is proposed that the continuously iterated process of thinking has resulted in the gradual, yet progressively accelerating, cultural exteriorization of the features of the algorithmic organization of *consciousness* as defined earlier, especially of the more recent approximately 40,000 year old brain of *homo sapiens* (Vandervert 1991). This process constitutes the unfoldment of cultural history (Vandervert 1991, 1992). As the algorithmic organization of the brain feeds upon itself in its autocatalytic search for symbolic patterns that maximize information processing and energy inflow to the overall system, it *inherently* bestows (dynamic from pre-existing dynamic) upon them appropriate portions of its own algorithmic patterns — the patterns that must undergird shared symbolic mental models of, for example, mathematics, science, art, music, if they are to be of any adaptive advantage. (Symbol systems in themselves are worth nothing if not produced and read by humans or human-designed contrivances.) The thus exteriorized algorithmic patterns that appear in symbol systems are therefore not really new patterns, but

are in a variant isomorphic form that has proven to be a newly useful advantage to the creature's survival.[5]

Figure 7: *Simplified positive feedback autocatalysis (self-organizing) energy diagram illustrating the exteriorization of mathematical symbol systems from the algorithmic organization of the brain. Symbol systems and mental models feed back into the algorithmic organization of the brain, which can thereby modify the environment in new ways. The appearance of the figure-eight Mobius energy loop connecting world, brain, and mind is more than coincidentally reminiscent of Hofstadter's (1979) 'strange loop'. In NP it is its algorithmic origin. For more detailed illustrations of autocatalytic energy diagrams consult, for example, Odum (1983, 1988) and Odum & Odum (1981).*

The autocatalytic transformation to symbol systems constitutes the evolution of a second universal variant of the conscious perceptual-cognitive order of the brain *that is now applicable to the energy-information manipulation of the entirety of those things and events perceived, cognized, and moved about, including the brain and its operations themselves*. This means, once exteriorized in shared mental model form, the powerful fractal holonomic neural energy dissipative patterns that once only governed 'seeing' a tree, for example, can be applied to the manipulation of the complete energy/matter patterns that constitute the knowable 'external' tree *itself*. The tree 'itself' (as it is constructed by the brain) can be 'fractalized' and 'holonomized' in the form of exteriorizeable mental models in the same fashion that the brain created that representation of it in the first place — a comparatively rapid cultural unfoldment into mental model form of the maximum-power evolutionary process that originally instantiated it. The fractal-holonomic brain algorithms can create (are autocatalytically exteriorizeable as) models of a number of levels of abstraction and complexity leading to those of its own algorithmic organization. Since the same transformational processes that are behind the evolution of the encapsulation of real world forces in fractal-holonomic conscious perception/cognition are also behind the evolution of their isomorphic exteriorization in symbol systems they are, therefore, necessarily mappable back onto those original real world forces — thus the necessary workability of science and mathematics in the 'real world' (see footnote 1). We should no more be surprised by the workability of mathematics in the real world than we are at the *possibility* of music and art. For human beings, locked inside the general chaotic attractor loop depicted in Figure 7, a system's essence is its overall fractal-holonomic existence. The autocatalytic thinking process that emerged from the continuously generated space-time, spectra algorithms of consciousness represent the actual relationships among world, brain, and mind

Maximum-Power mental models feedback storage, skills, etc., that lead to increased inflow of available energy from the environment for use by the energetic algorithmic organization of the brain - for use by consciousness.



The experience of "thinking" is the autocatalytic self-referential "mining" of the algorithmic organization of the brain.

Figure 7.

that undergird what Bohm (1973) and Bohm & Peat 1987) refer to as the *holomovement*. Bohm's theoretical model seems incorrect, but he has the conclusion essentially right.

In summary, we can now define consciousness and mind dynamically and interdependently. *Consciousness* is the activity of the algorithmic organization of the brain that is associated with the continuously generated, fed forward fractal-holonomic neuromatrix of the body universe (the uniquely human slice of reality arising originally from the generalized Lotka scenario). The self-contained activity of consciousness is an encapsulation of the activity of the Lotka scenario that differentiates itself from the larger dynamics of the environment. *Mind* arises autocatalytically from the feedforward dynamic of the fractal-holonomic neuromatrix of consciousness in the form of culturally shareable mental models. The feedforward dynamic 'mines' the algorithmic organization of the brain in fractal maximum-power manner for modeling patterns that increase the probability of energy flow available for use by the brain. *The mental models of mind are thereby mappable back onto the neuromatrix of conscious experience — back onto experienced human reality. Mind and body are algorithmically isomorphic.*[5] With consciousness and mind dynamically nested as described above, we can understand the perplexing problem of how it is possible to simply sit quietly thinking, and create a new idea, system of equations, or technology that works in the 'real world'. Consciousness, thinking, and mind are dynamically interconnected in a seamless web — in a fractal symmetry — see Figures 4 and 7.

7. The autocatalytic exteriorizations of the fractal minds of Immanuel Kant and Albert Einstein: A dynamical unification of intuition and science

Within NP, the same argument that described the relationship between consciousness and mind in the last section can be used to dynamically illustrate (a) the exteriorization of space-time brain organization into the space-time mental models of Kant, and Einstein, and (b) a connection between intuition (conscious brain) and science (mental models). Space and time constitute the fundamental dimensions of the algorithmic organization of the brain as encapsulated from the Lotka scenario (see Figure 6). A previous paper (Vandervert 1992) summarized this situation as follows: "Brains as Space-Time Geometry Machines: The Evolution of the Maximum-Power Matrix", and "The Maximum-Power Evolution of Geometric Mind: Energy Comes to

'Know'" (pp. 257-261). It is not surprising that our greatest thinkers, Kant and Einstein are arguably two of them, would, through thought, exteriorize space-time mental models as fundamental to reality (see Figure 7). Within the brain to mind autocatalytic context of NP, the mathematics of phase spaces, and phase portraits, for example, are *themselves* exteriorizations in mental model form of the space-time organization of the brain.

7.1. *The* a priori *intuitive bases for mathematics and science: The Kantian exteriorization*

Kant (1781/1929, 1783/1953) described space and time as being a priori (*before experience* is the evolutionary interpretation of this term) *in* us. That is, space and time, he argued, are imposed upon what we refer to as nature by the fundamental organization of our minds (his term). Kant's *a priori* represents hardwired aspects of the brain — hardwired aspects of the algorithmic organization of the brain (cf. Vandervert 1993). In NP Kant's *a priori* space and time are interpreted as the direct counterparts of the space-time that (a) arose through the fractal dynamics of the Lotka scenario, and (b) are described by Melzack's hardwired body neuromatrix, and Pribram's holonomic brain theory.

Kant (1983/1953) then described the synthetic (ampliative) *a priori* unfoldment of mathematics *from* this brain-inherent space and time:

> Now space and time are the two intuitions [Kant's 'intuitions' are brain-inherent constructions] on which pure mathematics grounds all its cognitions and judgments that present themselves as at once apodictic and necessary; for mathematics must first exhibit all its concepts in intuition, and pure mathematics exhibit them in pure intuition, i.e., *construct them* [italics added]. Without pure intuition (as mathematics cannot proceed analytically, namely by analysis of concepts, but only synthetically) it is impossible for pure mathematics to make a single step, *since it is in pure intuition* [space and time] *alone that the material for synthetic judgments* a priori [Kant's emphasis] *can be given* [italics added]. (Kant 1983/1953:39)

It is absolutely central to the entire framework of Kant's scientific metaphysics that it be understood how synthetic judgments/cognitions a priori are possible *at all*, that is, how concepts, not analytically related, can be known to belong together a priori (see Kant 1783/1953:27-35 for an extreme emphasis on this point). For Kant, mathematical discovery involves two interrelated ideas and arguments (the dynamics were a mystery to him): (a) mathematics is always a *constructional* variant on the space and time inherent in the brain, and (b) these

variants are synthetic judgments/cognitions *a priori* that come about through some sort of *ampliative* (Kant's term) processes that are themselves inherently nested within the pure intuitions of space and time (Kant 1781/1929:577ff). Kant did not understand the nature of the ampliative processes by which mathematics is constructed from space and time. NP is in complete agreement with Kant as to the above description of the construction of mathematics from the 'material' of space and time, and *proposes further that the ampliative process that is involved in the construction is the self-referential/autocatalytic process described earlier and depicted in Figure 7*. Stated in the more modern terms of this chapter, Kant, 200 years ago, was describing the natural unfoldment of the brain-to-mathematics autocatalysis treated earlier (see also Vandervert 1992:261-264, Vandervert 1993:283-284). Perhaps if Kant had provided illustrations showing the construction of mathematics from the space-time of the brain he might have offered something that we could relate to Figure 7.

The foregoing updating of Kant's argument on the *a priori* origins of mathematics elucidates two general perspectives of NP. First, it provides a direct dynamical, unifying connection between brain-based intuition and mathematics/science. (Kant extended his mathematics argument to science and metaphysics.) Brain-based intuition, as described in NP, is actually the process by which fundamental science and mathematics *can* come into being. Second, Kant's account of an a priori space and time is interpreted as a classic example of how *thought (autocatalysis) can derive its mental models from no where else but the original neuromatrix of space-time consciousness* (see Figure 7). Through his great ability to *think*, Kant was able to describe the fundamental aspects of the organization of his own brain. It is this process, precisely, that was behind the ability of the ancients to model the possibilities of the forms of human reality somewhat accurately as in, for example, Taoism (Vandervert 1990:10). Lao Tzu was in much the same position as Kant (different cultural context), and we will see in a moment, so was Einstein.

Evidence from first person accounts of discovery in pure mathematics/science overwhelmingly support an essential role of intuition (see, for example, Hadamard 1945; Koestler 1964). Probably the most insightful and telling first person description of the fundamental dynamical connection between intuition and mathematics/science by way of the space-time body-brain was that provided by Albert Einstein. However, before getting to that account it will be helpful to describe briefly Einstein's overall view on thinking and intuition.

7.2. *The intuitive leap to the axioms of science: The Einsteinian exteriorization*

Einstein (1981) proposed that *all* fundamental or axiomatic new ideas in science (and, we can assume, new axiomatic ideas in psychology) can originate *only* in intuition:

> [...] the supreme task of the physicist is the discovery of the most general elementary laws [axioms] from which the world-picture can be deduced logically. But there is no logical way to the discovery of the elementary laws [themselves]. There is only the way of intuition, which is helped by a feeling for the order lying behind the appearance, and this Einfuehlung is developed by experience. (Einstein 1981:12)

The role of intuition in the discovery of the axioms of science is as absolutely fundamental to Einstein's epistemology as it is to Kant's scientific metaphysics.

Einstein (1956) described in great detail how he thought intuition fit into the overall process of scientific thought in a personal letter to his close friend, Maurice Solovine. While Kant did not provide us a figure illustration of mathematics arising ampliatively from his *a priori* space and time, Einstein did provide Solovine with just such an illustration of the entire process of *his* version of *thinking* (see Holton 1979 for the most complete discussion and analysis).

Figure 8 is an adapted version of Einstein's illustration of a continuously iterated cyclic process of scientific thinking. The process loop begins with everyday experience, then involves a *necessary intuitive* leap to fundamental concepts or axioms of science, and then back through the testing of predictions (p) or logical consequences against experience. It is important to note that the arrow that arches to the level of axioms does not come into contact with the level of everyday experience. Like Kant, Einstein felt that the intuitive leaps to the axioms were free *constructions* of the human mind, but also like Kant, he was not able in his time to describe dynamically this construction process itself — how we get from the plane of experience to the axioms.

Einstein's illustration and argument are much like the thinking loop that appears in Figure 7. In NP Einstein's intuitive leap *is* the fractal autocatalytic process which generates the mental models of axioms from the algorithmic organization of the space-time, spectra neuromatrix of the body, of consciousness. The neuromatrix belongs in the little gap Einstein left between the plane of everyday experience and the axioms. The body neuromatrix (or human consciousness) acts as the primary level organizational filter that selects

axiomatic patterns from the potential chaos of everyday experience. In NP the body neuromatrix filter includes not only the space-time spectra described earlier, but also the neurology the governs the perceptual constancy mechanisms (Vandervert 1990).[6] Of course, as mental models are acquired by the brain, they act in conjunction with the above as a secondary, nested level of filtering.

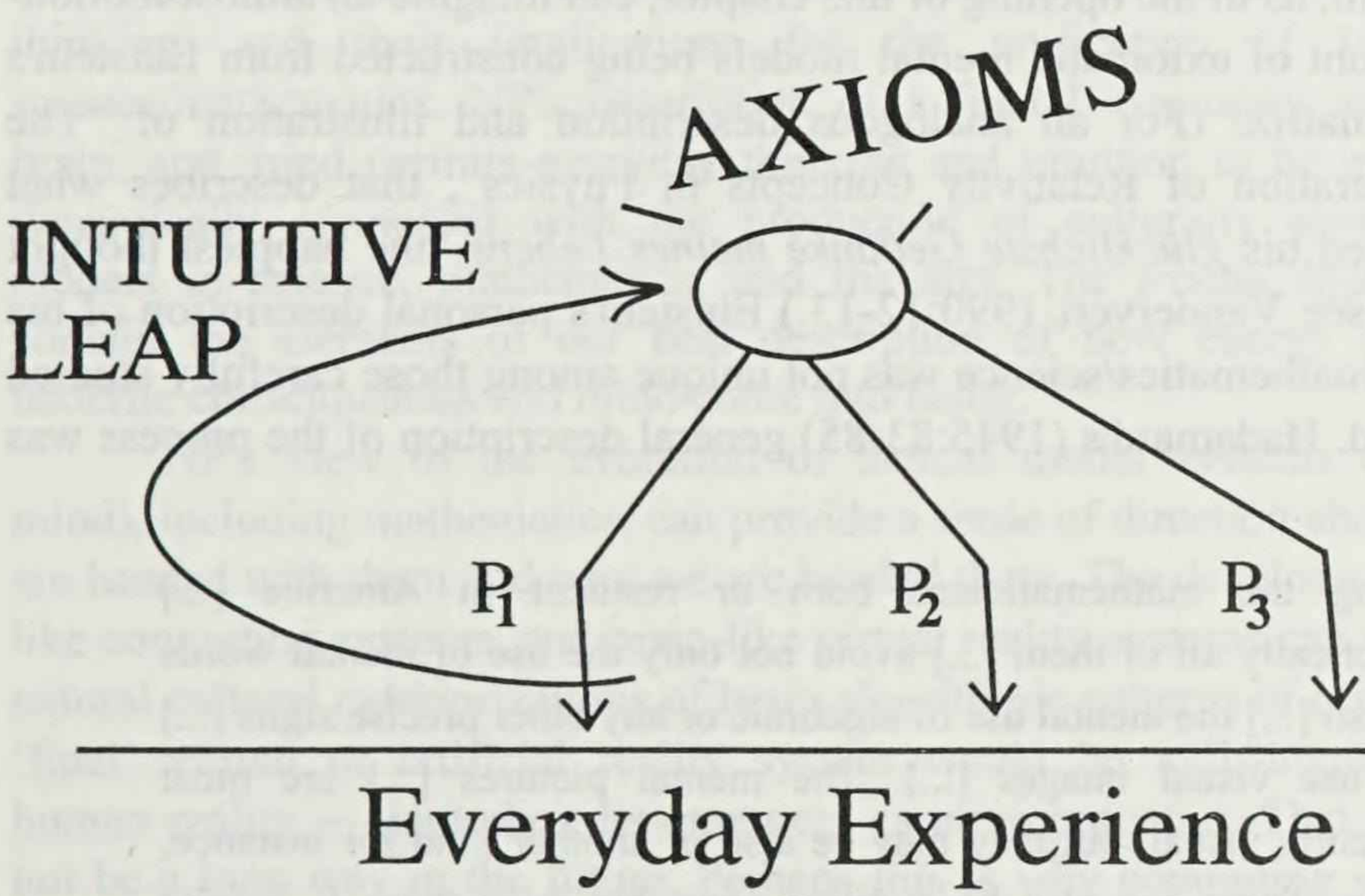


Figure 8: *Einstein's illustration of the role of intuition in the creation of the fundamental principles or axioms of science.*

The above described activity and role of the body neuromatrix in scientific/mathematical discovery is illustrated beautifully in Einstein's classic first person account of his own method of mathematical creation:

> The words of the language, as they are written or spoken, do not seem to play any role in my mechanism of thought. The physical entities which seem to serve as elements in thought are certain signs and more or less clear images which can be 'voluntarily' reproduced and combined. [...] taken from a psychological viewpoint, this combinatory play seems to be the essential feature in productive thought — before there is any connection with logical construction in words or other kinds of signs which can be communicated to others

> [...]. The above-mentioned elements are, in my case, of visual and some of muscular type. Conventional words or other signs have to be sought for laboriously only in a secondary stage, when the mentioned associative play is sufficiently established and can be reproduced at will [...]. In a stage when words intervene at all, they are, in my case, purely auditive, but they interfere only in a secondary stage as already mentioned. (Hadamard 1945:142-143)

Here we again, as in the opening of this chapter, can imagine an almost motion-picture account of axiomatic mental models being constructed from Einstein's body neuromatrix. (For an analogous description and illustration of "The Fractal Generation of Relativity Concepts in Physics", that describes what Einstein called his *glücklichste Gedanke meines Lebens* "the happiest thought of my life", see Vandervert 1990:12-13.) Einstein's personal description of his creations in mathematics/science was not unique among those carefully studied by Hadamard. Hadamard's (1945:83-85) general description of the process was as follows:

> Among the mathematicians born or resident in America [...] [P]ractically all of them [...] avoid not only the use of mental words but also [...] the mental use of algebraic or any other precise signs [...] they use visual images [...]. The mental pictures [...] are most frequently visual, but they may be also of another kind for instance, kinetic. There can also be auditive ones, but even these [...] quite generally keep their vague character. (Hadamard 1945:83-85)

In light of the foregoing overall picture of the intuitive creation of fundamental ideas in mathematics and science, it is not surprising that Einstein, arguably our greatest scientist, provided the world with a model that took it from the space *and* time of Kant to unified space-time in the special theory of relativity, as it is in the dynamical unfolding of fractal sets, and as it is in holonomic brain theory.

In NP the 'body universe', of a Kant or an Einstein, or of anyone, is the cradle of intuition, and its neuromatrix is the *only* pathway to the axioms of mathematics and science (see Figures 4 and 7). The intuitive approach, far from being less than an ideal approach to the discovery of the axioms undergirding the world-picture, may be in fact the *only* way we can break into that realm — that realm that is nature embedded in us — the fractal symmetry of world, brain, and mind.

8. Conclusion and implications

It is a contention of NP that the most complete understandings of phenomena are obtainable with the interpenetration of disciplinary boundaries. Drawing upon interrelated ideas and mechanisms from fractal geometry, dynamical systems theory, general systems theory, psychology, thermodynamics, evolutionary theory, neuroscience, philosophy, and holonomic brain theory, this paper describes the interconnections among consciousness, mind, and thinking, and their implications for the unification of intuition and science/mathematics. NP's description of a fractal symmetry among world, brain, and mind permits everyday thinking and intuition to be understood as dynamically connected with the production of culturally sharable mental models in science, mathematics, and the arts. The *fractal hypothesis* may contain the elements of our best description of how energy patterns that underlie consciousness and mind come into being.

NP's view of the evolution of mental model systems (collectively, mind), including mathematics, can provide a sense of direction about where we are headed with them and why we are headed there. The development of brain-like computing systems, and brain-like virtual reality systems can be viewed as natural cultural exteriorizations of brain algorithmic patterns of organization. A 'final' virtual or artificial reality system would be indistinguishable from human reality — including its emergent creative potential. That may or may not be a long way in the future. Perhaps this is why computing systems have led us to redefine mathematics, for example, as *the science of patterns*, (Steen 1988). Computing systems are approaching perhaps their own origins in the patterns of the brain. Along this line, Moravec (1988, 1992), for example, has predicted a future evolution of robotic brain-like systems through the following sequence: the dumb robot (ca. 2000-2010); learning robots (ca. 2010-2020); imagery world-modeler robots (ca.2020-2030); reasoning robots (ca. 2030-2040); human equivalence (2050 and beyond). According to NP, Moravec's scenario is in complete agreement with an evolutionary unfoldment culminating in the full cultural exteriorization of *appropriate portions* of the algorithmic organization of the brain in symbolic mental model form — that is what it will take, precisely, to obtain human computational equivalence in a computing system (Gödel notwithstanding; see, for example, Nagel & Newman 1958). At this point the mind-body relationship will have achieved a true *central-energy-state-identity*.

