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Chapter 3

Performance of Intelligent Systems Governed by Internally Generated Goals

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3.1 Abstract

Intelligent behavior is characterized by flexible and creative pursuit of endogenously defined goals. It has emerged in humans through the stages of evolution that are manifested in the brains and behaviors of other vertebrates. Perception is a key concept by which to link brain dynamics to goal-directed behavior. This archetypal form of intentional behavior is an act of observation into time and space, by which information is sought to guide future action, and by which the perceiver modifies itself through learning from the sensory consequences of its own actions. Chaotic brain dynamics creates the goals, expresses them by means of behavioral actions, and defines the meaning of the requested information. These acts include the making of representations (e.g. numbers, words, graphs, sounds, gestures) for communication to other brains in validation and coordination of experience. The failure of artificial intelligence to achieve its stated aims can be attributed to taking too literally these man-made descriptive representations as the tokens of brain action, whereas in brains there is no information, only dynamic flows and operators.

3.2 Introduction

The dawn of the Information Age with the proliferation of digital computers brought a flurry of optimism regarding the feasibility of using the new devices to emulate the performance of humans in solving complex problems by rational devices. McKenna (Chapter 6, this volume) notes that programs in considerable variety were initiated to

explore and exploit this new opportunity for human advancement. As he so clearly describes, the existing devices and programs in artificial intelligence (AI) have failed to match performance qualifications of biological intelligent systems. The questions he raises are, why, and what can be done about it? There are several possible answers. In my opinion the key to finding answers lies in noting the heavy reliance on numbers and number theory in the use both of digital computers and of a broad range of devices that include neural networks, fuzzy logic, probabilistic reasoning, and genetic algorithms as well as the symbolic logic of classical and functional AI. There are no rational numbers in brains, nor is there a foreseeable way of computing with real numbers to simulate continuous time variables (Blum et al., 1989). Dynamical analog devices, which simulate but do not compute, are closer to biological reality, but the development of advanced new analog systems has been largely eclipsed by the seductive “certainties” of digital computation, which are now being developed in the emergent field of “neurocomputation”. Neural modelers may object to being grouped with cognitivists and other practitioners of rule-driven symbol manipulation, but neurodynamics as I conceive it is so far from both that they appear to merge, like stars in a distant galaxy that is seen from our own (Freeman, 2000).

Artificial neural networks (ANN) are stable devices that require highly structured, restricted environments for their operation. They are programmed to perform tasks designated by their creators, using information that is provided by their sensors. They are hierarchical in the sense of nested components corresponding to plug-in units in mother boards.

Biological neural networks (BNN) are characteristically unstable, untutored systems that operate in open, unconstrained environments. They devise their own goals and seek information through their sensors that is needed to reach those goals. They

Table 3.1. Some properties that distinguish ANN from BNN.

ANN	BNN
Stationary	Unstable
Input-driven	Self-organizing
Task-oriented	Goal-oriented
Nested circuits	Micro-macro interactive
Computational: - bits - symbols - information	Dynamic: - flows - patterns - meaning
MEMORY	REMEMBERING
An object	A process
Representations	Trajectories
Gradient descent	State transition
Retrieval	Construction
Test by matching	Test by action

are hierarchical in a different sense, which requires the co-existence of a myriad of components (atoms, molecules, and neurons) at microscopic levels, leading by their interactions to emergence of macroscopic, self-organizing patterns that constrain the interactive elements (Freeman, 1995). From this perspective the lack of success in emulating BNN with ANN is not due to lack of knowledge about components, such as the various types of neurons, neurotransmitters, membrane receptors, neuromodulators, trigger zones, and brain architectures. The failure is due to inadequate use of known rules of self-organization. Nowhere is this more important than in the endogenous construction and flexible implementation of goals within organisms and, sooner or later, in artificial devices that some researchers hope will offer an improvement over the way that domesticated animals and obedient children perform for humans now.