We can begin to wonder about the possibilities of what some 'final or full cultural-level exteriorization' of the algorithmic organization of the brain

might be like. According to NP's emergent hypothetical realism (see Footnote 1), that outcome is presently unpredictable and not yet fully imaginable; however one might imagine a science/arts technology in full control of the same emergent evolutionary process that brought humans to consciousness and then to mind — an emergent 'self-selection' toward entropy minima (maximum information) where ultimately anything and everything imaginable might be realizable. This might be a virtual reality system that could explore the endless emergent possibilities of the algorithmic organization of the brain — somewhat as we explore the seeming endless possibilities of the Mandelbrot set, only on an unimaginably larger, and more complex scale. Here would be a *true* theory of everything; here would be, as Stephen Hawking (1988:175) put it, 'the mind of God'. Perhaps this would represent the cultural-level exteriorization and understanding of the deepest of mysteries, of our consciousness of the universe itself. This, however, would only be the beginning of a new emergent level of human understanding.

Notes

1. Although one might interpret NP's focus on the algorithmic organization of the brain as a skull-bound solipsism, NP is *not* a solipsism. NP represents an 'emergent hypothetical realism', that is a variant on Campbell's (1959, 1974) 'hypothetical realism' emphasizing emergence that comes with the evolution of symbol systems. NP proposes that the algorithmic organization that becomes encapsulated in the brain mirrors *a* real world accurately, but in addition proposes that real world can be modeled cognitively in symbolic form in a variety of unpredictable, but deterministic, *emergent* ways. The cognitive models of, for example, Einstein's relativity, Gödel's incompleteness/inconsistency, Heisenberg's uncertainty, are all implicated here. Compare NP's emergent hypothetical realism with, for example, Lorenz (1941/1962a:29; 1977, chapter 1), MacLean (1990, chapters 1 and 29), and Pribram (1986, 1991:xxii-xxix).

2. In NP an *algorithm* is any set of rules, including those which govern chaotic dynamical systems, that perform translational or transformational operations (mathematical, mechanical, linguistic, neurological, metaphorical, homological) that link problems, input data, and solutions. At the same time algorithms cannot solve problems (cannot do work) either in theory or practice unless transferred in some thermodynamic manner. The thermodynamic *methods* of heat and work constitute the definitional bases for all algorithms. Algorithms are therefore also orderly methods of energy/information *transfer* that will provide solutions to problems (see e.g., Atkins 1984, chapter 2). NP's definition of

algorithm places the origins of all algorithms in the evolution of problem solving in the brain as depicted, for example, in Figures 6 and 7. In the thermodynamic scheme of things, since no change of any kind can occur without an energy/information flow (not even an abstract thought about algorithms, or an observation), there can be no such thing as 'nonalgorithmic' problem solving. Penrose (1989), for example, discussed the relationship of algorithms to mathematics, and to a small degree mental processes. Penrose's description of algorithms occurs at the level of the mental models of mathematics and artificial intelligence as if these mental models somehow represent the fundamental nature of reality, and then works backward to the problem solving organization of the brain. Thus he is forced to infer that some processes of consciousness — for example, intuition — must be 'nonalgorithmic'. By describing algorithm at the mental model level only, some aspects of consciousness for Penrose become inexplicable and thus his term nonalgorithmic. Yet, he uses terms like 'see' and 'feel' in the brain process intuitional sense as if these come to consciousness free of any rules or methods (nonalgorithmic) at all — a rather surprising suggestion for a physicist! When it is recognized that all algorithmic organization begins in the brain, and these, in turn, give rise to the mental models of mathematics and artificial intelligence, the term nonalgorithmic could only mean 'nonbrain'. In NP what Penrose calls nonalgorithmic are the deterministic, yet unpredictable features of chaotic nonlinear dynamical systems. These are not ruleless nor methodless. For more complete discussion of algorithms see Vandervert (1991, 1992).

3. See also MacLean (1991), and Vandervert (1990-1992) for discussions of chaotic/fractal brain processes.

4. Mental models in NP are *representations* of conscious reality as defined earlier (space, time, spectra and constancies) which are *self-similar* in many ways, but not in all ways, to what is being represented. These models vary in level of abstraction (remoteness from what they represent) and in complexity. A common breakdown of types of mental models, in order of increasing abstraction and complexity, is the following continuum: (a) *iconic* (in its own image), (b) *analogic/homologic* (parallel in form, but not self-same), (c) *symbolic* (algebraically isomorphic) (Ackoff, Gupta & Minas 1962).

5. Within the system-theoretical framework Bertalanffy (1967) described *algorithmic isomorphism* among machines, brains, and conscious mind:

> Obviously, logical operation performed in consciousness and the structure and function of the brain "is" not an electronic computer with transistors, wires, currents, programs and the rest. But in their formal structure they are comparable. Similar algorithms obtain: a computer (and a brain in its rational aspects) is, as it were, a materialization of logical operations, and vice versa

> logical operations are the conceptual counterpart of the functioning of a suitably constructed computer. This correspondence is a rather deep one. Boolean algebra and binary notation used in modern computers, the functioning of synapses according to the all-or-none law, and Aristotelian logic in thinking are structurally the same; the same algorithm or abstract model applies. (Bertalanffy 1967:100)

The algorithmic unity of world (machines in Bertalanffy's example), synaptic configurations in the brain, and mind (the subcircuitries for the mental model of, for example, Aristotelian logic) is the central positivistic tenet of NP (Vandervert 1988, 1990). Since, in NP, everything knowable is based upon the algorithmic organization of the brain, there are necessarily no 'nonalgorithmic' processes possible. This position would be falsifiable with the demonstration of something moving about at absolute zero. Such a demonstration would, however, violate the third law of thermodynamics.

6. Lorenz (1959/1962b) articulated the idea that the mechanisms of the perceptual constancies might underlie the operations of scientific activity; although he did not have at his disposal a specific process by which to connect them:

> Without the perceptual apparatus, above all without the literally *objectifying* achievement of the so-called constancy mechanisms, we could know nothing about the existence of those natural units of varying duration which we call *objects* [...]. If one assumes a real external world at all, one has to concede that the way in which the simplest forms of space orientation and perception transmit to us, by analogy, knowledge of extra-subjective actuality; is basically equivalent to the way in which the highest forms of reason [science, in this context] do the same (differing only in degree of analogy reached). (Lorenz 1959/1962b:37-38)

Lorenz seems to have been close to developing a NP-like neuroepistemology. In this regard see also Lorenz (1941/1962a, 1977).

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Appendix

Fractal Maximum-Power Principle

The maximum-power principle may be stated as follows: *Those systems that survive in the competition among alternative choices are those that develop more power inflow and use it to meet the needs of survival.* They do this by: (1) developing storages of high-quality energy; (2) feeding back work from the storages to increase inflows (self-referentially); (3) recycling materials as needed; (4) organizing control mechanisms that keep the system

adapted and stable; (5) setting up exchanges with other systems to supply special energy needs; and (6) contributing useful work to the surrounding environmental system that helps maintain favorable conditions (Odum & Odum 1981:32-33). Lotka (1922, 1945) formulated the maximum-power principle, suggesting that systems prevail that develop designs that maximize the flow of useful energy through feedback. These feedback designs are sometimes called *autocatalytic* (self-releasing, or feeding upon self) (Odum 1983:6). The autocatalytic relationship between brain and mind is one of *positive-feedback*, whereby energy dissipation is progressively accelerated. The maximum-power principle is a macro principle of self-organization (Odum 1988; Vandervert 1991) that *itself* becomes encapsulated in the algorithmic organization of the human brain, thus giving rise to the possibility of the evolution of the fractal-holonomic neural subcircuitry of the mind. It is manifest, for example, in the self-organization of the perceptual constancies, cognitive systems (e.g., Stadler & Kruse 1990), and in the autocatalytic emergence of mental models (Vandervert 1991, 1993).

Fractal Autocatalysis

The autocatalytic feeding back of higher-quality energy into increased energy inflow into the brain, as described by the maximum-power principle, can be viewed as an energy appearance of fractal organization. Odum (1988) expressed this relationship in the following manner:

> Ecosystems, earth systems, astronomical systems, and possibly all systems are organized in hierarchies because this design maximizes useful energy processing. These systems look different until they are drawn with energy diagrams [...]. The series of energy transformations in the hierarchies formed by self-organization are cascades of successive energy fractions, which explains why Mandelbrot's (1977) fractals often describe nature. (Odum 1988:1133-1135)

The relationship between the algorithmic organization of the brain and the algorithmic organizations of its mental model circuitry configurations can be viewed either in terms of *self-referential* energy flows (causal pathways), as Odum has done, or in terms of *self-referential* fractal energy designs (Vandervert 1991).

Recognition of the equivalence between the fundamental characteristics of maximum-power-principle hierarchies and those of fractal energy designs, namely self-similarity (not self-sameness), self-referencing, and infinite hierarchy nesting, leads to the central principle of NP governing the cultural evolution of mind: in its production of mental-model brain circuitry, the algorithmic organization of the brain can increase energy inflows to itself most efficiently (fractal maximum-power principle) by feeding back algorithmic mental model designs that are *similar* to itself. This is so because the brain, being at the top of the energy hierarchy, represents the highest-quality energy configuration and could not feed

back designs other than or superior to its own. Thus the brain is constrained to create its mental models, for example, science, art, technology, computing systems, virtual reality, in its own dynamical image, so to speak.

The Fractal-Like Roots of Mind:
A Tutorial in Direct Access

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1. Introduction

The aim of the present paper will be to display what the possibilities for fractals to 'be' mind are, in a sense more than just mathematical models of different processes in nature and in the brain. To prove that, we should give an account of how fractals become accessible, if at all, to consciousness. I chose for my argument the analysis of the work of two 'phenomenologists' — the phenomenologist of nature in experimental mathematics, Benoit Mandelbrot, and the phenomenologist of mind in psychology of perception, James J. Gibson. In the third part of this article I will discuss some implications of fractal mind hypothesis.

A mathematician or computer scientist could benefit from this contribution in becoming aware of the psychological purport or significance of nonlinear dynamical modeling of different systems. A psychologist could become better oriented to the potential of a class of formal models which seem appropriately to approximate some aspects of perceptual processing. A brain scientist might benefit by considering the conjecture developed here about the 'direct interface' (no 'hidden layers') between mind and brain in the case of perceptual processing (among others). A linguist may become better oriented into the range of differences between language-specific and language-nonspecific mind processes and structures. A philosopher could consider the point about the margins-of-reality and the possibilities for formal specification of the latter.

2. The challenge of fractal geometry

2.1. *Can one see a fractal?*

The answer might look self-evident: Yes, of course. And the first proof that comes to mind, *vox populi, vox dei*, is the massive fascination with fractals in the last ten years. This is by itself a phenomenon requiring explanation — that so many people far away from mathematics, physics, etc., became enchanted with something mathematicians themselves only twenty years ago conceptualized as 'mathematical monsters'.

If we think a bit more, the convincing (first-person) 'evidence' for the reality and possibility for direct access to fractals seems to come from 'fractal forgeries' (cf. Mandelbrot 1983). When one looks at some computer-generated fractal images, there are cases when they definitely look like some aspects of pictures taken from nature. That seems to be an intuitively plausible 'proof' that fractals are available in nature and we can see them 'directly' — fractal for fractal. But please note that with this preliminary step in approaching the problem we already introduced two troublesome concepts — 'intuition' and 'to look like a picture (taken from nature)'.

We seem, as a matter of fact, to be further away than our initial intuitions were prone to situate us from the definite answer to our question, can we SEE a fractal, because the latter depends (among others) on what we mean by 'seeing' and what by 'fractal'. Is the fractal an object from reality, a mental image, an ideal mathematical object, or the way the brain computes for us the things we manage to see? We have first to locate fractals somewhere in their 'primary reality' in order to be able afterwards to sketch the way of access we have in 'seeing' them. Penrose (1990) located them in the realm of Platonic mathematical objects. Mandelbrot (1983) made his explicit choice, when he projected fractal geometry to nature itself, but in reality he remained a bit ambiguous. In his presentation, he treated fractals as mathematical objects, too; in nature, from the other side, we can find fractal-like forms (cf. the discussion below). He did not discuss explicitly the problem about the relationship of fractals to mind and to brain functioning (except for two remarks about mammalian brain folds and brain geometry, treating brain as a physical object; cf. Mandelbrot 1983:113, 162), while everybody would agree (at least in principle) that in order to see and think about fractals, the mind/brain of the thinker must fulfill its job and 'have access' to them, in one or other way. The other possibility — that we cannot see fractals but can talk about them — was also found possible to maintain (this is, in effect, the position of Leyton

1992:158). Analogically, nobody ever saw quarks, but there are physicists who believe in the existence of the latter in nature and who talk about them.

When one looks at a fractal, one is supposed to perceive it (or some approximation to it), and think about it, e.g., "I see now the Mandelbrot set", etc. But maybe one can also imagine a fractal? One can imagine a cow, rotate a mental image of a polygon or make a mental model of one's way back home from one's office, but can one, in this way, imagine the Mandelbrot set? The reader is advised to try for him/herself the following: Find a good picture of Mandelbrot set in color. Stare at it for several seconds, focusing on different aspects of it, without losing the 'context' of the set as a whole. Close your eyes and try to visualize the set. Please consider afterwards why one cannot imagine it in any more or less precise detail (i.e., to form a 'dense' enough image of it, but not a vague contour) even in its most preliminary approximation.

There is a caveat to the statement made in the previous paragraph. Even if we cannot intentionally visualize a fractal (as the reader may already convinced him/herself), we can see in our dreams fractal-like structures (cf. Shepard 1983; Shepard, Downing & Putnam 1985). We have reports about fractal-like patterns from the investigations of some altered states of consciousness (e.g., the complex geometric synaesthesias of Klüver 1966; cf. also Horowitz 1970, 1975; Hunt 1985, 1992). In other words, even if perception seems dominant in giving us potential access to fractal-like structures, it is not the only source for our experiences of this sort; there are clues that some self-organizing processes in the brain as an autonomous system might obey the laws of dynamical systems (cf. Globus 1995; Hardcastle 1995; Kelso 1995) and their outcome in mind may have a fractal-like structure. This is the reason we will speak about the impossibility of imagining a fractal pattern as impossibility to visualize *intentionally* the process or the outcome of its formation.

There is a further aspect to our question. If we can see a fractal (let's accept provisionally this possibility for a time being), can we also 'see' that we see a fractal, i.e., can we become aware that we see a fractal, but not, say, a set of slanted regular polygons? In other words, there is an aspect to this problem which we cannot escape from touching upon: What is the relationship between experiencing (seeing) a fractal and becoming aware of the nature of this same perception? I would like to point out, that 'to think about a fractal' and 'to become aware of a fractal' do not necessarily coincide. We can assume the existence of conceptual awareness of a fractal, when we think that some pattern is fractal or fractal-like, but this is not the same as 'perceptual awareness'. We can be perceptually aware of the specificity of the voice of some acquaintance

of ours without being able to conceptualize, why (due to which features) we manage to distinguish the uniqueness of his voice.

In the case of fractals, the relationship between conceptual and perceptual awareness looks, from some point of view, unlike the example with the voice differentiation. After the popularization of fractal pictures many people started to talk about fractals and some even decorated their dining rooms and saunas with their computer-generated approximations (images). But when we look around in the world we continue to be unable to discern on first look is some pattern fractal (or fractal-like) or not fractal at all. The relationship between perceiving a fractal and becoming aware of fractality is, probably, quite problematic, otherwise fractals could have been discovered not only 25 or so years ago, but at the time of Plato or Leibniz. In other words, they seem to be something quite nonself-evident and very difficult if at all possible to willfully imagine and become conscious of. They touch in a subtle way the problem of *the limits of our capacity to become aware* of some things at the expense of others in the mental economy. Fractals display some aspects of the formal structure of the 'horizon of discernibility' in our apprehension.

The next question to face is: When we manage to see a fractal, if we at all can achieve this feat, what happens in the brain? Can we expect that performance to be an outcome of mind/brain parallelism (symmetry) in processing of fractal surfaces of natural objects or of pictures generated by computer graphics? In this case, a fractal in the brain is *non-different* from the fractal in the mind, independently of our stance on mind/brain problem — dualism, identity, etc.

If one thinks that this is the end of the troubles, s/he is wrong — there is a further question we must face. The attempts to prove the fractal-likeness of some patterns in nature itself turned out not to be an easy task, too. If we compare the set of phenomena, where fractal modeling was attempted, we may get the impression that fractal-likeness, as much as it looks at first sight ubiquitous, on closer scrutiny finds its place somehow at 'the margins of reality' both literally and metaphorically, e.g., far away in the universe or in the fluctuations of EEG of the brain we cannot currently make good sense of. This can also make us wonder, how much of fractal modeling belongs to the model (with its idealizations) and how much to the object modeled with these means.

As the reader may already convinced him/herself, the more we discuss the possibility for *direct access* to fractals (fractals in nature = fractals in mind), the more troublesome our problem turns out to be. As a matter of fact, it starts to become evident that the idea about the direct access to fractals requires a proof of the following type: fractals in nature ≡ fractals as mathematical objects

≡ fractals in brain ≡ fractals in mind. This and only this fourfold *correspondence*, if proven, would be convincing for the possibility for us to see fractals *directly* (if we start from form in nature, as Mandelbrot did).

2.2. *More about mathematical and physical reality*

Can a visual illustration be of some use or even prove something in mathematics? This was the explicit question to which Mandelbrot (1983:21-23) dedicated a special paragraph, where he pointed out that mathematics in its development in the last 100 or so years moved in the direction of believing less and less in the 'eye' and the possibility for intuitive apprehension. He cited, in this relation, a famous saying of Georg Cantor in reacting to some so called 'mathematical monster': "To see is not to believe".

The problem, however, turns out not to be simply related to the possibility to visualize different mathematical structures (the ability to imagine formal manipulations and their outcome), but also to the possibility to 'see' the structures in the world as they really look like. This seems to be, as a matter of fact, the purport of the passage cited by Mandelbrot from P.A.M. Dirac (in the preface from his 1930 *Quantum Mechanics*):

> [Nature's] fundamental laws do not govern the world as it appears in our mental picture in any very direct way, but instead they control a substratum of which we cannot form a mental picture without introducing irrelevancies. (cited according to Mandelbrot 1983:21)

The trouble is not simply related to the possibility for access with one's 'mental eye' to different types of mathematical structure and the potential manipulations with it during the process of mathematical thinking and discovery, but also to something else. With mathematical structures we can model things we are unable to discern in the real world because of the capacity of the mathematical models to embody structures we are not able to imagine. With mathematical structures we are unable to imagine we model the way the world really is. That might sound paradoxical, but this is the purport of the claim: The "real 'real'" structure of the world is *impossible* to access directly in the 'mental pictures' of perception-cognition continuum. We can visualize this structure only at the expense of introducing anthropomorphic irrelevancies. We have no *direct access* to the world's elemental nature. The structure of the world is impenetrable and will remain opaque in its basic or fundamental laws probably forever. The same holds for the immortal objects of the world of mathematics. We can model veridically the real world with mathematical patterns because of, among others, their irrepresentability to senses.

The 'final' background or 'canvas' of images we can experience (as rooted *both* in the world and in the brain [because the latter is also part of the world]) is itself out of the representative capacity of mind. And there is such a 'ground', according to the belief expressed by Dirac. Its inaccessibility seems to be not due simply to the micro- vs. macro-scale of its implementation, because we can imagine a case where a self-similar fractal pattern is enacted on both scales in one and the same physical system.

In discussing the purport of the statement of Dirac as quoted by Mandelbrot, we saw that there are several aspects in mapping some formal structure to mind and the world. We require a more detailed discussion of each of them. Let's now make an attempt to consider them one by one in their relationship to the capacity to see and visualize different objects.

2.3. *The mathematical reality as a visual representation at the edge-of-evanescence*

The explicit aim of Mandelbrot (1983:21-23) in the paragraph we commented upon was in line with the way a mathematician discusses the relationship between mathematical structure and its representability in mind (its capacity to be directly accessible or visualized). To the trend negating the functionality of visualization in mathematical modeling, Mandelbrot juxtaposed his doctrine that at least in some branches of mathematics like fractal geometry, the opposite of the tenet 'to see is not to believe' is true.

Nevertheless, Mandelbrot subscribes to the 'standard' view about the ideal nature of the mathematical objects. The latter view is as follows. Any attempt to illustrate geometry is based on a convention. We represent the ideal mathematical objects like the straight line, which in mathematics is imagined to be unbounded and infinitely thin and smooth (i.e., at the *edge-of-evanescence* from imaginal representability; practically impossible to imagine realistically), as a line of finite length, positive thickness, and rough edged. For all practical purposes, however, it suffices that a geometric concept and its image should fit within a certain range of characteristic sizes, "ranging between a large but finite size to be called outer cutoff and a small but positive inner cutoff" (Mandelbrot 1983:22).