3.3 Perception as an Active Process

An intelligent device must learn about its body and its environment in order to deal with them effectively. The learning requires an interface between the limited capacity of the organism and the unlimited complexity of the world, and it is done through perception. Classical ANN treat perception as passive. Devices wait for stimuli, and the information impinges on sensors, in which simulated action potentials serve as symbols that are to be manipulated according to logical rules, such as through serial processing into feature detectors, binding into representations of objects, template storage, retrieval, matching by correlation, pattern completion, and task control. BNN are based in active perception. The forms of sensory stimuli are conceived in advance and sought by active looking, listening, sniffing and fingering, with selection for perception only of those limited aspects of the environment which are anticipated and important to the searcher. Every act of perception is based in the goal for which the sensory input is needed to construct meaning. The key problem for neuroscientists and knowledge engineers alike is, how do the goals of intentional activity emerge from the organization of brain systems?

Clearly the work is done in brains by specialized cells. Neurons, like people, are infinitely complex and varied in form and function, but they can only function properly in organized groups. This is shown by their characteristic forms that distinguish them from all other cell types in the body: dendrites and axons. The requirements for high densities of connectivity explain their architectures (Figure 3.1). Extensive branching of the dendrites gives a large surface area for synapses from incoming axons, while providing the necessary channels for synaptic currents to be converged to the trigger zones, from which axon branches diverge to carry the integrated pulse output to many other target neurons. The fibrous tissue infiltrated with capillaries and supporting glia in which the densely packed neurons are embedded is called “neuropil”. It forms by the outgrowth of the connecting filaments starting well before birth, and the growth continues throughout life (Figure 3.2). The patterns of connection appear to grow with few specifications by the genome. They are sculpted by

learning from experience, with strengthening or proliferation of some synapses and weakening or deletion of others. Cortical neuropil in particular is highly malleable, and it is the main organ of BNN. The distributed sparse connectivity of immense numbers of neurons is the basis for its interactive dynamics. The dense plexus of axons and dendrites particularly in the superficial layer of cortex provides the anatomical basis for its self-organization (Freeman, 2001).

Figure 3.1. Neurons generate loop currents with their sites of electromotive force in synapses and the significant sites of integration at trigger zones. The same currents flow across the extracellular tissue resistance, and the sums of the potential differences from local neighborhoods manifest local mean fields in electroencephalographic (EEG) potentials. Reproduced by permission from Freeman (1992). © World Scientific, 1992.

The growth and maintenance of neurons in neuropil requires that they be continually active. Because they transmit by impulses, their outputs have the form of repetitive pulse trains. Neurons have the capability for relaxation oscillation comparable to

Figure 3.2. The outstanding characteristic of cortical neuropil is the rich connectivity among neurons, which is established early in life and continues to grow throughout maturity. The preferred method of visualizing the connecting filaments is by silver impregnation using the Golgi stain, which selects less than 1% of the neurons. Otherwise, nothing can be seen. Adapted by C. Galapp from drawings by Ramón y Cajal (1911) with permission from Éditions Maloine.

the beat of the heart, but they seldom show periodic firing. Their pulse trains typically seem random. These firing patterns are due to excitatory interactions. In early development before there are sufficient connections, the neuropil is inactive, manifesting a zero level point attractor (Figure 3.3, “Deep Anesthesia” – this state can be forced onto adult cortex by use of anesthetics). When the growing neuropil reaches a critical level at which the anatomical connection density exceeds unity, a non zero point attractor emerges that homeostatically regulates sustained background activity. The attractor is produced by a first order phase transition that converts a zero point attractor to a repeller (Figure 3.4). The activity of an area of cortex at this stage typically shows nearly “white noise” fluctuation superimposed upon a slowly drifting baseline (Figure 3.3, “Waking Rest”).