Please note that even if there is a difference between an ideal mathematical object like that of a straight line and a fundamental law of nature (in the case discussed by Dirac above), they were implicitly equated by Mandelbrot in the context of the book, making them indistinguishable from each other on the ground that they both are irrepresentable without introducing

irrelevancies. What is the basic 'irrelevance' in the case of representing mathematical objects from fractal geometry? It is related to the specificity of fractal structure — all self-similar fractal curves are unbounded and infinitely thin; each has a specific lack of smoothness; each of them has the characteristics of scaling. To represent an infinitely scaling fractal is as possible as representing an unbounded straight line.

The purport of the argument is that we cannot see mathematical objects; we see approximations to them. We cannot see fractals, but we can see fractal-like shapes. When we stare at the Mandelbrot set itself, we see not the set itself but an approximation to it. This is the case even within the range of application of 'to see is to believe' doctrine.

The same is the situation with our capacities to see the physical reality on the microscale Dirac discussed above. What is troublesome in this equation of representability (mathematical object = object from reality) is, however, that the *tertium comparationis* for it is a negative one — the inaccessibility in principle to senses. For some time in the history of science both mathematicians and physicists tried to get 'outside of the horizon' of what is in principle possible to see and they expressed this *Drang* in the form of the dictum "To see is not to believe". Mandelbrot broke this vicious circle from some perspective. What the consequences are remains to be considered.

2.4. *A revision of the relationship between real and ideal shape*

If it is accepted as self-evident by professionals nowadays that the Euclidean geometry is an idealization of the forms we actually can face in the environment, we can try to approximate the actual shapes *we see* in nature with different formal means. This exercise, unlike the modeling in microphysics, is dependent on the eye by definition. And it turns out that the 'monstrous', the most counterintuitive to the mainstream mathematics (at some stage of its development) orientation is closer to the way the forms of nature look compared to Euclidean forms we became accustomed to manipulate in the school. The 'monstrous' turned out to be better applicable to some aspects of form in nature than the ideal and regular shapes. Mandelbrot points out, in this association, that he was the first to show that D (the fractal dimension) can be used successfully in the description of nature (Mandelbrot 1983:16). And he writes three pages later that even such preliminary type of modeling of natural shapes as that with idealized scaling fractals already can provide "first approximations of the natural shapes to be tackled" (Mandelbrot 1983:19).

As we can see, the aim of Mandelbrot is with some formal means by a set of oscillating moves of idealization and ramification to model the way *the*

actual shapes from nature look. But he forgets emphatically to stress the importance of the omnipresent *tertium comparationis* in this strategy — the visual perception and its capacities. If we say that some fractals look like a mountain, or alveolus, or the tissue of the brain itself, that is right — they LOOK like one another. The *tertium comparationis*, the INTERFACE, ultimately, is in the structure of perception. This is the level of primary reality of fractals. If there is something fractal-like, it is FIRST and foremost to be searched at the level of perceptual structure, and only secondarily to be projected somewhere else. This is the way the 'father' of fractal geometry approached the problem. His explicit treatment of the doctrine 'to see is to believe' might be open to criticism, but the way he approached modeling is available in his casebook for unprejudiced (from psychological point of view) inspection.

Fractals acquire their meaning as approximations to some real shapes from nature but not *vice versa*. They are idealizations of some features of the structure of real shapes we see around us. And the similitude between the model and the shape from the real world it models is judged by the eye:

> A formula can relate to only a small aspect of the relationship between model and reality, while the eye has enormous powers of integration and discrimination. (Mandelbrot 1983:22)

Mandelbrot says it; for us it remains to draw the consequences. To make it clear, I do not claim that the physical reality is what it looks like (otherwise the pursuit of natural science would be superfluous). I only try to find a home for fractals and what and how they are supposed to implement.

2.5. *More about mathematical monsters and introducing mathematical intuition*

Mandelbrot (1983) takes as a mainstream straw man from the discipline of mathematics Hans Hahn (1956), in order to display how unreliable the intuition, imagination and beliefs of mathematicians might be. What for many professionals in the field looked like 'mathematical monsters', turned out to be more realistic, more nature-like, from some points of view, than the age-old Euclidean geometry. I have no intention here to analyze in depth such controversial concepts like 'mathematical intuition' or 'mathematical imagination', but some remarks are appropriate in the context of our discussion what it could mean 'to see', 'to visualize' (or 'to imagine'), 'to logically analyze (= to think about)', 'to remember', and the like in the context of fractal geometry.

Mandelbrot cites the following passage from Hahn (1956) as an introduction to the way of thinking of the latter author (in order to continue repeatedly to use his book as an example, what the intuition should not have been like):

> [...] the character of [a *non*rectifiable curve or of a curve without a tangent] entirely eludes intuition; indeed after a few repetitions of the segmenting process the evolving figure has grown so intricate that intuition can scarcely follow; and it forsakes us completely as regards the curve that is approached as a limit. Only thought, or logical analysis, can pursue this strange object to its final form. Thus, had we relied on intuition in this instance, we should have remained in error, for intuition seems to force the conclusion that there cannot be curves lacking a tangent at any point. This first example of the failure of intuition involves the fundamental concepts of differentiation. (Hahn 1956; cited acc. to Mandelbrot 1983:35)

When introducing another basic mathematical monster — that of Peano curve — Mandelbrot (1983:75) also uses the occasion to cite Hahn (1956) in order to make an objection to his way of thinking. The latter author says that those objects also are totally counter-intuitive and extravagant. Mandelbrot, however, comments to the effect that when a mathematician makes some effort to "examine a good Peano graph with care" he starts to become aware that professionals like Hahn lack "geometric imagination". The right operation (not unlike some meditative exercises) in facing Peano teragons is, according to him, of the following type:

> [...] after Peano teragons are observed attentively, letting one's thoughts wander about, it becomes very difficult *not* to associate them with diverse aspects of Nature. (Mandelbrot 1983:59)

Please note that Mandelbrot does not suggest imagining the stages of construction of a Peano teragon with one's 'mental eye', but observing a drawn (finished) graph of it attentively, in a concentrated way, while at the same time letting a free play of thoughts around this form given in perception. This is something different from the problem suggested by Hahn, who seems to be preoccupied with the possibility of modeling the way of construction of Peano curve up to its limits in real time before one's 'mental eye'.

The story repeats itself for the Sierpinski gasket (cf. Mandelbrot 1983:131), where Hahn points out that a curve made up of nothing but branch points seems totally to elude intuition.

A final stroke against Hahn is made in a special paragraph "On Intuition, Old and New" and the object of disagreement this time is the

Brouwer pattern. Here one basic belief of Hahn comes out in open air, when he claims that "in simple and elementary geometric questions, intuition is a wholly unreliable guide. It is impossible to [let it] serve as a starting point or basis of a mathematical discipline. The space of geometry is [...] a logical construct" (cf. Mandelbrot 1983:150).

The curious thing is that Hahn is right, but not from the point of view he expresses explicitly. He is right in pointing out that the Euclidean geometry is a 'logical construct' due to some idealizations imposed on the way perception itself represents space (cf. the discussion of direct perception by Gibson 1979 below). But he seems to be strictly wrong, when he maintains that 'intuition' becomes what we happen to learn and habituate to 'at our mother's knee'.

The response of Mandelbrot (1983:150) to Hahn on this occasion is not completely convincing. He proclaims the need 'to train intuition to perform new tasks', because the typical mathematician's view of what is intuitively acceptable is wholly unreliable. To 'train intuition', however, makes sense to me only if we accept the thesis that one can train oneself not to hinder intuition, but not to 'educate' it, or 'harness' it, or whatever. And the only technique of value Mandelbrot (1983:59; cf. above) explicitly gives in this respect, itself requires serious psychological interpretation in order to serve as a guide, what one is supposed to do. If anything, the association of 'intuition' is not with 'training', but with 'spontaneity'. Spontaneity and training look like antonyms, having the functional value of opposites in everyday experience. What one can train for, however, is how not to hinder the expression of intuition, its spontaneous emergence. This makes more sense.

The discussion of monstrosity and intuition can make us aware that the necessity to keep apart the forms accessible in perception, imagination, intuition, and thinking was felt by mathematicians, in one or other way, in their creative work. The new forms, as apprehended in reality and as discovered in the process of mathematical thinking, come from the perceptual realm 'at the edge-of-evanescence'. In this respect, the pathos of fractal geometry is based on the foundational value of perception in discovering new mathematical forms, but not on a purported (mystical) access to some (supernatural) realm of mathematical objects, as repeatedly suggested by some mathematicians.

Penrose (1990), for example, very much wondered that there are physical laws that have truly *phenomenal* accuracy, and are, moreover, extraordinarily amenable to precise and general mathematical treatment (the 'wonderment' motive about the 'unreasonable effectiveness of mathematics' in managing to describe the world around us was introduced by Wigner 1960). He

proposed to consider them as providing theories he called SUPERB, i.e., literally matching the phenomenon in question. As a case in point he brought to attention the Mandelbrot set. This set exists for Penrose 'out there', (as if) independently from the conceptions of any particular mathematician and from different implementations according to the particular technology of any particular computer. Its existence is not material, in any ordinary sense, and it has no spatial or temporal location: "It exists, instead, in Plato's world of mathematical entities" (Penrose 1990:647).

Penrose relates to each other the mathematical entities, physical laws and our capacity to apprehend both of them in the following way:

> The relation between the real physical world and the Platonic one is a mysterious one. The very existence of the SUPERB physical theories begins to give the seemingly "solid" matter of our experiences an apparently nebulous "mere mathematical" Platonic existence, whereas examples such as the Mandelbrot set seem to make the Platonic world more concrete. Might the two worlds be, in some sense, actually the same? The whole issue of consciousness seems to me to require a much deeper investigation of the relation between the physical world and Plato's world than has been achieved so far. (Penrose 1990:654)

It is significant to notice that Penrose (above) tried to associate the physical world and the world of mathematical entities through the phenomenon of consciousness (seemingly quite *ad hoc* in this context), but not explicitly through the mediation of conscious *perception* (and/or cognition and/or imagination) with its laws of structure formation.

In this context, we can better appreciate an aspect of the significance of fractal geometry. It gave impetus to distinguish between 'mathematical imagination' and 'mathematical (or formal) structure of perception'. What is at stake in fractal geometry is the latter. Here we can locate the contribution of Mandelbrot (in the context of our discussion): The fractal geometry extends the inquiry of geometry beyond the bounds of 'mathematical imagination' into the realm of the 'formal structure of perception'.

Mathematical idealizations, according to the view presented here, introduce factors of 'irrelevance' to the perceptual images we form of reality. This irrelevance is responsible for the approximate relationship between model and object of modeling. Mathematicians and physicists however maintain, *vice versa*, that perception introduces irrelevancies into the way the physical world turns around (cf. the opinion of Dirac above). From a second side, the latter nevertheless strive to achieve SUPERB models or theories (cf. Penrose 1990)

which literally match the phenomena from nature. From a third side, they continue to believe in the existence of a separate Platonic world of mathematical entities. These views is very difficult, if at all possible, to make commensurable in a coherent way in a single theory.

To get things right for the class of situations we are talking about which share the feature of visibility, we could state the following: The 'primary reality' of this type of mathematical models, if any, is in the structure of perception. While Merleau-Ponty (1964) is well-known for his philosophical thesis about 'the primacy of perception', here we are talking about the latter's primacy in formal terms.

2.6. *Dimensions and images in representing space*

In modeling the perceptual space (our own object and the self-unconscious object of every mathematician who strives for phenomenological accuracy by formal means), it turns out that we need more than one dimensionality. This might look implausible, because we feel we live in an uniform space, while the space on a large scale in the universe might be considered nonuniform for physical reasons (but we are not in touch with the latter). Our own intuition of living in an 'uniform' space might lead us to accept something else: For every visually representable set its useful dimensions must coincide, i.e., form what Mandelbrot names *dimensionally concordant sets*, as is the case with Euclidean geometry. A *tour de force* along these line is the Radical Computational Vision of Leyton (1992) with its foundational concept of *well-formedness* (i.e., dimensional concordance). Nevertheless this may turn out to be a wrong intuition about the structure of the perceptual space (if we prove that we can see fractal for fractal) because fractals are mathematical sets which are *dimensionally discordant* (cf. Mandelbrot 1983:14). A fractal is dimensionally discordant by definition, because its topological dimension D_T is always an integer, but its fractal dimension D need not be an integer, i.e., $D > D_T$. The two dimensions do not coincide while they characterize one and the same space.

An illustration of the concept of topological dimension D_T can help us orient into the problem of the possible relationship between two discordant dimensions. D_T is the same for all single island coastlines on the planet Earth, e.g., Great Britain, Sumatra, Cuba, etc., because they all are topologically identical to a circle. What makes each one of them an 'individual' is their fractal dimension D, because the latter characterizes differences in the nontopological aspect of form. As a matter of fact, "most problems of real

interest combine fractal and topological features in increasingly subtle fashion" (Mandelbrot 1983:17).

It is at this point that the concept of effective dimension is introduced. This is done with the help of two 'images' we will now analyze in more detail. According to the first 'image', we must consider effective dimension as concerning the relation between mathematical sets (like D and D_T) and natural objects. Physical objects 'by themselves' such as a veil, a thread, or a tiny ball should all be represented and thought as three-dimensional shapes. However, physicists and mathematicians can imagine a veil, a thread, or a ball as being of a 'lower' dimension, if they are fine enough, e.g., of dimensions 2, 1, and 0, respectively. Especially interesting is the case where we can choose the direction of collapse or emergence of a dimension. For example, we can choose to represent a two-dimensional thread with theories relating to sets of dimension 1 *or* 3, modifying the latter in corrective terms and judging which one of them is a better geometric model of the physical object in question. The better one is determined after the fact, as involving the smaller corrections. In some cases, the mathematical model can continue to be helpful in representing appropriate aspects of the object in question even when corrections are omitted. At this point Mandelbrot (1983:17) moves to a conclusion, which does not look to me self-evident from the illustration just given: The effective dimension, *ergo*, inevitably has a subjective basis. And why? Because it is a matter of approximation and therefore of degree of resolution. But 'approximation' is not necessarily equivalent to 'degree of resolution', e.g., if we try to match, for example, a set and an object in a superb (Penrosean) way. Please also note that the degree of resolution in the example with the thread can move not only in the direction of 'collapsing into a lower dimension', but also in the direction of 'emergence into a higher dimension'.

The second 'image' helps us better to orient into the subjective basis of the effective dimension. If we imagine a ball of 10 cm diameter made of a thick thread of 1 mm diameter, the latter will possess in latent fashion several distinct effective dimensions. Depending on the position of the observer, one of the latter (potential) effective dimensions of the ball becomes the actual effective dimension of its representation. To an observer placed far away, the ball appears as a point, i.e., as zero-dimensional figure. From a distance of 10 cm resolution, the ball of thread is a three-dimensional figure. At 10 mm, it is a mess of one-dimensional threads. At 0.1 mm, each thread becomes a column and the whole becomes a three-dimensional figure once again. At 0.01 mm, each column dissolves into fibers, and the ball once again becomes one-dimensional etc., with the dimension crossing over repeatedly from one value

(0, 1, 3) to another. When the ball is represented not as a single point, but as a finite number of atomlike points, it will become zero-dimensional again. In other words, each object from the world can exhibit a succession of different effective dimensions. In the case of the dimensions of the ball, the latter were all integers (cf. Mandelbrot 1983:17-18). Some of them, like 0 and 1 effective dimension are definitely approximations to the 'real' three-dimensional form of the ball in question (according to the discussion of the first example introduced above). The situation is further complicated by accepting the possibility that one and the same object can be approximated not only by a succession of different effective dimensions, but that the relationships between the latter are not always possible to be well-defined, i.e., there are certain ill-defined transitions between zones of well-defined dimension. These transitions are reinterpreted as being *fractal zones* within which $D > D_T$ (Mandelbrot 1983:18).

If we try to construct a single representation of the space introduced in the examples discussed after Mandelbrot above, we will soon start to find inconsistencies among the two images. The situation is much more complicated than we should have expected. Mathematical sets can characterize natural objects in different ways on different occasions depending critically on the distance from the observer. Several mathematical sets or combination of their features can describe in more and more subtle way one and the same object in some space, 'spatializing' in different way the object in question (i.e., forming 'a common region'; cf. Palmer 1991, 1992). The problem with the representation of the object turns out to be that of the way we represent 'the space of the object', but not of 'the object in space'. This is quite important to acknowledge. In other words, here we are speaking about the possibilities of mutual inclusion of spaces and spaces within spaces and the relationships between spaces with concordant vs. discordant dimensionalities. At stake is also the problem (not discussed by Mandelbrot) that the observer him/herself is not outside the space (as 'the space of the object') s/he observes. The relationships between different spaces and the transformations they can undergo with their ill-defined limits and zones, also remain unexplored territory.

To summarize, there are two different conceptualizations of effective dimension in Mandelbrot (1983). The first concerns the relationship between mathematical sets and natural objects. The dimension of a mathematical set is an approximation to the dimension of a natural object. A set of the former dimensions can approximate the dimension of the latter in different ways for different occasions. The second conceptualization introduces the notion of

fractal limits (ill-defined zones) in the relationship between an object and an observer. The combination of the features of dimensions D and D_T is dependent on the distance from the observer from a potential object, but not one and the same for all the positions in the perceptual space (or field). The latter combination (or ratio of contribution) changes in some limit situations.

As simplified and/or implausible the relationship between images of space and space 'itself' might look, the our discussion can help us become aware of the significance of the problem. In mathematics itself it seems that dimensionality and the possibilities for its conceptualization continues to be one of the most challenging areas of research. This is due to the necessity for mathematicians to imagine different types of spaces — physical, astrophysical, mental, neural, abstract, etc. ones. For an orientation how problematic is the concept of dimension from mathematical point of view, it is enough to consult how many different entries for 'dimension' are available in the index of Mandelbrot (1983). Some twenty of them are listed there.

Given this situation, it seems to me most plausible to maintain the following position. Perceptual space, which is our topic of primary concern, is not an Euclidean one. It *aims at* well-formedness, i.e., at dimensional concordance of an Euclidean space, but is, as a matter of fact, a dimensionally discordant set (this is also in line with the theory of perception of Marr 1982, cf. e.g., his 2.5 sketch).

3. An analysis of the phenomenology of visual microstructure

Before we continue in more detail the discussion of the formal aspects of fractal-like mind, we need better orientation where we are supposed to look for its possible implementation. I will maintain here that one (but not the only) very plausible candidacy would be some aspects of the structure of perceptual processing of information. For this reason below I will represent as close as possible to the original a line of thought of James J. Gibson (1950, 1973, 1979) which was not, to my knowledge, pursued in the literature on psychology of perception, while it deserves serious (re)consideration in the light of the current developments in formal modeling of both brain and mind. I will discuss here, more specifically, the problem how much information about the environment is veridically represented in the structure of perception before the imposition of the famous differentiation of figure and ground. From some point of view, the presentation here could be considered as a new reading of the theory of Gibson, specifically, about the possible ways of formal implementation of the microstructure of visual perception.

3.1. *Why the study of perception is of primary importance in the analyses of reality and brain structure*

The capacity of perception to represent the world around us looks today more bewildering than ever with the growing awareness in cognitive sciences that the patterns of perception should somehow fit not only to the structures of cognition, but also to the patterns of activation and inhibition in the brain, and to the structure of reality itself. Many scholars would in principle agree that perception actually somehow fits all of them:

(1) It is definitely commensurable with some aspects of the structure of cognition and motor activity (as well as incommensurable with others);
(2) It must be implemented in some way in the brain; and
(3) It must represent the world around us with at least some degree of veridicality (the ideal being imaged as the achievement of the so called 'projective correspondence') in order to make us effective in acting within it.

The problem is to uncover how perception interfaces not only with cognition and motor schemata of activity, as was and is investigated in cognitive sciences (cf. e.g., Rock 1983; Churchland 1986; Lakoff 1987), but also with reality and with its brain implementation. We must also not forget to inquire what makes perception unique and functionally definable on its own, i.e., as not reducible to patterns of cognition, emotion, imagination, etc., and the way of their implementation in the brain.

3.2. *What is 'direct' in 'direct perception'*

The aim of the inquiry of Gibson (1979) was to analyze how the structure of perception fits to the structure of the world and to the ways of acting and behavior of human beings endowed with a perceptual system. Initially, we should discuss what 'directness' of perception is supposed to mean in the theory of direct perception. The first hunch would be that 'direct' means that we get images of the objects in the world in a direct way, i.e., in *projective correspondence* (according to a symmetry along an axis — the idealized axis of the retina) to the object from the outside world. Basic to this orientation would be the view that the simplest type of vision is realized when a 'basic' form (say, a drawing of a rectangle or circle) from the environment is copied as a form on the retina. According to this belief, form is basic and we can investigate the

most basic forms in perception through experiments with Gestalts (or good forms from Euclidean geometry). This would be the basis of the belief that forms are directly perceived, and those of them fitting Gestalt principles would quite well correspond to objects in the environment.