Figure 3.3. Four patterns of EEG time series are shown from the olfactory system. Cortex under deep anesthesia that suppresses interactions replicates the silence of embryonic cortex before connections have reached threshold for sustained interaction. In waking rest the activity resembles white noise. With arousal under conditions that lead to intentional behavior the EEG develops aperiodic oscillations with spectra that tend to the “ $1/f_n$ -type”, where $n \sim 2$ (Barrie et al., 1996). In the olfactory EEG as shown, the background state is interrupted repeatedly by inhalation under limbic control (middle trace), which manifests a phase transition to a more highly structured form, indicated here by the oscillatory “bursts”. Under intense electrical stimulation the olfactory system activity is briefly suppressed, and as it recovers, it enters into a low-dimensional chaotic state that is characterized as a partial complex seizure, a form of epilepsy (Freeman, 1975, 1988). Recovery is by a phase transition directly back to the normal waking state, as shown by the concomitant return of normal EEG and behavior. Reproduced by permission from Freeman (1987). © Springer-Verlag GmbH & Co., 1987.

In early stages of embryological growth the excitatory interactions predominate, and the sustained activity promotes the growth of connections. Around birth or soon thereafter the inhibitory interneurons form connections with the excitatory neurons, providing negative feedback that allows for the induction of a phase transition (Hopf bifurcation) to a limit cycle attractor. Thereafter, local areas of cortex can generate nearly periodic oscillations at the characteristic frequencies determined by their passive membrane time constants and their connection densities (Freeman, 1975). However, during normal activity of the cortex the local areas of neuropil are continually interacting with each other over short and long range connections, so that they sel-

dom sustain periodic activity. As elaborated below, long range connections between areas of cortex sustain oscillators with incommensurate frequencies, leading by further phase transitions to aperiodic activity that is governed by strange attractors.

Learning in the course of normal behavior requires modification of the synaptic connectivity throughout the neuropil. The aspect of learning that I want to concentrate upon is the role played by aperiodic activity in the brain to implement learning. Aperiodic time series are locally unpredictable, but over longer time intervals they are constrained and bounded, so that unlike noise they have internal structure that is not manifested in sharp spectral peaks. It can result when competing components in a dynamic system cannot agree on shared frequencies but cannot escape each other. In systems that are autonomous, noise-free, and low in dimension, that are exemplified by the Lorenz, Rössler and Chua attractors, and that are typically described by a third or fourth order nonlinear differential equation, this type of activity is called “deterministic chaos”. The activity in brains as in many other complex systems is not deterministic chaos, because it is driven by and embedded in noise (Freeman, 1996; Freeman et al., 1997). But it is not noise, because it is dependent on cooperation among the vast numbers of neurons which make up the various parts of the brain. This coordination and cooperation shrinks down the phase space of possible activity patterns. Therefore it can be looked upon as stochastic chaos, because the activity arises from and regulates the largely autonomous activity of millions of neurons that are weakly coupled by billions of synapses (Freeman, 1975, 1992, 1996).

3.4 Nonlinear Dynamics of the Olfactory System

The parts of the brain that generate stochastic chaos are not autonomous. They are not only coupled with each other; they are directly involved with the environment, which includes the body as well as the outside world, into which the brain acts by means of its musculoskeletal system, and from which it receives sensory feedback through the several sensory ports. These principles are exemplified by measurements of the electroencephalographic (EEG) activity of the olfactory system (Figure 3.3). This sensory port has three stages of processing following the receptors in the nose: the olfactory bulb, the anterior nucleus, and the olfactory cortex (Freeman, 1975). The bulb receives the receptor input and generates spatial patterns of amplitude modulated (AM) chaotic carrier waves, that is, aperiodic time series having the same irregular wave form over its entire extent. The olfactory cortex receives input from the bulb, performs spatiotemporal integration, and transmits its output into the limbic system, which is the closest approximation in the brain to the CPU of a computer (Freeman, 1995). The anterior nucleus is an intervening control element. Each of these three components is made of neuropil that has millions of neurons, and they interact by both excitatory and inhibitory pathways.

Figure 3.4. A bifurcation diagram illustrates the main states of the olfactory system. Of particular interest is the repeated emergence during inhalation of an attractor landscape with a collection of basins of attraction possibly corresponding to quasiperiodic limit cycles under noise, each basin corresponding to a learned class of stimulus. Reproduced by permission from Freeman (1987). © Springer-Verlag GmbH & Co., 1987.

The EEG during learning in the olfactory system has been studied, first in order to identify the changes in EEG patterns induced by learning, and then to simulate those changes with a model of the olfactory system that consists of a network of ordinary differential equations (Freeman, 1992). The basic module at the nodes of the network is a local population modeled with a linear second order equation with a static sigmoid function. A two-dimensional array of these nodes simulates the distributed interactions of the neuropil; each main part having its characteristic frequency that differs from those of the others. The three oscillators are coupled by long feedback pathways with delays that are dispersive, owing to distributions of conduction velocities and distances within the axonal pathways, which operate as low pass filters. At least one of these long pathways consists of excitatory neurons that excite other excitatory neurons. This constitutes positive feedback, which is responsible for a positive Lyapunov exponent in a model linearized at a typical operating point in state space. Other long pathways contain excitatory neurons that act upon inhibitory neurons, which provide negative feedback that constrains and compresses the activity in the phase space of the olfactory system. So we have continual operation of coupled oscillators which cannot agree on a common frequency, but which cannot escape each other or settle into a point or limit cycle attractor. The resulting activity of the system is governed by a global chaotic attractor (Figure 3.5).

Figure 3.5. The bifurcation diagram from Figure 3.4 is rendered in a perspective drawing, in which the central plateau is seen to be surrounded by a chaotic moat, which is the catch-all basin for “I-don’t-know” reactions to novel stimuli. Reproduced by permission from Freeman (1987). © Springer-Verlag GmbH & Co., 1987.

The activity is observed in the EEGs recorded from the three components of the olfactory system, because these extracellular potential differences are established by the flow of current that determines the firing of action potentials, though I emphasize that the extracellular current is epiphenomenal, an indicator and not an operator (Freeman and Baird, 1989). In awake animals that are not engaged in olfactory exploration, the EEGs show that the global activity of the system is governed by a basal attractor that is maintained for minutes to hours, keeping the olfactory system in readiness for action. When the animals are aroused, the EEGs change (Figure 3.3, “Motivation”). The recordings reveal a brief burst of activity, on the order of 50–100 msec in duration, with each inhalation. With continuing respiration the bursts form a sequence of oscillations, which is the manifestation of the control of the olfactory system by the rest of the brain, particularly the limbic system, which is primarily responsible for search strategies using the sensory systems. The repeated bursts with breathing show that search as in sniffing engenders the organization of patterns of neural activity that create the olfactory knowledge in the brain, which is in fact being sought by the brain.

The brief burst of oscillation with each inhalation is concentrated in the gamma range of 20–80 Hertz range, unlike the basal activity that has a broad “1/f” spectrum

(Freeman et al., 1997; Chang and Freeman, 1996), and it is lower in dimension than the background activity. Each burst has a spatial pattern of amplitude and of phase at the center frequency, which differs from each burst to the next. These findings show that each burst is formed by a first order phase transition from the basal chaotic attractor to a more tightly constrained part of the olfactory state space (Figure 3.1). A conjectural image of the state space of the olfactory system (Figure 3.4) shown in perspective (Figure 3.5) is designed to show that during inhalation, a phase transition takes the system from its chaotic basin with a central repeller to open an attractor landscape with a collection of basins, one for each odorant that an animal has learned to discriminate. These small attractors can also be described as wings of the global attractor, in analogy to the Lorenz butterfly with two wings. The amplitude modulation (AM) spatial patterns generated by the wings are then transmitted from the bulb to the olfactory cortex. The sequence of bursts comprises a set of frames of dynamic states, like the frames in a cinema, and they manifest the way in which the limbic system strobes the olfactory environment in order to update its grasp of the ever-changing surround.