Gibson's answer to the question what directness should mean, however, is quite different. Perception does not pick up forms, it picks up sequential transformations. The latter consist of invariants and disturbances, of continuities and discontinuities on different scales, of discrete and flowing parameters of the information picked up from the environment, but not of forms, contours and objects on a background. Perceiving is a registering of certain definite dimensions of invariance in the stimulus flux together with definite parameters of disturbance. The invariants are invariants of structure and the disturbances are disturbances of structure (Gibson 1979:249).

Gibson points out, that when we are looking, for example, at the Niagara falls, but not at a picture of these same falls, our perception will be a direct one, i.e., when we perceive the external world, we perceive it directly, but not through the mediation of some image. This is an important point, because practically ALL other theories of perception presuppose, in one or other way, the mediation of some kind of image between the external world, and the world we can access perceptually. This 'image' is the retinal one to be mediated by the coding and decoding activity in neural pathways or through a set of psychophysical correspondences (cf. e.g., Hubel 1988). All that is dismissed by Gibson (1979:147).

If there is a 'correspondence', we should search for it along different lines. Oppositions between three different and complementary classes of phenomena are made to correspond to each other in the theory of direct perception as follows:

Environment:	persistence	vs. change;
Ambient optic array:	preservation	vs. disturbance;
Perception:	invariance	vs. disturbance.

In the environment we have the complementary processes of persistence and change implemented by different mechanical, chemical, etc. events and states. In the ambient optic array, we have the processes of preservation of structure vs. disturbance of the structure of light patterns. The perception picks up the latter processes from the ambient optic array as invariances vs. disturbances of structure, which give us information about the events and states in the outside world.

If there is a mapping from environment to perception, it is through registration of persistence as invariance, and of change as disturbance. But this

mapping is not a direct one. It is mediated by the structure of the ambient optic array — the patterns of light in the air around us. This is what we see 'directly', but not objects from the world. It remains to be seen in more detail what the concepts just introduced are supposed to mean and how they were applied in the theory of the direct perception in making sense from: (1) the structure of the environment to be seen; (2) the structure of the patterns of light in the ambient optic array; and (3) the structure of the perceptual patterns themselves. It is appropriate to mention immediately, however, that while Gibson differentiated conceptually in a straightforward way the differences along the vertical line of persistence-preservation-invariance (the general parameter of 'stability'), he seemed less confident in making different change-disturbance-disturbance, because he did not find it possible to distinguish conceptually the disturbance in the optic array from the disturbance in the perceptual structure. This is one alternative for an interpretation of the taxonomy he made. The other alternative would be that he implicitly was inclined to identify the two types of disturbances as formally indistinguishable (this will be my own position; I would not like, however, to impose the latter interpretation as the one actually intended by Gibson).

3.3. *What it is to be a world to be seen*

Before discussing the specificity of perceptual structure itself, we should first analyze, as Gibson did, what types of information are available in the environment, which the system in question could pick up, as it is clear that we are unable to perceive quantum fields and atoms, although we are persuaded that they objectively exist.

For describing the environment Gibson postulates the necessity of distinguishing between substances, medium, and surfaces. The medium is the air (sometimes water). The surfaces are the interfaces of substances and the medium (Gibson 1979:22). An interface between a substance and a medium is a surface to be seen. The primary givens of reality we can discern are not objects, but surfaces. Gibson gives a preliminary list of ecological laws of surfaces, which are not independent of each other and must be considered in combination. I will list them here in order to make aware the reader how much information of different types about the world we can pick up veridically (with an accent on the importance of texture, in this respect) from environment:

(1) All persisting substances have surfaces, and all surfaces have a layout;
(2) The surfaces differ in resistance to deformation, depending on the *viscosity* of the substance or resistance to flow; they differ in *hardness* or rigidity;

they differ in *density* or mass per unit volume; in *elasticity* or the tendency to regain the previous shape after deformation; in *plasticity* or the tendency to hold the subsequent shape after deformation. Those are characteristics of substances which can be seen *directly*, although presumably it is possible to explain them by the microphysical forces of attraction among molecules (Gibson 1979:20);

(3) Any surface has a characteristic texture, depending on the *composition* of the substance. It generally has both *layout texture* and a *pigment texture*;
(4) Any surface has a characteristic shape, a *large-scale layout*;
(5) A surface may be strongly or weakly illuminated, in light or in shadow;
(6) An illuminated surface may absorb either much or little of the illumination falling on it;
(7) A surface has a characteristic distribution of the reflectance ratios of the different wavelengths of the light, depending on the substance. This is what is called color, in the sense that different distributions constitute different colors (after Gibson 1979:23-24).

Only few substances such as clay are amorphous, i.e., lacking structural components, but most of them are geometrical aggregates, that is, they are made of crystals and clumps, of cells and organs, of structures nested within structures. Substances differ in all sorts of ways. A substance is fairly well specified by the color and texture of its surface. Substances are formless and cannot be counted; their number and the possibilities for their compositions and mixtures is not fixed. We discriminate among surface colors and textures, but we cannot group them and we cannot order them (cf. Gibson 1979:241-242; this is the case, among others, because we cannot make solely relying on intuition an arrangement along a single scale of complexity; for the latter concept cf. Wackerbauer *et al*. 1994) while we manage to see them.

What is a surface to be perceived, then? The answer is simple and straightforward. Perception treats as surface in the world any part of the visual array that has a *sufficiently dense* discernible texture gradient. There is a gradation here from the transparent (no discernible texture) surface, through different translucent surfaces and up to completely opaque ones.

There is more, however, to the story of the microstructure of environment (as it will be represented the microstructure of perception), but not simply 'density parameter'. The experimental studies show that the optical information for 'surfaceness' (coming from the surfaces themselves) is not just in the relative proximity (i.e., density) of the units on the surface, but in the *nonpermutation of the adjacent order of these persisting densely packed units*

over time (Gibson (1979:188). The latter aspect can give us a clue how microstructure can evolve in time as either persisting or changing even in the case when there are no changes in the mean statistical measures of the density parameter.

What specifies in an event from the outside world is a *disturbance of structure*. The latter can specify events without necessarily being similar to them. For example, the physical motion of rotation of a disk, described as a rotary spin measured in degrees of arc per second of time, is specified as a shearing of 'texture' of the optic array at the contour of the circle (cf. Gibson 1979:171). While the physical description about the bodies is of the type commensurable with the classical physics, the description of the information about this motion in the optic array (to be discussed below) and in the perception proper is not of that type. This is important to acknowledge even in the cases where we have in the physical world clear-cut cases of motions fittingly described according to the laws of classical mechanics. The physical description in this case and in very many others does not fit the perceptually proper one, i.e., 'to see is not to believe', if one is a physicist (like Dirac) or a mathematician aiming at formal modeling of processes in the physical universe.

In these circumstances, it remains to be seen in more detail where we are supposed to search for a correspondence between a pattern from the world and a pattern in perception, i.e., what actually would mean directly to perceive persistence and change.

3.4. *What is available as information for perception in the ambient optic array*

The perceptual system has direct access not to the objects from the outside world, but to the ambient optic array. The latter is defined as the information for perception about the surfaces in the outside world. It is specified in the structure of light that reaches us. The perceptual system is not supposed passively to receive (or mirror) it, but actively to explore the environment in order to get the information it requires at some moment in time. The components of the *ambient optic array* are the visual angles from the objects of different size in the world (the larger the object in the visual field, the larger the angle representing it). These angles are named *intercept angles*. They become vanishingly small at the line of horizon between the earth and the sky. Their change in size results not only from the distance to the observer (between observer and the horizon), but also from changes in the point of observation.

There are important differences in the representation of information through intercept angles and in a coordinate (be it in 2 or 3D) system (which matter for the way we envisage and formally model perceptual processing):

(1) The optic array is conceived as a *nested hierarchy of solid angles* all having a common apex instead of as a set of rays intersecting at a point;
(2) Every solid angle, no matter how small, *has form* in the sense that its cross-section has a form, and a solid angle is quite unlike a ray in this respect;
(3) Each solid angle *is unique*, whereas a ray is not unique, and can be identified only arbitrarily, by a pair of coordinates;
(4) Solid angles can *fill up a sphere* in the way that sectors fill up a circle, "but it must be remembered that there are angles within angles, so that their sum does not *add* up to a sphere. The surface of the sphere whose center is the common apex of all the solid angles can be thought of as a kind of transparent film or shell, but it should not be thought as a picture." (Gibson 1979:68);
(5) The structure of an optic array *is without gaps*; it is completely filled in, it does not consist of points or pixels, or spots or components that are discrete minimal units. Every component consists of smaller components (cf. Gibson 1979:68).

The information pickup from the ambient optic array is a continuous act. The latter array is a sea of energy which flows and changes without sharp breaks, i.e., without serial and rigid discrete timing of the intake and output from the optic array to the 'buffer' of perception and from the latter to cognition and memory. The optic array as well as the process of perceiving from it is a stream, and this is a reason why William James' description of the stream of consciousness (James 1890, Chap. 9) could apply to the latter. "Discrete percepts, like discrete ideas, are 'as mythical as the Jack of Spades'." (Gibson 1979:240) The other side of the coin, the possibility of flowing discretizibility (in space and time) of the quanta of information intake from the environment, however, was not considered by him.

The *static aspect* of the information available in the ambient optic array is delineated in the following way:

> Within the boundaries of any form, however small, there are always other forms. This means that the array is more like a hierarchy than like a matrix and that it should not be analyzed into a set of spots of light, each with a locus and each with a determinate intensity and

> frequency. In the ambient hierarchical structure, loci are not defined by pairs of coordinates, for the relation of location is not given by degrees of azimuth and elevation (for example) but by the relation of inclusion. (Gibson 1979:68)

The *dynamic aspect* of ambient optic array has the following characteristics. What specifies an event in the optic array is a certain disturbance in the invariant structure of the array. The beginning and the end of the *disturbance* in the light correspond to the beginning and the end of the event in the world (Gibson 1979:102-103).

Different aspects of the disturbances in the ambient optic array can specify mechanical, chemical and other types of events happening to the surfaces in the outside world. Especially troublesome for formal treatment are those events, where a surface is ruptured or broken, because the mathematicians were not very successful in dealing with the problem of discontinuity and intermittency at the time Gibson (1979:104) wrote about that. The optical transitions that specify dissipation, evaporation, sublimation, dissolution, disintegration, and decay, among others, seem to be complex variants of the substitution of one texture for another. No systematic experimental study or attempt at formal modeling and computer simulation were made, but children notice them, are fascinated by them and follow them closely (for current research on the ontogenetic development of texture perception cf. e.g., Atkinson & Braddick 1992; Rieth & Sireteanu 1994; Sireteanu *et al.* 1994). All of us seem to be visually most sensitive to those types of changes, although the mathematical analysis and simulation of them was scarcely attempted (cf. Gibson 1979:107).

It is very important to make clear the *double* aspect the relationship between events in the world and their counterparts in the optic array. The disturbances in the optic array are not similar to the events in the environment they specify, in the sense that the optic motions are unlike physical motion (cf. above; in cases like this, Dirac's claim holds true, but this is half of the truth, in my opinion). The correspondence between physical event and optical disturbance can be found in the sequential order of realization. In most general terms, in the ambient optic array it is a disturbance in the invariant structure that specifies an event in the world. The correspondence between the event in the world and the disturbance in the optic array is at the beginning and the end of both of them. That is about as far as the correspondence goes, Gibson (1979:103) claims.

Gibson was inclined, it seems however, to accept the case for 'projective correspondence' between the movement of optic array structure and

the structure of the corresponding surface from the world for the texture of a surface and the possible changes in it (as available in the optic array):

> What happens in the array when a surface in the world is deformed? It is plausible in that case to suppose that the deformation of the optical texture is a copy of the deformation of the substantial texture, since the optical units are projections of the substantial units, by natural perspective, and are in one-to-one correspondence with them. It would seem that the uneven flow of the surface of water in a river — the bubbles and flecks of the surface — has a corresponding flow of the optical texture in the array. But this does not hold for the ripples or waves over the surface, because the ripples do not move in the same way the textured surface does. The fluctuation of light and shade does not correspond to the surface. And, of course, if the crests of the waves are high they will begin to hide the troughs, and the occluding edges will spoil the projective correspondence. (Gibson 1979:104)

For mechanical events, when the array is ruptured or broken, the mathematical continuity of the surface texture fails and so does the mathematical continuity of the optical texture. As the crack in the surface becomes a gap, occluding edges appear where there were none previously. As the gap widens, a new surface is revealed. A different optical texture (or blank space without recognizable texture) fills the gap and is added to the array. This emergence of a new structure is the crucial information, which specifies the event. A mathematical description of the vicissitudes of continuity/discontinuity would be very desirable in order to catch the nature of the correspondence in question (cf. Gibson 1979:104).

For chemical events, the array involves colored and textured surfaces. Especially intriguing are the processes of waxing or waning of a surface as seen by an observer. The processes of evaporation, sublimation, condensation, dissipation, freezing, dissolving, crystallization, etc., were never considered as processes accessible to perception (cf. Gibson 1979:99). Those optical transitions that specify these processes in the environment seem to be complex variants of the substitution of one texture for another (or of appearance vs. disappearance of texture).

What would be very desirable is a description of the possible kinds of the disturbance in the optical structure of the array. A list of discussed phenomena and their way of availability in the optic array is given by Gibson (1979:107) as follows:

(1) Progressive deletion and accretion of units on one side of a contour (displacement of an object against a background);

(2) Progressive decrementing and incrementing of gaps (displacement of an object against a sky);
(3) Shearing or slippage of optical texture at a contour (rotation of a disk);
(4) Perspective transformation by foreshortening and its opposite (turning of the face of an object);
(5) Magnification to the limit and minification (approach and recession of an object);
(6) Deformation (fluid, viscous, and elastic events);
(7) Emergence of new structure (rupturing);
(8) Nullification of texture (dissipation in the sky);
(9) Substitution of new texture for old (dissipation on earth);
(10) Change of color structure (chemical events).

At this point I will cite Gibson (1979) at length in order to display how close he came to treating some aspects of the structure of the optic array and of perception itself as relying on fractal-like computation:

> Can these disturbances of structure be treated mathematically? They surely cannot all be treated with the same mathematical method, for some of them do not conform to the assumption of the theory of sets. Some of the above changes do not preserve a one-to-one mapping of units over time, inasmuch as the array gains or loses units in time. Accretion or deletion of texture during occlusion is one such case. Foreshortening or compression of texture preserves one-to-one mapping only until it reaches its limit, after which texture is lost. The emergence of new texture with rupturing of a surface, the nullification of texture with dissipation of a surface, and the substitution of new texture for old are still other cases of the failure of one-to-one mapping, or projective correspondence. In all of these cases it is not the fact that each unit of the ambient array at one time goes into a corresponding unit of the array at a later time. [...]
>
> On the other hand, some of these optical disturbances do seem to preserve one-to-one correspondence of units over time, namely, the perspective transformations, the deformations or topological transformations, and even the shearing or slippage of optical contour. In the case of a partial permutation of spot-texture, or a radical permutation such as the random displacements called Brownian movement, there is still a persistence of units without gain or loss. The invariants under transformation, the ratios of proportions and relations among units, are richest for the disturbances at the

beginning of the above list and poorest for the permutations at the end, but invariants are discoverable throughout. A disturbance of connectedness or adjacent order is more serious than a mere disturbance of form. A complete scrambling of the adjacent order of units is still more serious. But a mathematical theory of invariants may be possible for all these disturbances of structure with persistence. What is lacking is a theory of the invariants that are preserved under disturbances with *nonpersistence* of units. (Gibson 1979:108-109)

Such a theory nowadays is provided by fractal geometry. For example, in the case of invariants under displacement, when we consider spatial homogeneity, scaling, and self-similarity of the patterns involved, we can maintain that different parts of one and the same motif or trail of Brownian motion can never be precisely superposed on each other (i.e., they are not the same and made of same elements). Nevertheless, these parts can be made to be superposable in a statistical sense (cf. Mandelbrot 1983:18).

Gibson (1979) finishes Chap. 6 of his book with the following paragraph deserving once again to be cited:

> The optical information for distinguishing the various events can only be various disturbances of the local structure of the optic array. A very tentative description was given of certain types of optical disturbance: deletion-accretion, shearing, transformation, magnification-minification, deformation, nullification, and substitution. These disturbances have only begun to be studied, and the mathematical analysis of them has scarcely been attempted. Nevertheless, strange to say, they are what we are visually most sensitive to, all of us, animals, babies, men, women, and moviegoers (Gibson 1979:110)

3.5. *Invariance and disturbance in perceptual structure*

In the theory of direct perception it is maintained that there are invariants underlying different types of change in the optic array. While awareness can be gained for both persistence and change, it is the invariants that underlie change. This seems to imply that there are rules or algorithms for extraction of invariants from the fluctuating ambient optic array. Actually what Gibson had in mind in insisting upon this idea is determined by the necessity to explain how the flow of the array due to the change of perspective in the self-motion

and locomotion of the observer does not destroy the structure beneath the flow, as we experience all the time during our motion a permanent environment around us.

Four kinds of invariants are postulated to explain this:

(1) those that underlie change of illumination;
(2) those that underlie change of point of observation;
(3) those that underlie overlapping samples; and
(4) those that underlie a local disturbance of structure (Gibson 1979:310).

In principle, it is possible to try to consider all different changes in the optic array as transformations in the sense of mappings. The theory about invariants under transformation was recently developed by Leyton (1992). The problem, however, is that not all of these transformations can be understood as one-to-one mappings, either projective or topological. For example, if we consider the possibilities of extracting invariants of the kind (4) above, they include not only displacements and rotations of rigid detached objects, but also different types of deformations of rubbery surfaces, e.g., that of rippling or fluctuating water, the trembling of the leaves of a tree, etc. The surface and the tree, however, are considered to be continuations of themselves, the same flow of water, the same tree, by virtue of some persistences, non-disturbances, invariants of structure, which obviously contribute to the feeling of the continuity and stability in the perception of the visual world (cf. Gibson 1979:311). It is not necessary to extract or integrate them, as they are available at the moment-to-moment basis in what is seen.

It is important to become aware that the theory of the information pickup does not require *memory* either for the proper functioning of perception, i.e., in the case, for example, of the recognition of familiar shape or texture. The perceiving of the world begins with the pickup of invariants and disturbances; it does not depend on the past experience, except for the learning how to employ attention to the ambient optic array in order to extract more specific information from it on different occasions due to the orientation, expectations, motivations, etc. The latter learning might well be equated with the metaphor of 'attunement'. The state of the perceptual system is altered when it becomes attuned to information of a certain sort (at the expense of other types of information). In this way the system can become selectively sensitized to differences which were not noticed before (Gibson 1979:254). This way of modeling of the way of performance of the perceptual system in learning to cope with an unpredictable environment seems to fit well the model

of the perceptual learning (for smell) proposed by Freeman and his group (cf. Skarda & Freeman 1987), which is discussed by several authors in this volume.

While the attunement to the invariants was easier to operationalize, the problem with the attunement to disturbances seems less concretely specified in this theory. There are many parameters of disturbance of the ambient optic array. For example, the deletion and accretion of texture at the edges of some form in the array specifies the motion of an object (figure) over the ground (this is the parameter of accretion-deletion). Other mentioned are those of polar inflow-outflow, compression, transformation and substitution. If a parameter of optical disturbance is distinguished, an event is perceived (Gibson 1979:250). What is not discussed, however, is how much disturbance and of what type(s) would be considered 'critical' for detection of an event. How does the perceptual system 'attune' to those events and what is the meaning of the attunement from formal point of view? There are also tricky problems related to the intermittency/flow in time of the information pickup by the perceptual system from the ambient optic array (already mentioned above).

3.6. *What is a texture to be perceived*

A standard presentation of this topic in psychology of perception looks as follows. Texture is the structure of a surface, as distinguished from the structure of substance underlying the surface. The texture is a structure on a micro-scale. In the environment to be perceived, those structures are of the size-level around centimeters and millimeters. The texture in perception specifies in each case the composition of a surface of a substance from the outside world.

Texture refers to any visible features of a surface that look homogeneous in size and spacing. The textural homogeneity of a surface, however, may be only statistical. In other words, individual elements of texture may vary somewhat in size and spacing while still maintaining local averages of size and spacing that remain 'the same' across the surface. Such local variation introduces noise into the underlying relations between surface layout and projected surface texture without systematically distorting it. On the other hand, if the size and spacing of texture elements vary systematically across a surface, then these underlying relations can be systematically distorted (cf. Sedgwick 1986:21-23).

It is appropriate to point out that different measures of texture were introduced, such as the angular width of individual texture elements, the

angular width of a given number of texture elements along a specified line, the number of texture elements per unit of angular width (texture density).

> Almost all the mathematical formulations of texture information and most of the experimental work on perceiving spatial layout from surface texture have been done with artificially simplified textures, such as checkerboard grids, parallel lines, and randomly spaced points or circles, presumably because such textures can be analyzed and manipulated most readily. (Sedgwick (1986:21-23)

After the introduction of the problem of texture and its potential importance for the visual perception of layout by Gibson (1950), the standard treatment of texture is included under rubrics like 'texture and perspective', 'shape from texture', or 'texture discrimination' (cf. e.g., Julesz 1971; Sedgwick 1986). What is not readily discussed, however, is how texture is supposed to be implemented in mind and brain (cf. however the works of Graham 1991, 1994; Graham, Beck & Sutter 1992; Ben-Av & Sagi 1992; Braun & Sagi 1990; Polat & Sagi 1994; Rubinstein & Sagi 1990; Young, Landy & Maloney 1993). We, correspondingly, need better conceptualization of what it takes for texture to be available at the edge of our capacity to discern between 'same' and 'different'.

The first characteristic feature of texture is the *nestedness* of its units. Surfaces are aggregated of different units in a nested way — rocks from crystals, plowed soil from clumps, grass from grass blades, etc. The second characteristics of a texture of a substance is that it is seldom *homogeneous*, but is more or less aggregated of different homogeneous substances. They form its chemically determined texture, the conglomerated one to which is given the name of *pigment texture*. The third characteristics of substance is that it is seldom completely amorphous, but is more or less aggregated of pieces and chunks and crystals of the same stuff. The surface of the corresponding substance will have some physical texture along the dimension of smoothness-roughness continuum and is given the name of *layout texture* (cf. Gibson 1979:25).

It is worth while to note the difference between *nesting* and the *layout texture* (or texture *scale*), a difference not clearly delineated by Gibson but, potentially, of some significance in our context. Nesting could be conceptualized as a repetition, on a different scale, of one and the same or similar pattern in the real world, which is seen in perception. The layout texture may repeat one and the same or similar pattern on one and the same scale in the environment, but due to perspective, the latter would appear as nested to perception. These two different sources of 'scaling' are made indistinguishable

in the act of perceiving because of a specific feature of the latter — that its own structure is of visual angles nested within each other, independently of the two possible sources of scaling effects (the first is due to the structure of the outside world, the second — to the imposition of perspective by perceptual system). A similar differentiation was introduced by Leyton (1992:109-111) in distinguishing between compression and scaling.

Gibson is aware about the problem of 'measurement' of texture and makes the following statement which might look quite puzzling to those theorists (like e.g., Leyton 1992) who strive for a well-defined structure of perception:

> When the chemical and geometrical units of a surface are relatively small, the texture is *fine*; when they are relatively large, the texture is *coarse*. If the units are sufficiently distinct to be counted, the *density* of the texture can be measured as the number of units in an arbitrary unit of area, a square centimeter or meter. But this is often very hard to do because units of texture are generally nested within one another at different levels of size. The texture of commercial sandpaper can be graded from fine to coarse, but the textures of vegetation cannot. Moreover, the units of texture vary in form, and there are forms within forms, so that the "form" of a texture escapes measurement. The ideal pigment texture of a checkerboard and the ideal layout texture of a tessellated surface are rare. [...] The texture in each case specifies what the substance is, what the surface is made of, its composition. (Gibson 1979:28)

When we look at some surface structure we can easily verify by ourselves that it frequently 'flows', and undergoes different types of deformation and destruction in very complex ways. Usually, the surface is something unary, having relief. It is normal for a surface to have both a *pigment texture* and *componential texture*, i.e., the surfaces usually are both spotted and rough. The completely uniform and smooth surface is an abstraction. The *density* of the texture is dependent on the possibility of attuning to the quantity of elements per unit of surface. While 'to discern' requires at least two different entities or states to be discerned as different and/or same, the attunement is, from formal point of view, of same with same.

Texture in perception determines what is the 'content' of the surface in question. There is a relationship between the componential, pigment and shade texture, which is quite complicated. The texture, generally, is supposed to give the microstructure of perception, while the macrostructure is given by its componential (or compositional) structure. Their relationship is relative to each

other, to some degree, but after some limit, the perceptual system is claimed to be unable to discern elements (or ' perceptually localizable objects'), in order to extract from them 'componentiality' (on a macroscale). The color of the texture also gives information about its content — uniformity vs. diversity. Different substances from the world are characterized according to their distribution of the coefficient of reflection of the lengths of the waves of light falling on them.

The correspondence between the structure of the objectively given surface in the world and the optic array that represents (mirrors) it is established according to the following presupposition. Every deformation of the optic texture is in projective correspondence to some deformation of the matter's texture; this seems plausible, because the elements of the optical texture are projections of the matter's texture and are made to correspond to each other because of the natural perspective.

We can now see that texture in perception can provide us with a lot of veridical information about the world, including not only its 'content', but also through homologies in formal specification.

3.7. *About the layout texture and the limits of discernibility*

In the previous section we discussed the nature of nesting vs. scaling (layout). This difference applies first and foremost in introducing natural perspective and its limit — the terrestrial horizon. The latter is considered to be a part of the natural perspective (unlike the artificial perspective as a technique for picture-making).

The natural perspective is conceived as the study of an ambient array of solid angles that corresponds to certain distinct geometrical parts of terrestrial environment — those that are separated by edges and corners. There are gradients of size and density of mutual inclusion along the meridians of the lower half of the array, the earth, with sizes vanishing and *density* becoming infinite at the horizon (Gibson 1979:70). Every solid angle included within an array, large or small, could be enlarged or reduced, or compressed, or wiped out. This could be the case due to changes in the environment, to movements of the human subject perceiving it, or due to the application of different technologies for accessing the environment like telescopes, microscopes, etc. The horizon, in this context, could be envisaged as the natural limit of perspective for terrestrial surfaces (Gibson 1979:84).

The horizon never moves, unlike the proximate objects. It is dependent, however, on the reciprocity of the observer and the environment — the

perception of here and the perception of infinitely distant from here are linked, as one can prove to oneself by looking around on a hill, climbing a tree or flying with an airplane above this same hill. This linking of the unique self with the infinite set of points making the horizon might look as something quite paradoxical. The feeling of infiniteness of the distance to the horizon is actually due to the density of the optical texture at the limit of the seen.

The relationships of horizon with the texture, and especially of the texture of the ground, is quite suggestive. The densities of the latter become infinite at an infinitely distant horizon. Only at that limit the optical structure of the array becomes wholly compressed. However, even with an *implicit horizon*, as is the case in a room, the gradients of density (cf. Gibson 1979:163) show where the earth-sky line (= horizon) could have been. (The introduction of the term 'implicit horizon' is one cue among others to qualify as marking the necessity of positing an immanent structure to perceptual field, to my judgment.)

Here it is appropriate to make the difference between the horizon and the things to be seen 'outside' of the latter. The motions and events (= disturbances in the optic array) of the things in the environment to be perceived are of a different order from the motions of celestial bodies in space. The ancient observers were already aware of that, although for us with the knowledge of physics this difference — between heavenly objects vs. objects-on-earth — became blurred. The heavenly bodies do not come to rest on the ground as ordinary objects do. The sun, moon and stars seem permanent, appearing to revolve around stationary orbits in perfect cycles around the earth and continuing to exist indefinitely. Their size and distance from us are indeterminate and they are outside of the horizon, as they rise and set behind it. Their motions are very different from the motions of the objects on earth. The character of their surfaces is indefinite and of what substances they are composed is, respectively, not clear, i.e., they lack appreciable texture, when observed with an unaided eye. Unlike the reflecting surfaces at the earth, they radiate light (cf. Gibson 1979:259). From different points of view, they form an optic array, which seems to have characteristics opposite to those of the ground-affiliated earth array.

The basic differences between movement and change in the terrestrial vs. celestial world boil down to the following. The fundamental laws of motion hold for celestial mechanics, but the events of the terrestrial world are mostly made of surfaces, not of bodies in space. And these surfaces often flow or undergo stretching, squeezing, bending, and breaking in ways of high mechanical complexity, unlike the visible motions with the heavenly bodies.

The environmental motions should be best thought of as *changes of structure* rather than changes of position of elementary bodies, *changes of form* rather than of point locations, or *changes in the layout* rather than motions in the usual meaning of the term (Gibson 1979:15).

However, there is also an important similitude between the structures in the celestial world and the events in the terrestrial world, which gives some credence to the proposal of modeling the universe in the way that we model the ecological world. If we consider the density of the texture patterns on the earth, it looks quite evident that latter's density would be much higher than the one of the discrete stars on the starry sky. But at the horizon of discernibility of the starry horizon we get to formations which might well look not unlike the ones at earth's horizon. The point is that there is some similitude of the structure of the earth horizon and universe horizon from formal point of view. And the real core of the problem is this: The horizon of discernibility might be at least as much a problem of perception as of the structure of the universe as such. In other words, when Mandelbrot (1983) presented a model of texture for some astrophysical structures, he actually modeled the structures of the perceptual horizon phenomena (= 'margins of reality') as fractal zones. The latter could be due to nesting, scaling or both. Here we come to a meeting point between the explorations of Mandelbrot and Gibson.

3.8. *The meaning of attunement*

We can introduce the problem about the possible ways to compute on-line and store textures with discussion of an example provided by Julesz (1971). He points out that most textures in our environment are neither entirely random, nor completely regular. Skin, hair, fur, wood and other epithelium-like structures are macroscopic aggregates of densely packed biological cells of similar shapes. Most solids, such as minerals, metals, fibers, etc. are macroscopic aggregates of crystals. The textured surfaces of these familiar materials and organisms are determined by the microscopic structure of their components (Julesz 1971:118).

When we face these surfaces, however, we have the following twofold problem:

(a) When we see a new texture we never saw before, how do we manage to see it at all, and how do we become aware that we never saw this texture before? and
(b) When we recognize a familiar texture we remembered, how do we achieve 'identification' in the case of microstructures in mapping input with the stored in memory patterns?

The availability of a detailed texture (so called eidetic) memory for every surface we saw in our life looks as something very highly implausible. We are nowadays especially aware of that because we all know what type of a load on computer memory is the processing of images and their storage on hard disks. If there is something very troublesome in the link between perception and memory, it is epitomized in the question, how new and old textures are processed in perception. Whatever the fate of the supposed parallelism in the way of mutual implication of micro- vs. macro-structure in the real world and in perception (above we discussed in detail the proposal of Gibson, which looks to me the most reasonable, as a whole), the problem of 'familiarity feeling' (recognition) is one of the notorious problems in understanding perceptual consciousness since its apt introduction by William James (1890), and most troublesome, in computational terms, it is in relation to textures.

In order to recognize or recall some texture as familiar, we could use the following strategy, according to a conjecture, narrated by Julesz (1971:118). To recall the texture of a walnut panel, silk dress, or of Mandelbrot set, one does not have to store each point of it. It might suffice to store a few rules that would generate some representation of these textures. In principle, according to Julesz (1971:118), one could "store the shape of a single molecule or biological cell and build up adjacent macroaggregates from thousands and millions of these building blocks, according to some random rules". These rules would determine the average macroaggregate size, preferred orientation, length-width ratio, etc. But this principle of texture generation in recall and recognition seems to be most unlikely and can serve only as an illustration, how a relatively limited memory can store a program capable of generating detailed textures. And the very idea that the real structure of environment (as physically available and describable) is represented and stored in this same way in the brain seems highly implausible.

This model cannot be saved, if we move along the possibility of introducing second- or still higher-order statistics in the memory of textures (cf. Julesz 1975, 1981). The proposal, informally, was that even if we are unable to memorize every detail of a girl's face, we can imagine the same girl by recalling that her face has certain skin texture. "A relatively small number of statistical parameters of typical stored clusters such as a few higher-order moments might describe textures" (Julesz 1971:118). The difference from the previous model is in the basic components to be stored. The previous ones were single elements, while here we have clusters. But even this does not alleviate the problem, as Julesz (1971:119) himself recognizes.

The question of recall and recognition of the familiar textures is a one currently with no plausible answer. It can serve as an illustration and support of the point, too, that seeing and recognizing both familiar and novel textures

displays the capacity of perception to perform independently from memory, from the one side, and, from the other, is a further challenge how that can happen.

Gibson introduced the concept of 'attunement', it seems, for at least two different reasons (which complement each other). The first one is the necessity to account, how the directness of perception is achieved and, if perception supposed to be direct, direct to what it is? The second reason was to help eliminate the necessity for memory access and matching of the patterns during specifically perceptual information processing.

Perception processes information from the environment by a doubly-oriented procedure. The perceiver extracts the invariants of structure from the flux of stimulation, while still noticing the flux. The extraction of invariants is described in more detail by Gibson (1973, 1979), while the attunement to the microstructure of the world remained much less specified. The basic problem here is that we cannot expect according to the same theory of direct perception, that we remember more and more samples of different textures during our life in order to become more and more 'sensitized' to their specificity. We see those textures before we manage to make some discriminations between them. In other words, they were computed for us by perception, the latter becomes attuned to them before being capable to discriminate between any set of them. The 'attunement' here has some special characteristics. The perceptual system responds to the stimulus information along the lines of metaphors like 'resonating', 'extracting', 'optimizing' or 'symmetricalizing' (Gibson 1979:245-246).

Attunement was understood by Gibson, most generally, as information pickup. The latter process involves not only overt exploratory movements that can be measured, such as orienting, exploring and adjusting some components of the perceptual system (in order to get access to appropriate information), but also activities internal to the system in question which was more difficult to conceptualize (measure, formalize) at the time Gibson worked, e.g., such as *optimizing*, *resonating* and *extracting invariants* (Gibson 1979:263; cf. Leyton 1992 for up-to-date computational approach to the aspects of 'optimizing' and 'extracting invariants' in an perceptual space aiming through symmetrization to its limit of Euclidean dimensionality).

The attunement to the disturbances and invariants of microstructure from the ambient optic array remain to be conceptualized and investigated in more detail in future experiments. In most general terms, I see the solution along the following lines. This process proceeds through an attunement to the rhythm of the light patterns — the pattern of synchronicities and oscillations in the optic array. The latter rhythm is the stimulus information available for

pickup by the perceptual system. It is evident that the perceptual system can attune (rescale through self-modifying organization; the latter constitutes the most basic type of learning; cf. Anderson & Mandell, this volume) in different ways to the input. The attunement, at this level, actually consists in that of matching the *constraints* on organization (in the real world structure) with those of self-organization (in mind/brain) in the evolvement of the pattern in question, both in space and in time. These constraints (unlike all possible on formal grounds constraints — a much broader class) have phenomenologically available correlates in perceptual experience — in my opinion, this is the key to the fractal geometry of mind/brain performance (for brain considered as a self-organizing system cf. Globus 1995). The latter way of performance maps directly to the structure of the outside world (specified as patterns of light).

3.9. *Directly seeing what: A summary*

I went into considerable detail discussing the theory of direct perception, because of the purport of the latter for the doctrine 'to see is to believe' in the context of formal modeling of the visible aspects of natural objects. Mathematicians, seemingly without exception, are not aware of these aspects. Psychologists find the discussed theory for different reasons controversial (cf. e.g., Marr 1982; Rock 1983:250-253; Wertheim 1994), while the philosophers and linguists, as a rule, are not aware of its consequences for phenomenology, epistemology and the relationships and interfaces between verbal cognitive structure and the structures of perception. Below I will summarize the important consequences of this theory for the way we can see the world and judge the mapping between a formal model of an object and the object itself (as it looks like).

When we model the visible aspects of the physical, mechanical, chemical, biological, etc. structure, we do not model this structure 'by itself', i.e., as *Ding an sich*, but the way it is 'represented' in the ambient optic array and consequently picked up by the perception. The common denominator for all types of changes and persistences in the world is the structure of light as available in and accessible from the optic array.

The specificity of the macrostructure of the physical, chemical, biological etc. patterns, as a rule, is unlike their specifications in the ambient optic array. We cannot infer from the perceptual structure of the object its 'own' physical, etc., structure even in the cases when we consider the surfaces and the surface motions in the world and their representations in perception. Otherwise, science and experimentation would be superfluous.

But when we speak about the microstructure of perception, world and ambient optic array, things start to look different. At the 'edge-of-evanescence', at the edge of the capacity of perception to differentiate same vs. different, we do not seem to use some normalization techniques of the type 'make whatever you cannot differentiate same', i.e. self-same teragons, tiles, etc. At the edge-of-evanescence we have to face 'neither same nor different' option and the latter option currently seems best implementable by the edge-of-chaos phenomena.

We have seen that perception is capable of computing in considerable detail the 'unlimited potential density in depth' parameter on-line, i.e., the outcome of the computation of the features of nesting and scaling. This seems to be the reason for Gibson to maintain that for every localization or point of the perceptual field, even if it is cluttered with objects, perception computes, where the line of the horizon should have been (cf. Gibson 1979:163), i.e., the implicit horizon phenomenon. Presumably, the latter happens when perception computes the density parameter of the limits of the field.

4. The fractal aspects of mind and what 'direct access' to them is supposed mean

Above we discussed in some detail aspects of the ecological approach to visual perception. The pathos of this approach, in our context, was that we directly access the world at some level of its givenness, but not through the mediation of some 'images' and through processes of coding and decoding them, or analyzing and integrating them once again at different stages of visual information processing in mind. The chances for directness of access were ranked highest for texture perception, as it comes closest in its formal characterization to some level of structure in the ambient optic array, the latter coming as close as possible to the microstructure of the surfaces of the objects from the outside world. It is curious to acknowledge that we come as close as possible to direct correspondence (or mapping, or attunement) between the three worlds mentioned (those of outside reality, mind, and brain) through equating 'correspondence' with the edge-of-evanescence of 'same' and 'different' and the readiness to distinguish anew the unpredictable.

4.1. *Direct mapping vs. 'hidden layers' at the interface of brain/mind: The possibilities of directly accessing patterns in the brain*

In this section I will apply the notion of 'directness' to the interface not between mind and world but between brain and mind. The meaning of directness, in this context, would amount to the 'symmetry hypothesis', i.e., the

hypothesis about the existence of an interface of direct accessibility in brain/mind functioning. In order to elucidate my proposal, I will consider briefly for the sake of comparison the connectionist model of mind proposed by Smolensky (1988). Actually the latter model is a hybrid one, as the author claims that some of the features of connectionist models are closer to modeling mind functioning, while other — to brain functioning. In other words, this model is very fitting to discuss here for the sake of comparison.

According to Smolensky, the behavior of the connectionist (subsymbolic) system is determined by its harmony function, which computes a surface or 'landscape' of harmony values over the space of network states. Under some idealization, the *competence* of the system is described by *hard* constraints: Ohm's Law, Kirkhoff's Law — the laws of circuits with simple periodicity. The *performance*, however, of subsymbolic systems is achieved by satisfying a large set of *soft* constraints. The system is fundamentally soft. Its behavior can be analyzed at a higher (conceptual) level and with well-posed problems and enough computation time the competence of the system can be described by the hard rules (constraints) of circuit domain. The performance of this same system, however, uses radically different computational mechanisms, points out Smolensky. The performance approximates to competence in idealized cases when it has enough computational resources, information and time to compute the 'global harmony peaks (or maxima)' (Smolensky 1988:20). But in the brain/mind functioning with limited resources and limited time windows for execution, the global maxima are inaccessible. (And even if accessible, I don't see how they will make difference for switching the behavior of the system to computing in a radically different way.)

Subsymbolic computation is the evolution of a dynamical system. The input to the computation is a set of constraints on the states which are accessible to the system. The dynamical system evolves in time under the defining differential equations. It typically approaches asymptotically some equilibrium state (the input). The function relating the systems input to its output is its competence theory. But the latter is quite different from the performance theory of the system which is the differential equations governing the system's moment-to-moment evolution. Relating the performance and competence of cognitive systems coincides with one of the principal tasks of dynamical systems theory — relating a systems' local descriptions (differential equations) to its global (asymptotic) behavior (cf. Smolensky 1988:20).

As interesting and promising as this scenario might be for other reasons (cf. the differentiation of hard and soft constraints), the basic problem with it boils down to the possible ways of access to the 'conceptual-level spreading

activation' (*ibid.*) of the nonlinear systems in action. We feel neither minima, nor maxima, nor attractors. The description continues to be that on the level of an *abstract* landscape with subconceptual representations of the concepts. At this level, accordingly, the *bathroom* 'representation' will be a pattern of activation, and the system's recognition of its prototypicality will consist in the 'harmony peak' of a coherent activated combination of features, e.g., availability of has-window, has-toilet, has-shower, has-towels, etc. It is in this sense that categories turn out to be attractors in a connectionist dynamical system (cf. Smolensky 1988:21).

But we still must face the problem that the accessible to consciousness cognitive representation of a prototypic *bathroom* does not look like an attractor or 'harmony maximum', even if we imagine it as decorated with images of the type of Mandelbrot set and Hénon attractor. It *looks like* an image, which is possible willfully to construct and/or reconstruct before one's 'mental eye', i.e., as an image schema (cf. Lakoff 1987). It remains unclear, however, where to look for visible traces of nonlinearity (in this respect, cf. the discussion above about the relationships between mathematical cognition, imagination and perception).

If this is the case, we have no other choice but to posit the indirectness of the relationship between the accessible to consciousness representation of *bathroom* and the connectionist 'representation' of the latter, which is associated with it (be it as description, implementation, or both). This relationship of association could be enacted by a hidden level, or, still more plausibly, by several hidden layers or sublevels of structure in a multilevel connectionist, neural, or mind pattern. If the latter is the case and having in mind the wide divergence in the ideas of how the hierarchies might look like in the brain and in the mind (cf. the Introduction to this volume for a brief overview), we reach an impasse. The only way, to my mind, to face straightforwardly the latter trouble is to posit the possibility of an interface between brain and mind, where the access to a (subconceptual) pattern in mind is simultaneously access to this same pattern in brain. I suggest the availability of such a level of direct access in brain/mind functioning. Without the latter, the other levels of brain/mind performance would be impossible to actualize; however, in the great majority of the cases, this level of direct access remains implicit, i.e., not currently accessible to consciousness.

Positing the necessity of an interface between brain and mind which is potentially directly accessible every moment of our conscious experience (in the sense formulated above), implies a radically different approach to the problem of the hierarchies of functioning in brain and mind. Furthermore, I claim that this 'edge-of-chaos' interface between them will, necessarily, have a fractal-like structure.

This is a turn which is not self-evident in the context of the ecological approach to visual perception. In the theory of direct perception we discussed above, information refers to specification of the observer's environment, not to specification of the observer's receptors or sense organs (retina, areas in the cortex, etc.). Gibson (1979) was emphatic in making incommensurable the neurophysiological specifications of the way peripheral and central nervous systems perform and the formal specification of the patterns of perception. He was busy to tie the structure of perception with the structure of the world and the ways we have access to the latter. It is one of the most self-evident facts about perception that the latter is representing the world around us, but not the brain processes implementing it. What is specified by perceptual information are the qualities of objects in the layout. On the other hand, what is specified by sensations are the qualities of the receptors and nerves. In Gibson's view (1979:242), information about the world cuts right across the qualities of sense. There are no thresholds for information like those for sensation (stimulus thresholds). Sensations are evoked by energy-specific stimuli, while information is not energy-specific, etc. Information is conceived as available in the ambient array energy flux, not as signals in the nerve fibers. The qualities of visual experience that are specific to the stimulated receptor (retina) are not relevant to the perceptual information pickup, but are incidental to it in the sense that they are the vehicle for the information pickup.

Gibson insists, that whatever makes some transformation coherent in perception must be already made *coherent* in the transformation of (some part of) the optic array and the perceptual system simply picks up the already coherent pattern, but does not make it coherent by some set of constructive and/or reconstructive operations. The 'integration' of individual sensory elements is not necessary in the process of perception (as is the case in the Gestalt theory and in the contemporary attempts to develop neurological justification or implementation of those principles in the brain; cf. e.g., Singer 1994; Singer & Gray 1995), because they are already available as a coherent pattern to be picked up (attuned to) directly from the optic array (cf. Gibson 1979:174).

This seems to be a point strictly contradicting the ideas about the active and self-organizing brain, but the situation is actually still more paradoxical than that — the brain (and mind, correspondingly) cannot discern, it seems, (below some critical level) patterns to which it attunes from those due to self-attunement. This would be my own conjecture. Those phenomena which are accessible in the fractal zones of perceptual field could be due either to the structure of the surface of the object itself or to the immanent structure of the perceptual field, i.e., they could be due either to nesting or to scaling, and

perception models both of them with one and the same formal means. Currently, there are already experimental results giving support to the view that the brain learns (attunes) how to distinguish textures at the early stages of its maturation during the ontogenetic development of the individual, e.g., via imprinting-like setting of default constraints on its dynamics (cf. e.g., Atkinson & Braddick 1992; Karni & Sagi 1991). There are nowadays also neurophysiological and psychophysiological investigations in support of the view that the organization of retina of the eye itself can help pick up textures in spontaneous discriminations of stimuli (cf. Kehrer 1988, 1989; Braun & Sagi 1990; Shipley & Shore 1990, Sireteanu, Fronius & Constantinescu 1994; Stone 1993; Meinecke & Kehrer 1994). The problem about the interface between organization and self-organization in brain/mind requires much deeper appreciation and reconsideration in the current context of research.

4.2. *Fractal-likeness: The prospects of studying texture in experimental mathematics*

In a recent article, Kurths *et al.* (1994) point out that in 1960s and 1970s it was found that nonlinear systems with only a few degrees of freedom are capable to generate a rich variety of behavior from regular to chaotic-looking patterns. The latter ones with irregular deterministic dynamics were further found to be different from stochastic processes. There are two different possible approaches in facing the behavior of the nonlinear dynamical systems:

(1) through characterization of their structural invariants, e.g., fractal dimensions;
(2) through their description by means of dynamical invariants (or constraints), e.g., Lyapunov exponents or Kolmogorov entropy (Kurths *et al.* 1994:219).

However, the hope to find evidence for low-dimensional deterministic chaos in real-world systems could be substantiated only in few cases. For example, Mandelbrot (1983:328) points out that the fractality of Brownian motion could be considered fully proved from mathematical point of view. Other authors, however, are more optimistic and speak directly about fractality and deterministic chaos in the phenomena of life and in the brain itself (cf., e.g., West 1990:191-208 and the contributions to this volume for more references and discussion).

One reason for being cautious is that the real-world objects and systems cannot be described by one or two, be it structural or/and dynamical invariants.

These systems function in an environment, i.e., are not completely autonomous, and are object of noise-like fluctuations (cf. Kurths *et al.* 1994:219).The concept of fractal dimension induced a lot of enthusiasm, as Peitgen, Jürgens & Saupe (1992:244) point out, among others because it created the expectation that the fractal dimensions would allow us to discover an extremely economic way to describe a set of phenomena, which previously looked as if being of utterly overwhelming complexity. For example, a very complex looking texture of an image could be stored in the memory of a computer just with a simple formula to be iterated many times for the reproduction of this image, when necessary. As a matter of fact, one of the early attempts to model texture with fractals in artificial intelligence (cf. Pentland 1983) was inspired with an aspiration along these lines.

This enthusiasm, however, was premature. It turned out that there are serious limitations in the application of the concept of fractal dimension, as well as there are other variables involved in the formation of fractals and fractal-like structures, which are not investigated in more detail.

In most general terms, the study of real-world nonlinear systems is not based on the dichotomy of deterministic vs. stochastic behavior detection, but on the more generalized notions of order and disorder and on the flowing 'interface' between them at the edge-of-chaos. A system, which is capable to perform and switches from regular to chaotic behavior can be maintained to be of highest level of complexity (compared to a deterministic or a stochastic system). At the phase transitions between regular to chaotic behavior, the complexity (considered as a set of constraints on the possible evolvement of the system) of this dynamical system is regarded to be highest. The routes out of chaos and into chaos from order display a set of dynamical and structural invariants, which should be of high priority in investigating and modeling (cf. Atmanspacher *et al.* 1992:278). (For a classification of the measures of complexity cf. also Wackerbauer *et al.* 1994; Kurths *et al.* 1994.) The point is that there are at the interface in question such invariants, which seem to be identical in their formal specification for very different in their physical implementation real-world systems.

While the routes out and into order from chaos are of interest for many disciplines, some specificities of fractality and fractal-likeness would be a high priority in investigating the possible implementation of brain/mind interface. For reasons given above the latter are not readily discussed in the literature (to my knowledge) and their brief analysis could help us clear the ground for the future research in this area.

The first caveat is to distinguish between fractals and fractal-like structures. The second caveat is to become aware that the current fractal modeling is, by necessity, of quite simple kind. The majority of the analyzed up to the date fractal-like structures and fractals (as mathematical objects) are low-dimensional, i.e., with fractal dimension < 3. The third caveat is that it is not clear what is the contribution of invariants other than fractal dimension to the dynamics of evolvement and the final pattern of the corresponding fractal-like structure (cf. below).

The fourth caveat is due to the way fractals are currently produced by computers. In the computer, an algorithm is given; the iteration many millions of times of the relatively simple *fixed* algorithm gives rise to form like the well-known Mandelbrot set. Consequently, there is a gap between the way of computer simulation, as currently envisaged played on computers, and the way the perceptual system itself performs. In most general terms, the real-world systems are self-organizing systems, unlike their computer models. The ideal (simplistic) way of creation of fractals cannot, correspondingly, hold true because real world systems (as mentioned above), including that of perception, are neither completely autonomous in their functioning, nor lacking properties of self-organization.

In the case of perception we must also face the following challenge: How a self-organizing system can and does evolve in a way capable to represent appropriate features of another system (that of visual optic array in our example discussed throughout this article). The metaphor Gibson (1979) used for expressing this capacity of (co)-evolvement is 'resonation' or 'attunement'. It is the latter capacity that gave the possibility for direct access to the real world by the perceptual system, even if implemented in the small encapsulated 'black box' of the brain.

The fifth caveat is that we still know very little what invariants of fractal structure matter to the formation of perceptual structure. The point is that the fractal dimension itself turns out to be neither always necessary, nor sufficient condition for establishment of the fractal-likeness of some structure. We should be aware, first and foremost, that the concept of fractal dimension is not a single and coherent one. Mandelbrot (1983) tried the broadest possible definition of it. This becomes evident, when one compares other attempts to define the latter concept on the basis, e.g., of some critical feature as, for example, that of self-similarity (cf. Lauwerier 1991:80). Lauwerier (*ibid.*) finds the concept of fractal dimension at all inappropriate, because the latter already has at least four other definitions (except that given by Mandelbrot), and for this reason chooses to speak instead of 'capacity' of a geometrical figure in line with Kolmogorov's proposal.

In some cases, as it turns out, there are several different dimensions, which give different answers, what is the 'dimension' of an object (cf. the discussion in Section 2.6). For example, in the case of nonlacunar fractals the similarity but not the Hausdorff dimension fittingly expresses the fractal dimension (Mandelbrot 1983:314). It is also quite possible to imagine that a given pattern is a mixture of different fractals, each one with a different fractal dimension. In such a case, it is not difficult to guess that the conglomerate will have a dimension of the component(s) with the largest dimension. That would mean, from its side, that the resulting number gives account only to the fractal dimension with the highest numerical value in the mixture. From this highest value we cannot make an inference about the values of other ones. The specification of the mixture, from its side however, would require something more on a par of a spectrum of numbers which gives information about the distribution of fractal dimensions in a structure, called multifractals. An attempt in this direction is an article by Mandelbrot (1988) himself (cf. Peitgen, Jürgens & Saupe 1992:244).

If fractal dimension is not enough or could be defined in different ways on different occasions, we must still face the question, what are the other potential constraints on the evolvement of nonlinear dynamic systems that lead to invariants of fractal structure perceptual system is capable of differentiating?

4.3. *Words, concepts, metaphors and images in looking for invariants of fractal structure*

Even when a definite D fits quite well to some pattern in nature, this is the case (if we are talking about the forms we can perceive) within some range of scaling defined by Mandelbrot as inner and outer cutoff and we must take care to fix this constraint (ramification R). But the specification of the latter, once again, is not enough. This is the reason why Mandelbrot (1983:139) introduced the explicitly metaphoric concepts of lacunarity, percolation, and succularity, among others.

The introduction of the control of fractal structure by invariants (named with metaphoric concepts) just mentioned is for the sake of mimicking by purely geometric means (cf. Mandelbrot 1983:84) of the texture of galaxy clusters. At the level of sky's fractal D (with possible inner and outer cutoffs) or the universe 'horizon' (Mandelbrot 1983:86, 91, 261) we are forced to face some 'screen effects' (as I named them). We have sources of lights and sources of refracted light stretched in currently indeterminate distances. They form the

'texture' of the sky to which Mandelbrot (1983:310-325) dedicates two chapters in the most advanced part of his essay.

While this author considers 'texture' as an elusive notion, he immediately proceeds to model several individual facets of it by quantitative means: "In fact, much of fractal geometry could pass as an *implicit* study of texture." (Mandelbrot 1983:310). Two of these facets — gaps and lacunarity and cirri and succularity — were explicitly studied in the context of creating astrophysical models. Please note that they were not applied first to the perceptual structure of texture, but projected as far in the universe, as man can *discern* (with his instruments). And the inference that was made was of the following type: Where we see fractal-like forms (e.g., *sirri*) far away in the universe, we may infer local nonuniformities of space (locally Riemannian space) due to the nonuniform distribution of matter in it (cf. Mandelbrot 1983:86). But is this an *always* valid inference about the structure of the object in question? If I am right in positing immanent to the structure of the perceptual field fractal zones, this cannot be automatically accepted as being the case. The local nonuniformities of the perceptual field at the edge-of-evanescence could be localized as 'common regions' (cf. Palmer 1991, 1992 for the latter concept) by the perception-specific (-immanent) processing.

The concepts introduced above are strictly and explicitly metaphoric. *Lacuna* in Latin means "gap"; a fractal is called *lacunar* if its gaps tend to be large. *Succolare* (sub-colare) seems a proper neo-Latin for "almost to flow through"; *percolare* means in Latin "to flow through" (it is worth while noticing that the latter concept is related to Bernoulli percolation through lattices; cf. Mandelbrot 1983:127); a *succolating* fractal is one that 'nearly' includes the filaments that would have allowed percolation. The filmy fleecy clouds are called *sirri* by meteorologists; this cirriform structure is not a matter of fractal D, but of narrow 'near-streams' or 'near-filaments' (Mandelbrot 1983:310-311).

Another set of metaphoric neologisms in conceptualizing the way the sky structures look like is given in *curdling*, *tremas*, and *whey*. *Trema* in Greek means "hole". *Curd* derives from the old English *crudan* "to press, to push hard". The free associations then run in the following direction: curds → cheese → milk → Milky Way → Galaxy (*gala* "milk" in Greek) → galaxies. *Whey* (a term Miss Muffet should not mind, according to Mandelbrot) is supposed to denote the space outside the curd (Mandelbrot 1983:76-77). All these etymologies, metaphors, and play with word meanings and images might look out of place in 'serious' mathematical modeling. Actually, it is by all means not simply a game for pastime, but fulfills a function.

All of them could be made to cohere (and this is important), if we imagine a virtual screen (or veil), capable of *both* emitting, as well as refracting light patterns in indefinite depth. It is quite a special type of a 'screen' (or 'mystic writing pad', in the metaphor Freud coined for modeling consciousness), because it can both emit light and refract light from other light sources. The apprehension of different clusters on this 'screen' would form different 'screen effects' the human perception manages to discern (i.e., this is the virtual screen of conscious perception). These effects display the limit of our capacity to consciously discern structure in the world; they show as well where to look for the interface of mind and brain (in the way the latter implements the former). The 'margins of reality' from within and from without seem to coalesce (from formal point of view).

The use of imagery and metaphors here have a function unlike the one in the cognitive theories of metaphor (cf. Mac Cormac 1985; Lakoff 1987). Here the metaphoric images point out in the direction of perceptually dense fractal-like correlates, which is impossible willfully to imagine, but which fit as much as possible to the willfully imaginable ones, e.g., as the visualized set of Mandelbrot fits to the perceptually dense set. These images and metaphors are intended to make commensurable the willful manipulation with geometric objects and the givenness of the formal structure of perception.

4.4. *Fractal-likeness in mind implementation*

It turns out that it is quite a challenge to find a place for fractals in the mind. It continues to be not very clear, for example, can the mind remember fractal-like structures, because they are extremely difficult (if at all possible) to recall and recognize as familiar (self-consciously in each concrete case) in the context of everyday functioning and experience. Fractals are impossible to imagine willfully, while we can easily talk and think about them. Fractals seem to come closest to implementability as mind in the microstructure of perception, according to the inquiry presented here. It seems, however, that they can be detected in other phenomena of mind functioning like the complex synaesthesias and some experiences in altered states of consciousness.

From a different perspective, fractals seem to find home at the critical boundaries where the mind and the world and the mind and the brain interface each other. Fractal-like patterns also seem to mark the 'margins' of our capacity to become conscious of some types of structure at the expense of other ones. They display the limit of our capacity to monitor the contents of our own minds.

In other words, fractal thinking in the processes of mathematical discovery and computer implementation and simulation puts on us the demand

to re-align in a new way our capacities to consciously perceive, imagine, think verbally and remember.

The application of fractal modeling to the phenomena of mind requires also a re-assessment of the nature and role of organization vs. self-organization in the functioning of brain/mind complex. If we consider visual perception (as I did in this contribution), the latter is organized by (attunes to) the input from the ambient optic array. It, however, remains still unclear, how the organization interfaces with the processes of self-organization in the brain, if we are inclined to accept the case for a single general format for self- and other-organized criticality. My own conjecture would be that this interface lies (is implemented) in the interwouvenness of the patterns of perceptual and motor activity in perception. The exploration of the environment for appropriate information (by the perceptual system) requires the integration into a common format of perceptual and motor activities. The latter implements the self-organizing aspect of perception, while the former attunes to the input from the ambient optic array.

It is because of reasons like the ones just given above that fractal geometry seems to be so challenging and gives such a promise for future investigations in the studies of brain and mind.

5. Conclusion

According to the logic of the approach developed here, we must expect to find fractal-like patterns in the brain which are indicative for direct attunement in processing texture coming as patterns from the ambient optic array. Those patterns are, furthermore, both brain- and mind-specific, because they are accessible to experience as its fine-grained texture (= the fluctuating in space and time density parameter of perceptual images). In other words, patterns like these form the interface between brain and mind. It is impossible to distinguish between them on the basis of form/content or from the point of view of quality/quantity, etc. The experimental verification of this hypothesis remains to be realized. The logic of the latter hypothesis is as follows: In some cases, objects of the environment can have fractal-like structure; this structure can be reflected in fractal-like patterns in ambient optic array; the brain/mind can attune to them in perception.

The interest and enchantment with fractals was and continues to a large degree to be no more than a symptom of the potential of fractal geometry to

master the interface between brain, mind and the world. The necessary modeling, simulation, and experimentation still remain to be done.

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Chaotic Dynamics and the Development of Consciousness

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1. The lay of the land

Consciousness research can drive one mad, for it is based on a paradox: consciousness can be explored only through consciousness. This means that the object of examination is also the means by which it is examined. To further complicate matters, research has the effect of raising consciousness. So, any attempt to increase consciousness about consciousness sets up feedback loops that alter the object of research at the very moment it is being employed as a tool. The process is always one step ahead of itself, so to speak, effectively eluding its own grasp.

No wonder consciousness research is full of such qualifiers as 'hypothesis', 'theory', 'supposition', and 'proposal'. True enough, we have discovered some impressive things about how certain aspects of consciousness develop: cognitive skills, the registration of visual cues on the cerebral cortex, the biology of synapses. Yet how humbling it is to realize that our efforts to articulate those discoveries involve a consciousness that functions at a level of sophistication that makes our discoveries look paltry in comparison. It's rather like playing with a toy boat in the swimming pool of the Queen Mary.

When Carl Jung was researching the psyche, he lamented the lack of an Archimedean point from which it could be observed (Jung 1924/1946, par. 163). Today, however, technology offers a close approximation of just such a perspective. With the development of CAT scans, PET scans, and MRI's, for example, it becomes possible to discern which areas of the brain are active

during which activities. With the further refinement of these imaging techniques, observations of brain activity during changes in behavior will surely reveal even more about its mechanics. Exciting as these discoveries are, they may not prove to be very satisfying. As Churchland & Sejnowski (1992) warn at the beginning of *The Computational Brain*,

> Our psychological life, too, is a natural phenomenon to be understood. Here as well, the explanations will draw on properties of the infrastructure that are certainly veiled and probably arcane, an infrastructure whose *modus operandi* may seem alien to our customary self-conception. Perhaps this is inevitable, for the very brain we wish to understand is also the brain whose unaided observation is focused at the macrolevel and whose design seems to favor large-scale concepts for the explanation of its own behavior; for example, superstructure concepts such as "is hungry", "wants food", "believes honey is in the hole up the oak tree", and "sees the grizzly bear approaching..." (Churchland & Sejnowski 1992:2)

It may very well be that further descriptions of the mechanics of the brain may yield very little in the way of explaining the complexities of consciousness.

If the closer we come to the intricacies of consciousness the more we push the limits of our consciousness, we cannot help but wonder if consciousness is capable of understanding itself. Intriguing as this dilemma may be, it may very well be the answer to our question, for the phenomenon of consciousness trying to understand itself resembles a fractal dynamic both in its self-similarity across scale and in its dimension. If consciousness is fractal, successful research necessarily will need to employ qualitative, rather than quantitative, descriptions of its essential dynamics.[1]

Consider topology. Here mathematics expresses a capacity of consciousness that perceives beyond the limitations of the sensory processes that provide data about the environment. For example, it reveals a complexity with regard to dimension that far exceeds what we see with the eye or feel with the hand. Sierpinski gaskets and carpets, Menger sponges, Cantor sets, and the like force our powers of conceptualization to match those of our intuition. To follow the metaphor of fractal dynamics, consciousness can investigate itself only by discerning the fractal attractors of which it is comprised at the moment. Discerning the fractal attractors of consciousness, however, can only occur through the mediation of a more comprehensive fractal attractor.

Consequently, the study of consciousness — an exercise in that which is being researched — establishes a cascade. That is, consciousness is a dynamic that replicates itself on many different levels. Increases in awareness

occur when aggregations of fractal attractors become subsumed under yet more fractal attractors, which in turn, become the components of more comprehensive fractal attractors. Such a process clearly has no terminus. Consciousness is never 'set'. It is an ongoing process of fractal cascades, the result of which is a continual increase in the capacity of its attractors to metabolize life experience. To reflect is to participate in this process by which attractors become subsumed under more comprehensive attractors.

But we're getting way ahead of ourselves. Let us heed the words of David Ruelle, who says that

> A meaningful physical discussion always requires an operational background. Either this is provided by an existing theory, or you have to give it yourself by the sufficiently explicit description of an experiment that can, at least in principle, be performed. (Ruelle 1991:13)

For an operational background we shall appeal to the theories both of C. G. Jung and of chaotic dynamics. The experiment will consist of looking at a folktale through the lens of Jung's theory to see if the symbols and metaphors bear any trace of chaotic dynamics.

Why Jung and chaos theory? First, both appear to be describing the same thing, namely, the characteristics of complex dynamical processes.[2] Second, neither believes that the phenomena they investigate are essentially quantifiable. That is, they cannot be reduced to smaller subunits. Third, both devote a major portion of their analysis to the kinds of patterns that emerge from chaos. In fact, each attests to the role of chaotic dynamics in generating patterns. Finally, consciousness is a function of the psyche, which is a function of the brain. No matter what else the psyche is, it is certainly related to the dynamical processes of the brain. Curiously, Jung described consciousness as an outcome of chaotic processes in the unconscious. While he did not presume to know the mechanics of the brain, he did demonstrate how unconscious processes are reflected in the images that accompany them. Chaos theory describes dynamic processes inherent in the natural order. In its elaborations of such processes as 'symmetry-building', it resembles Jung's explanations of the mechanics of the psyche sufficiently to suggest that the two may be analyzing the same thing.

Consequently, our 'operational background' consists of Jung's theories and chaos theory, while the analysis of a folktale provides the 'experiment that can be performed'. Why look at a folktale? In the words of Paul Ricoeur, "Meaningful action is an object for science only under the condition of a kind of objectification that is equivalent to the fixation of discourse through

writing." (Ricoeur 1991:150) While this chapter is itself an example of such an 'objectification', trying to analyze it as it is being composed is forbiddingly complex. Furthermore, as much of its ideation is probably idiosyncratic, it may be difficult to separate its relevance to the development of consciousness in general from that of this author in particular. Folktales, however, belong to the public domain, for they are not written by any one individual. Rather, they are the product of centuries of oral discourse that modifies and, eventually, standardizes them. If Jung is correct in his premise that the images, symbols, and metaphors that accompany psychic activity bear its imprint (that is, that the manner in which elements of everyday life become 'arranged' into configurations that carry 'meaning' reflects the activity of the psyche), folktales should bear the traces of the processes by which consciousness develops. In true fractal fashion, moreover, Jung also considered folktales to be devices by which consciousness itself was expanded.

Central to this discussion, obviously, is some understanding of what consciousness is. Bear in mind that giving a phenomenon a name, agreeing on its nature, and recognizing it when it occurs does not necessarily correspond to ascertaining its essence. This is especially true in the case of consciousness, a term that is used for everything from basic awareness, to the ability to recognize the familiar, to the ability to discern (through extrapolation) patterns in that which we have yet to see, to the ability to conceive of the hypothetical. All refer to what consciousness does. Equally central is understanding the doer, for consciousness is rarely mentioned independently of a subject who engages in the consciousness. "I think", "I reason", "I imagine", "I wonder", "I figure out": all come into being through me, through a subject who at least acts as a medium for consciousness and is at most synonymous with it. With regard to consciousness, agent and activity intertwine.

2. Jung's theory of psychological development

Jung had his own ideas about this. "Consciousness", he said, is "the relation of psychic contents to the ego" (Jung 1921/1949, par. 700). "The important fact about consciousness is that nothing can be conscious without an ego to which it refers. If something is not related to the ego then it is not conscious." (Jung 1928/1948, par. 18) Consequently, the ego is "a complex datum which is constituted first of all by a general awareness of your body, of your existence, and secondly by your memory data; you have a certain idea of having been, a long series of memories. [...] Therefore you can call the ego a complex of

psychic facts." (Jung 1928/1948, par. 18) In other words, the ego is the one to whom consciousness happens. Without an ego, no consciousness. Without consciousness, no ego.

Jung believed that everything, including consciousness, has its origin in the unconscious. Children are born with the ability to process their experience. Nevertheless, while they are certainly aware of their surroundings, to which they can adapt themselves to some degree, they can hardly be described as having either egos or the capacity to reflect. These come into being as a result of the dynamics (the 'fit', so to speak) between expectation and experience. For example, when an infant needs to be fed, lack of gratification brings into bold relief its expectation that the need will be met, an expectation that is intertwined with its expression of the need. The development of consciousness is reflected in the changes in behavior (crying, screaming, kicking, etc.) that follow upon the frustration of those expectations, generating a sense of agency that leads eventually to the infant's recognition of itself as 'I'. Expectation and consciousness essentially create feedback loops that educate the ego as it learns to understand and to integrate that of which it is aware.

While Jung believed that "people develop psychically on the same principle as they develop in the body" (Mc Guire & Hull 1977:324), to clearly understand his theory of psychological development, or *individuation*, it should be divided into synchronic and diachronic dynamics. Synchronic dynamics occur in time and constantly repeat themselves, as in the establishment of tensions of opposites, their resolution, and the subsequent appearance of new tensions between that resolution and new possibilities. Diachronic aspects are the result of the activity of synchronic dynamics through time. They begin somewhere and end up somewhere else: from less highly differentiated to more highly differentiated functioning, for example.

Jung grounds his analysis of the psyche in some assumptions: that there are such things as instincts, that they are present in the organism at birth, and that they have the power to command the attention and behavior of the organism. If instincts provide the impulses to action, archetypes determine the objects of those impulses. As "[...] the instinct's perception of itself, or [...] the self-portrait of the instinct" (Jung 1947/1954, par. 404), they provide mental representations (images) of that which can gratify the instinct. In their most basic form, they assist instincts in finding food, mates, safety, and even destinations. For example, migratory animals' ability to recognize destinations that they have never previously seen is the kind of functioning capacity for which Jung developed his theory of archetypes.

This mobilization of elementary instinctual dynamics into more complex processes that increase the survival and growth of the organism is fundamental to psychic functioning, from the most elementary to the more highly developed. By connecting instincts with everyday perceptions and experiences, archetypes lead some things to stand out from others. As the ego develops, perceptions and experiences invested with the power of an archetype command the attention of consciousness, exerting an effect on how the ego orients itself. Throughout psychological development, it is the role of archetypes to lead the ego into situations and relationships that increase the adaptive capacities of the organism. Thus, decisions about what career to pursue, school to attend, partner with whom to share life, are all influenced by archetypes. What is ultimately at stake is survival: physical, mental, and spiritual.

The mechanics of this process are a function of energetics. Jung defined the psyche as a function of psychic energy, which is "a hypothetical, fundamental striving" (Jung 1914/1915, par. 418). This energy (essentially a "life energy"; Jung 1928/1948, par. 31) is generated by tensions of opposites:

> The concept of energy implies that of polarity, since a current of energy necessarily presupposes two different states, or poles, without which there can be no current. Every energic phenomenon (and there is no phenomenon that is not energic) consists of pairs of opposites: beginning and end, above and below, hot and cold, earlier and later, cause and effect, etc. (Jung 1921/1949, par. 337)

That "[...] the psyche is characterized by differences in potential" is due to the activity of the archetypes, which establish tensions in the service of mobilizing psychic energy in various "directionalities" (Humbert 1988:92).

This is what is meant by saying that one is 'inclined' to do something, or that one is following one's 'inclinations'. Were one's perceptions and experiences never in conflict, one might be content simply to be borne along on an unreflecting course of life. It is the possibility of otherness that generates the need for consciousness. By emphasizing alternatives to one's conscious standpoint, archetypes complete a circuit along which one's attention can be inclined from actual to potential. While the activity of archetypes can lead phenomena to be seen as inherently contradictory (opposing points of view, pros and cons, the many sides of an issue, the horns of a dilemma), the tendency to perceive alternatives that are not necessarily reconcilable moves the psyche to struggle with its options. When the ego encounters the very different perspectives of the unconscious, it must often suspend its definitions of clarity, rationality, and specificity. For the ego that relinquishes such familiar categories, such an encounter can feel rather chaotic.

Thus, in the diachronic dynamics of development, tension builds consciousness. As everything has its opposite, the potential for tensions to develop are limitless. Throughout a lifetime, it is the tension between what is and what could be that generates growth. Yet, consciousness is not all that is generated by archetypes. Before the ego and consciousness develop the capacity to reflect, an elemental awareness responds to challenges to the organism. Early in life, perceptions and experiences become invested with the power of various archetypes, through which they tend to become associated with one another. When similar associations cluster around the power of an archetype, they form *complexes*.

As complexes continue to assimilate perceptions and experiences, their organizing power increases. For all complexes other than the ego, this organizing capacity is experienced as a 'feeling-tone'. Consequently, everyday life experiences become interwoven with a particular complex (or complexes) depending on the feeling-tones that are associated with them.

Also a complex, the ego organizes its associations not through feeling-tones, but according to rationality, definition, logic, and pattern: in short, according to those elements commonly attributed to consciousness. Consequently, the elements of everyday life that can become associated with the ego are not restricted to particular feeling-tones. Virtually anything is accessible to the ego, which

> has a great power of attraction, like a magnet; it attracts contents from the unconscious, from that dark realm of which we know nothing; it also attracts impressions from the outside, and when they enter into association with the ego they are conscious. If they do not, they are not conscious. (Humbert 1988:18)

The use of the word "attracts" is no coincidence, for the ego, like the other complexes, fits the definition of an attractor.

That the ego attracts contents from the unconscious and impressions from outside has some important implications. First, fantasy images that appear in consciousness reflect the workings both of the unconscious and of consciousness. Second, Jung's model of the psyche resembles a multi-layered series of attractors, one of which is the ego. Finally, if the ego can be described as a particular kind of attractor, namely, one that is characterized by consciousness, its activity also resembles those processes that are characterized by the kind of bifurcations known as 'symmetry-increasing'.

The ego's ability to attract the contents of the unconscious produces a tension between it and the complexes. Jung said:

> The development of consciousness and of free will naturally brings with it the possibility of deviating from the archetype and hence from instinct. Once the deviation sets in a dissociation between consciousness and the unconscious ensues, then the activity of the unconscious begins. (Jung 1927/1931, par. 724)

The ego's free will — it can choose to attract associations from other complexes and to organize them through rationality rather than feeling-tones — identifies it as conscious. The automatic behavior of the other complexes (feelings generated by a situation determine which complex will 'receive' the association according to the 'match' with its feeling-tone) relegates them to the unconscious. That the ego and the other complexes inhabit different dimensions of the psyche and behave differently creates a bifurcation (dissociation) that leads to oscillatory dynamics.

Jung emphasized that "The psyche is no different from the living being, it is the psychic aspect of the living being. It is even the psychic aspect of matter, a quality of matter..." (Mc Guire & Hull 1977:325) He clearly conceived of psychic structure as a function of dynamics, which he defined as energetics. Furthermore, that he conceived of dynamics as generated by (and, thus, characterized by) tensions of opposites calls to mind the activity of bifurcations and oscillations. If the traces of such processes are present in the images that accompany them, it should be possible to analyze them through such images. Before we attempt to do just that, let us quickly review the essentials of chaotic dynamics.

3. Chaos theory

In chaos theory, the word 'chaos' refers to *deterministic* chaos, in which patterns periodically appear and disappear, as opposed to *entropic* chaos, which never resolves into patterns, but simply deteriorates into total disorder, never to return. Much of what was once defined as entropic chaos now turns out to be deterministic. Only our inability to analyze its dynamics limited our ability to recognize it. With the advent of high-speed computers, however, that has changed.

3.1. *Iteration*

(Deterministic) chaotic systems continuously stretch and fold back on themselves in self-reinforcing loops, like the feedback in a microphone/speaker system. There, sound that entered the microphone is amplified and broadcast

by the speakers, whereupon it enters the microphone again, is amplified, and rebroadcast, thence to re-enter the microphone in a loop that continues to build upon itself to an ear-splitting screech. This is a simple geometric progression wherein not only the volume, but the rate of increase of the volume, quickly accelerates to infinity. The equations that describe such behavior recycle their dynamics, so that the result of each computation becomes the basis for the next.

Such equations are defined as 'iterative', from the Latin *iter*, or "journey". Unlike linear equations, which proceed in an orderly fashion to a predictable outcome, iterative equations determine their own destiny. Their outcome is rarely predictable, for where they have been is of little help in determining where they are going. In fact, iterative equations are so unpredictable that the slightest difference in starting point takes them to vastly different places. This extreme divergence of dynamics that begin in similar places — one of the defining characteristics of chaotic dynamics — is called 'sensitive dependence on initial conditions', or SDIC for short.

3.2. *Sensitive dependence on initial conditions*

With regard to weather patterns, for example, SDIC has become known as the 'butterfly effect' (cf. Pool 1989). A particularly dramatic way of portraying SDIC, it proposes that the weather in, say, Chicago can be altered by as minor an influence as a butterfly fluttering its wings in Beijing the week before. That such infinitesimally small events can lead to such enormous effects leads some experts to maintain that SDIC "imposes fundamental limits on predictability. [...] Science will never know certain things." (Pool 1989:1290-1293) "Never know certain things" is a statement rarely heard in the scientific — let alone in the technological — community. Yet, any pessimism it suggests is more than offset by the discovery that the underlying equations that determine the results of these extraordinary dynamics are themselves quite simple. Thus, while foresight may be diminished, understanding is often increased.[3]

Iteration and SDIC are phenomena that characterize not only the physical and biological sciences, but human behavior as well. For example, "once bitten, twice shy" and "Oh, what a tangled web we weave, when first we practise to deceive", both express the psychological insight that differences multiply over time. Even the very subtle differences between an affectionate embrace and a sexual one can lead to markedly different behavioral outcomes. But perhaps nowhere is SDIC more convincing than in the fact that children raised in the same environments develop very different personalities.

SDIC becomes a factor in human development when perception and experience establish feedback loops that iterate over time. Sometimes these become chaotic. Bateson *et al.* (1956), for example, developed the theory of the 'double-bind' to describe experiences in which the relationship between perception and experience becomes either so complex or so ambiguous that responses appear inconceivable. The behavior that develops out of such chaotic feedback loops often can seem bizarre. Nevertheless, said Bateson *et al.* (1956), analyzing the situations that lead to such behavior can render it not only understandable, but even appropriate.

Thus, the double-bind is a chaotic version of a fairly common experience. Virtually everyone knows what it's like to be besieged by alternatives. Whether trying to choose an entree at a favorite restaurant or immersed in a moral dilemma, the conflict between competing alternatives is so representative of human experience that it is a popular theme in literature, film, drama, sports, and so on. "Sophie's Choice", the lady or the tiger, to be or not to be, whether or not to eat the apple: all attest to the dilemma of choice. The problem is, of course, that alternatives beget alternatives. Trying to figure out the long-term consequences of choosing among alternatives can rapidly become mind-boggling. Not only that, sometimes the choices themselves are so complex that they provoke chaotic responses.

3.3. *Bifurcations*

The double-bind reflects another basic characteristic of chaotic systems. That is, expressed in technical language, chaos enters a dynamic system when its iterations *bifurcate*. Defined as a 'Hopf bifurcation', this simply means that as the process unfolds, the effect of a particular iteration is to generate two results instead of one. In effect, one computation yields two outcomes. As the dynamic continues to iterate, these two results themselves bifurcate into iterating systems, which continue to divide (bifurcate) into more sets of iterating dynamics: four sets, then eight, then sixteen, and so on. In very short order bifurcations occur so rapidly and generate so many new iterating/bifurcating systems that their dynamics defy analysis.

At this point one may be tempted to abandon hope of ever making sense out of chaotic dynamics. Until about twenty years ago, scientists shared that feeling. In the meantime, however, the computer revolution has made it possible to understand chaotic systems in an entirely new way, that is, *visually*. In fact, chaotic systems are perhaps best — and certainly most enjoyably — analyzed through the use of their visual representations.

3.4. *Attractors*

Because chaotic systems can be analyzed mathematically, they can be represented on a graph. These bear little resemblance to the familiar graphs of lines, planes, and solids, however. Instead, chaotic dynamics contain multiple bifurcations that double back upon themselves in bizarrely repetitious fashion. Graphing them reveals complex patterns of movement captured in time and space. Those images that reveal the outcome of complex dynamics are called *strange attractors*.

The term 'attractor' refers to patterns into which particular motions settle. For example, a pendulum that is subject to friction will eventually stop swinging. The point directly underneath the pendulum when it stops is called a *single-point attractor*, as it seems to attract the motion of the pendulum during each successive swing until it comes to rest directly over that point. A pendulum that is not subject to friction swings forever back and forth, constantly tracing out the same pattern of motion. This is called a *limit-cycle attractor*. There are other kinds of attractors (for example, rotational configurations that revolve around a center, tracing a doughnut shape called a torus) that settle down into constantly repeating patterns. Thus, graphs of limit cycle attractors consistently recapitulate themselves as they retrace their paths (circle, ellipse, torus, etc.).

Complex — or chaotic — dynamics, however, never retrace the same path, even though they trace out recognizable patterns. While these patterns share a generic similarity with simple attractors, their obvious peculiarities — primarily that they never repeat themselves in predictable ways — lead them to be called *strange attractors*. A strange attractor is the epitome of contradiction, never repeating, yet always resembling, itself: infinitely recognizable, never predictable.

3.5. *Fractal attractors*

Strange attractors often demonstrate a self-similarity that is scale-invariant. That is, looking at them from different perspectives — magnifying the images, for example — reveals identical patterns that repeat themselves at different levels. Like a picture on the cover of a book that shows two children reading a book, on the cover of which is a picture of two children reading a book, on the cover of which is a picture of two children reading a book — and so on — strange attractors are *fractal*, a term invented by Benoit B. Mandelbrot in 1975 (cf. Mandelbrot 1983:2) for patterns that resemble themselves across varying

scales. Self-similarity and scale-invariance are common properties of nature, discernible in coastlines, mountains, clouds, ferns, trees, rivers, and frost patterns on a window. Smaller patterns combine to form larger patterns that are exact replicas of the smaller patterns. Thus, scale-invariant self-similar patterns repeat themselves *ad infinitum*.

Strange attractors also demonstrate fractal dimension, meaning simply that their dynamics transcend topological dimension. A relatively simplistic example of fractal dimension can be constructed by drawing a line that never intersects itself around and around on a sheet of paper. Eventually the line covers the whole sheet of paper, except, of course, for the infinitesimally small spaces between the lines. So is this new configuration a line or a plane? On the one hand, it's still a line, because it can be traced all the way back to its origin. On the other hand, it fills in almost all of the planar surface of the paper. So at what point does it become a plane?

Mandelbrot proposed that no choice need be made. If a line has a dimension of one (length), and a plane two (length and width), a line that virtually fills in a plane can be assigned a dimension between one and two, depending on how much of the surface it fills. If it fills very little, its dimension is closer to one. If it fills a lot, its dimension is closer to two. Consequently, a very convoluted line would have a dimension something like 1.7; a very simple one, 1.3.

Mandelbrot believes that all strange attractors are fractal. Fractal attractors can be represented graphically as cross-sections of the three dimensional multi-orbiting systems that define their dynamics. Expressing them in two dimensions means essentially removing a slice of the attractor and viewing its orbits head-on. Each 'slice', called a Poincare section, reveals where and how orbits cross its plane.

Such a graph constitutes a "phase portrait for the full system [constructed] from time-series data for a single product [...] by slicing the orbit with a plane transverse to the flow" (Schaeffer & Kot 1985:407). Because iterative equations constantly repeat the same dynamics (chaotic systems stretch and fold back on themselves), every point on the graph denotes an orbit that leads to every other point on the attractor. Such a portrait of an attractor that is 'frozen' in one of its phases — the "phase portrait [constructed] from time-series data for a single product" — is a dynamic entity that contains all the information necessary to recapitulate the entire configuration of the attractor ("for the full system"). By mapping such points and assigning different colors to the rapidity with which they 'emerge' from or 'recede' into the plane (the directions of the orbits), extremely intricate patterns are created that resemble phantasmagorial works of art.

In short, a strange attractor "can be considered the limit set of an unstable manifold which is a curve of infinite length with an infinite number of loops without self-intersection and with a Cantor set as a cross-section" (Lauwerier 1986:59). Simply stated, a strange attractor is an area of unpredictability described by an infinitely long curve that goes on forever in loops that never intersect. "Unstable manifold" refers to the dynamic by which a fractal attractor connects a multitude of points in a manner that is unpredictable. Moreover, that such a series of loops has a "Cantor set as a cross-section", refers to a configuration discovered by Georg Cantor. Cantor sets are formed by removing from a line segment its middle third, doing the same for each remaining segment, and continuing that process *ad infinitum*. "The set generated in this way has the remarkable property of containing uncountably many points — i.e., the same number of points as the whole real line — yet being nowhere dense — i.e., for any point in the set one can always find a point not in the set arbitrarily close to it." (Gibson 1988:19-20)

Paradoxical as it may seem, creating more and more points within the same space generates less and less density. Cross sections of strange attractors resemble Cantor sets because they consist of some regions from which orbits disappear and others in which they reappear. Technically, "[...] the orbit leaves the plotting area but returns after a few iteration steps. We may imagine that the orbit is leaving along a branch of the unstable manifold and returning along a branch of the stable manifold." (Lauwerier 1986:83) Viewing the dynamics of fractal attractors as they evolve over time (as they iterate), reveals the secrets of their dynamics: where, when, and how their orbits deviate from their previous configurations.

Computer-generated graphs of fractal attractors demonstrate several essential characteristics. Among these are that the boundaries of the images can never be reduced to simple lines. Rather, focusing on smaller and smaller sections of the boundaries reveals greater and greater complexity. Furthermore, recapitulations of the original patterns appear at varying stages during the magnification process. Thus, self-similarity and scale invariance generate an order within the chaos.

4. Jung and chaos

That deterministic chaos elaborates patterns that are self-similar across scale is entirely consistent with C. G. Jung's model of the psyche. His premise that consistencies of form arrange diverse contents into complexes constitutes a kind of psychological analogue of fractal attractors. Consistencies of form, or

archetypes, resemble unstable manifolds along which orbits (psychic energy) disappear from the phase portrait (consciousness) and stable manifolds along which they return. They take the individual from stability to instability and back again. Here, instability and stability are defined in terms of consciousness and the ordering capacities of the ego. Thus, stability — as seen from the vantage of the ego — occurs when reduction, definition, and rationality can accurately describe a situation. When these cannot, as when the ego becomes enmeshed in unconscious dynamics, the ego experiences instability. The ego apprehends the activity of the archetypes through symbols, which are the images through which archetypes command its attention.

In the synchronic dynamics of individuation, symbols take the ego from consciousness to the unconscious and back again. In terms of chaos theory, they enable orbits to leave their 'track', wander around the attractor in an indeterminate manner, and return. In terms of Analytical Psychology, they break up the linear flow of consciousness, immersing the ego in the chaotic/non-linear flow of the unconscious and bringing it 'back' again.

Symbols are essentially interfaces. They transcend the realms of consciousness and the unconscious, bringing them together into an amalgamation wherein movement from the one to the other (and back) can occur. They are reflections of psychic dynamics, creations of the psyche for itself, so to speak. The content of a symbolic image is a part of everyday life. The form that such content takes, however, depends on archetypal influences. Thus, one is either drawn to or repelled by an image according to whichever archetype in one's own psyche finds an affinity for the image. And, correspondingly, to encounter the archetypal image is to be opened up to the archetype itself. Consequently, symbols are the mechanisms by which the psyche converses with itself. The goal of Jungian analysis is to make the ego aware of such conversations so that it can choose when and how to participate in them.

5. The analysis of symbolic images

All this takes place on the interface between the ego and the unconscious, in that region of the mind where consciousness is formed. This is Jung's central hypothesis: that consciousness is constantly in the process of being created, that such a process is the result of an intent residing within the psyche — more specifically, in that dimension of the psyche called the 'unconscious' — and that essential to this process are images from everyday life.

Consequently, in the diachronic dynamics of individuation ego and consciousness develop together. Through its openness, the ego comes into

contact with experiences that increase the categories by which consciousness can assimilate new data, which expands the ability of consciousness to integrate new data with old. In effect, these feedbacks between ego and consciousness, new and old, psyche and experience, individual and surround — all of which occur against a backdrop of unconscious influences — establish fractal cascades. Through symmetry building, these cascades build consciousness and contribute thereby to the constant refinement of the adaptive capacities of the organism. Folktales are a part of this cascade, for they are both created by the psyche and influence its development.

To illustrate how these dynamics are reflected in humankind's accounts of its experience, consider the following two folktales. Both are examples of scaling: the first through objects that appear in the narrative; the second, through the narrative itself.

The Water-Nixie

> A little brother and sister were once playing by a well, and while they were thus playing, they both fell in. A water-nixie lived down below, who said: "Now I have got you, now you shall work hard for me!" and carried them off with her. She gave the girl dirty tangled flax to spin, and she had to fetch water in a bucket with a hole in it, and the boy had to hew down a tree with a blunt axe, and they got nothing to eat but dumplings hard as stones. Then at last the children became so impatient, that they waited until one Sunday, when the nixie was at church, and ran away. But when church was over, the nixie saw that the birds were flown, and followed them with great strides. The children saw her from afar, and the girl threw a brush behind her which formed an immense hill of bristles, with thousands and thousands of spikes, over which the nixie was forced to scramble with great difficulty; at last, however, she got over. When the children saw this, the boy threw behind him a comb which made a great ridge with a thousand times a thousand teeth, but the nixie managed to keep herself steady on them, and at last crossed over. Then the girl threw behind her a looking-glass which formed a hill of mirrors, and was so slippery that it was impossible for the nixie to cross it. Then she thought: "I will go home quickly and fetch my axe, and cut the hill of glass in half." Long before she returned, however, and had hewn through the glass, the children had escaped to a great distance, and the water nixie was obliged to trundle back to her well again. (Grimm 1975:364-5)

The three images that preserve their self-similarity across scale are quite obvious. The brush, comb, and mirror all increase in size, frustrating the attempts of the nixie to pursue the children. That the transformation across scale occurs in threefold is also fairly common in folktales. Goldilocks has her adventures in the world of three bears. Even that which she experiences — the three chairs, three bowls of soup, and three beds — occurs in a threefold schema. Self-similarity exists across the scales both of size and of time.

Scaling is also present in the next folktale, that of "The Old Man and His Grandson". This time, however, the scaling occurs in the structure of the narrative itself.

The Old Man and His Grandson

> There was once a very old man, whose eyes had become dim, his ears dull of hearing, his knees trembled, and when he sat at table he could hardly hold the spoon, and spilt the broth upon the table-cloth or let it run out of his mouth. His son and his son's wife were disgusted at this, so the old grandfather at last had to sit in the corner behind the stove, and they gave him his food in an earthenware bowl, and not even enough of it. And he used to look towards the table with eyes full of tears. Once, too, his trembling hands could not hold the bowl, and it fell to the ground and broke. The young wife scolded him, but he said nothing and only sighed. Then they bought him a wooden bowl for a few half-pence, out of which he had to eat.
>
> They were once sitting thus when the little grandson of four years old began to gather together some bits of wood upon the ground. "What are you doing there?" asked the father. "I am making a little trough," answered the child, "for father and mother to eat out of when I am big."
>
> The man and his wife looked at each other for a while, and presently began to cry. Then they took the old grandfather to the table, and henceforth always let him eat with them, and likewise said nothing if he did spill a little of anything. (Grimm 1975:363-4)

Here the theme of the narrative is fractal. The boy observes his parents' behavior, extrapolates to his own situation (integrates what he observes with what he understands to be his relations with his parents), and repeats the behavior. This is the beginning of a cascade that builds upon itself when the parents observe their son's behavior, realize his extrapolation to the relationship between them, and understand its origin in their relationship with the grandfather. They can 'put two and two together', 'add it all up', or even 'draw

their own conclusions' from their new awareness. As a result, they attain a new level of consciousness that leads them to change their behavior.

The chaotic situation that existed between the parents and the grandfather, which began with the counterpart of a Hopf bifurcation portrayed quite literally in the separation of the grandfather from the table, has now led to the establishment of a new fractal attractor, namely, the parents' new awareness of the relationship between them and the grandfather, them and the son, and the son and the grandfather. This fractal attractor/awareness leads first to an expansion of consciousness and then to new behavior. In this case, consciousness leads to greater ego awareness, which leads to an action by the ego that may, at some time in the future, facilitate a further expansion of consciousness.

The potential for further expansion of consciousness is portrayed more elaborately in the next folktale, "The Old Woman in the Wood". In this tale, the servant-girl's willingness to accept her dilemma and to learn from it is the essential precondition for the narrative to progress to a higher level of consciousness, without which there could be no fortuitous conclusion.

The Old Woman in the Wood

A poor servant-girl was once traveling with the family with which she was in service, through a great forest, and when they were in the midst of it, robbers came out of the thicket, and murdered all they found. All perished together except the girl, who had jumped out of the carriage in a fright, and hidden herself behind a tree. When the robbers had gone away with their booty, she came out and beheld the great disaster. Then she began to weep bitterly, and said: "What can a poor girl like me do now? I do not know how to get out of the forest, no human being lives in it, so I must certainly starve". She walked about and looked for a road, but could find none. When it was evening she seated herself under a tree, gave herself into God's keeping, and resolved to sit waiting there and not go away, let happen what might. When she had sat there for a while, a white dove came flying to her with a little golden key in its beak. It put the little key in her hand and said: "Do you see that great tree, therein is a little lock; open it with the tiny key, and you will find food enough, and suffer no more hunger." Then she went to the tree and opened it, and found milk in a little dish, and white bread to break into it, so that she could eat her fill. When she was satisfied, she said: "It is now the time when the hens at home go to roost, I am so tired I could go to bed too." Then the dove flew to her again, and brought another golden

key in its bill, and said: "Open that tree there, and you will find a bed." So she opened it, and found a beautiful white bed, and she prayed God to protect her during the night, and lay down and slept. In the morning the dove came for the third time, and again brought a little key, and said: "Open that tree there, and you will find clothes." And when she opened it, she found garments beset with gold and with jewels, more splendid than those of any king's daughter. So she lived there for some time, and the dove came every day and provided her with all she needed, and it was a quiet good life.

Then one day the dove came and said: "Will you do something for my sake?" "With all my heart," said the girl. Then said the little dove: "I will guide you to a small house; enter it, and inside it, an old woman will be sitting by the fire and will say: "Good day." But on your life give her no answer, let her do what she will, but pass by her on the right side; further on, there is a door, which open, and you will enter into a room where a quantity of rings of all kinds are lying, amongst which are some magnificent ones with shining stones; leave them, however, where they are, and seek out a plain one, which must likewise be among them, and bring it here to me as quickly as you can." The girl went to the little house, and came to the door. There sat an old woman who stared when she saw her, and said: "Good day, my child." The girl gave her no answer, and opened the door. "Whither away," cried the old woman, and seized her by the gown, and wanted to hold her fast, saying: "That is my house; no one can go in there if I choose not to allow it." But the girl was silent, got away from her, and went straight into the room. Now there lay on the table an enormous quantity of rings, which gleamed and glittered before her eyes. She turned them over and looked for the plain one, but could not find it. While she was seeking, she saw the old woman and how she was stealing away, and wanting to go off with a bird-cage which she had in her hand. So she went after her and took the cage out of her hand, and when she raised it up and looked into it, a bird was inside which had the plain ring in its bill. Then she took the ring, and ran quite joyously home with it, and thought the little white dove would come and get the ring, but it did not. Then she leant against a tree, determined to wait for the dove. As she thus stood, it seemed just as if the tree was soft and pliant, and was letting its branches down. And suddenly the branches twined around her, and were two arms, and when she looked around, the tree was a

handsome man, who embraced and kissed her heartily, and said: "You have delivered me from the power of the old woman, who is a wicked witch. She had changed me into a tree, and every day for two hours I was a white dove, and so long as she possessed the ring I could not regain my human form." Then his servants and his horses, who had likewise been changed into trees, were freed from the enchantment also, and stood beside him. And he led them forth to his kingdom, for he was a King's son, and they married, and lived happily. (Grimm 1975:558-560)

One could indulge in a great deal of elaboration of the symbols of the narrative. The witch and the servant-girl may well be two sides of the same coin, for example, aspects of the feminine that are battling it out for the soul of the masculine. While such elaborations certainly contribute to a comprehensive understanding of the narrative, we are concerned here primarily with the role of chaotic dynamics in general, and of fractal attractors in particular.

The narrative begins with a literary counterpart of a Hopf bifurcation, which sets in motion a series of oscillations between the actual (servant-girl) and the potential (dove and forest). That "chaos often appears in an otherwise well-behaved physical system when it is "pushed" — a certain parameter of the system is increased so high that irregular motion sets in" (Pool 1989:27), is portrayed in the disaster that befalls the servant-girl's employers. The oscillations generated by this event intensify and bifurcate further throughout the narrative as the events unfold.

Several images suggest scaling: the dove and the bird in the cage, the servant girl and the old woman, the three-fold process by which food, shelter, and clothing are discovered. Fractal dimension exists throughout the narrative as well: trees that open, doves that talk, trees that become human, witches who cast spells. Like topology, these images force the hearers (readers) of the tale to stretch their concepts of the nature of reality into an imaginal place where categories are transcended. As thought struggles to keep up with fantasy, the mind is literally expanded. Dimensions appear that were hitherto inconceivable.

The process by which the known is relinquished in favor of the imagined can be a rather disquieting experience. This, too, is reflected in the tale, for central to the narrative is the disaster that leaves the servant-girl stranded and alone. Without this experience, nothing else can take place. To this she makes a critical response: rather than panicking or running away, she sits down next to a tree and places herself in God's hands. The intersection of crisis and trust creates the potential for consciousness to develop.

The narrative reaches its climax with the task that the dove gives the servant-girl. Through her interaction with the dove, the servant-girl has gained in courage and volition and is no longer helpless before events. When asked by the dove to perform a task, she readily agrees. This represents a development in the dynamic between the servant-girl and the dove. Previously it was the environment that responded. All that the servant-girl trusted would be provided, was. Now, however, the crisis that led to trust and to largesse generates a new crisis: the dove's request and challenge.

As the initiative shifts from the surroundings to the servant-girl, a new pattern — fractal in its similarity with the old — establishes itself. The surround must trust the servant-girl. Now she must be the one to respond. The merger of attractors here is subtle. Before the disaster, the servant-girl lived a life of duty and loyalty to her masters. She hardly had to think for herself. She had simply to obey. All her perceptions and behaviors were organized by this simple equation: duty and obedience. As a result of the collision between that attitude and the disaster that obliterates that lifestyle, however, patterns begin to coalesce. She is about to experience a novel challenge to her previous perspectives.

Following the dove's instructions, the servant-girl ignores the witch and looks for the ring. When the witch begins to sneak away, however, she must mobilize her courage and volition in order to successfully complete her task. Noticing the departure of the witch, she goes to investigate. At this point she has survived the temptations that might have distracted her (the witch's greeting and protest, the enticingly priceless rings), and sees that the witch has a cage in her hand, a cage that contains a bird with a ring in its mouth. The ring is the very one she seeks.

The caged bird is a fractal elaboration of the dove, which has also been trapped, but in a spell. Seizing the ring is a fractal elaboration as well: of the original situation in which the witch seized the freedom of the prince. These fractal events comprise a cascade, from which a new attractor must appear to supersede the attractor that is the spell. Essential to the appearance of this new attractor is the volition of the ego (servant-girl). She is equal to the task. Her old orientation of servitude has been replaced by a new attitude of will.

When the servant girl returns to the site of her encounter with the dove, however, nothing happens. The dove does not come to take the ring. But then, suddenly, everything changes. One reality folds into another. The spell has been broken. There is no defining event that reveals either the existence of the spell or its cessation. A new state of affairs simply comes into being. What could this mean? In this narrative, it seems that an old attractor (the spell), into which a dynamic (the prince and his soldiers) had been confined, has been replaced by another, from which potentials for new dynamics can appear.

The climax of the tale involves a transformation: from tree to prince, from forest to soldiers. The spell that had made it impossible for the essence of a phenomenon to reveal itself has been broken. Through the encounter between an attractor of the servant-girl's consciousness and the attractor of the spell, a new dynamic is established. In effect, "two chaotic attractors spawned by the period-doubling cascades merge to form one attractor with greater symmetry" (Field & Golubitsky 1992:111). "Symmetry" refers to the preservation of pattern through differing points of view. "Greater symmetry" refers to the consolidation of patterns that occurs when two or more attractors merge. With regard to consciousness, increased symmetry allows greater recognition and integration of patterns of increasing complexity. Anything that increases recognizability — symmetry, for example — increases the scope of consciousness.

The breaking of the spell is the result of the servant-girl's rite of passage: her encounter with the old woman. This event requires a penultimate transformation: of her perception of the relation between herself and the old woman (from that of a child to an adult to that of an equal), and of her behavior (from servile to assertive, from deferential to commanding). In other words, she must learn to see differently.

When she returns to the forest, nothing seems to have changed. But the transformation that has occurred in her perception and behavior is followed by a second transformation: that of the prince and his soldiers. In the terms of Analytical Psychology, she has confronted an unconscious complex (the old woman in the wood) and integrated it (by having to be conscious of what is taking place and of her role in the drama) into her ego. In effect, the transformation of the trees into men and the transformation of her consciousness are synonymous.

The increase in symmetry that evolves as a result of the servant-girl's transcendence of her previous orientation (duty and obedience) is beautifully portrayed by the ring, which, as perhaps the most symmetrical form that exists, demonstrates both 'flip' and rotational symmetry (Field & Golubitsky 1992:42-61). Successful negotiation of the terrain dominated by the old woman has required her to transfer the focus of her attention from the pile of beautiful rings on the table to the bird in the cage which the old woman is carrying off. In successfully negotiating this challenge, she obtains the ring that the dove has requested she retrieve. Because her consciousness is adequate to the task, she perceives a new reality that previously lay concealed behind the appearances of the forest. Finally, that which the hearer/reader experiences of the folktale is self-similar with the servant-girl's experiences *within* the folktale. Just as she

must stretch her consciousness to extrapolate from what she is told to what she must do, so must the hearer/reader extrapolate from that which is heard/read to that which is experienced. The fractal circle is complete. One attractor leads to another.

6. Summary and conclusion

Jung's metapsychology is built on the premise that the workings of the psyche are reflected in that which it generates, primarily images. He felt that the surprising uniformity of images and themes in folktales, myths, and dreams suggests that they are manifestations of dynamics common to the human psyche. In effect, they portray dynamic processes in the structure of the brain.

In his vocabulary of psychic development, the unconscious assembles the images that consciousness must decipher. The response of consciousness to those images influences the manner in which the unconscious assembles future images. In other words, the feedback between consciousness and the unconscious influences the character of the images. Furthermore, in Jung's view of the development of the psyche, psychodynamics involve bifurcations and oscillations, while psychic structures function like attractors. Both reveal their dynamics in symbolic images.

However the relationship between chaotic dynamics and the development of consciousness may be an open question, the similarity between the two paradigms is notable. The development of consciousness seems to begin with a Hopf bifurcation that occurs when the existing attractors of consciousness become inadequate to decipher a challenge. This first appears as a conflict that generates a tension of opposites, upon which follows a period of chaos, when all is confusion. This chaotic period corresponds to the ego's immersion in the unconscious. Finally, due to the feedback loops and scaling of the chaotic dynamics, new patterns re-emerge that coalesce into more highly articulated attractors. Jung defined this as the 'transcendent function', through which symbols appear that unite the poles of the conflict, consolidating them into new configurations that increase the ability of consciousness to integrate what was previously a fragmenting experience (cf. Van Eenwyk 1992).

That the similarity between Jung's theory of the development of consciousness and deterministic chaos is reflected in narratives that are collectively determined — primarily, but not limited to, folktales and myths — challenges the skeptic to propose alternative hypotheses. Hopefully, this essay can stimulate just such responses. For if from the conflict between this hypothesis and others emerge more highly articulated descriptions of the

growth of consciousness, that in itself will help to substantiate that this hypothesis that chaotic dynamics inform the development of consciousness is essentially correct.

Notes

1. For a challenging discussion of qualitative versus quantitative explanations of physical behavior, see Feigenbaum (1992).
2. For an in-depth discussion of their similarity, see Van Eenwyk (1991).
3. With regard to these two criteria for evaluating theories, see Toulmin (1963).

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