I emphasize that these AM patterns are not representations of or information about odorants (Freeman, 1991). They are dynamic operators that enter into other parts of the brain and induce the formation of yet larger cooperative patterns, which in turn solicit interchanges with multiple cortical and subcortical components in each hemisphere.

3.5 Chaotic Oscillations During Learning Novel Stimuli

Most of the bursts occur when the animal is not attending to or searching in the olfactory environment. They nevertheless have value, because they provide the important knowledge that there is nothing of interest at the present time and place, such as the scent of a predator or other sign of unanticipated danger. The burst is a message that is conveyed in the spatial pattern of AM of the chaotic time series in each burst, which has the same wave form in all parts of the olfactory bulb. This is a learned pattern, which is updated whenever the environment changes.

The process of learning involves changes in the synapses which interconnect the excitatory neurons within the bulb and within the cortex, which are co-excited by the sniffing of an odorant on any one trial. On repeated sniffs the cumulative changes in synapses between simultaneously firing neurons leads to the formation of a Hebbian nerve cell assembly for that odorant. The modifiable synapses are not at the site of input from the receptor axons transmitting to the bulbar neurons or at the site of input of the bulbar neurons to the neurons in the olfactory cortex. Those are important sites of modification in respect to signal normalization and logarithmic range compression, but not of associational learning (Freeman, 1975). The modifiable synapses are between the excitatory neurons, which can be described by matrices that are comparable to those developed by Stephen Grossberg, Teuvo Kohonen, Shun-ichi Amari,

John Hopfield, and James Anderson (Shaw and Palm, 1988) in associative networks with sparse, global feedback within each layer of interconnected neurons. The synaptic connections that form the Hebbian nerve cell assembly lead to re-excitation of the interconnected excitatory neurons and an explosive growth of activity by positive feedback. Even though the cell assembly contains only a minute fraction of the bulbar neurons, that explosive growth of activity directs the bulb into a basin of attraction that is defined by learning. Each time a learned odorant is in the inhaled air coming to the receptors, the olfactory system undergoes a state transition, by which the system is driven from its basal attractor and confined to the appropriate basin of the attractor landscape. When the stimulus is withdrawn by exhalation, the system is rapidly released to the basal state by the collapse of the landscape. Each local attractor gives a characteristic spatial AM pattern of the chaotic time series that is manifested in the EEG.

Now what happens when an animal gets a novel stimulus that it has to learn in order to get food or find shelter? The first thing that happens is the expected bursts don't occur (Figure 3.6). Just after each inhalation the limbic system expects a burst to arrive, and if it fails to come, that constitutes a signal to the animal that something is present in the environment, whose nature and significance are unknown. And that something must then be classified. If it is unimportant, it will not be accompanied by food or deprivation, and the bulb will react by diminishing the effectiveness of the output synapses of those neurons that were excited by the unwanted input. This is habituation, which forms an adaptive spatial filter to diminish the impact of irrelevant features in a current environment (Grajski and Freeman, 1989; Gray and Freeman, 1987). The unknown input will be made important when it is accompanied by reinforcement, such as food to a hungry animal, or aversive stimulation of some kind to a threatened animal.

But in either case, during the first episode, there is an absence of an AM pattern of burst activity (Figure 3.6). But there is activity being transmitted that is unstructured. What is happening is that the olfactory system goes to a chaotic basin and sends a message that tells the limbic system, "I don't know what this is, but it may be important!". If it is not, habituation takes place automatically without need for limbic intervention. If it is made important, habituation is blocked, and Hebbian learning begins, which requires coincident pre- and post-synaptic activity. What that deeply chaotic activity provides is the firing which is necessary to drive Hebbian synapses, but without pre-existing structure, which would only result in reinforcement of an existing attractor wing. There must be activity to drive Hebbian synapses, but that activity must be unstructured if a new chaotic basin of attraction is to be formed. So the chaos provides an essential mechanism for making a novel attractor for a novel odor, that is, making something that didn't exist before. That is the essential role that chaos plays. It is not only to bring about an alerting or orienting response, but also to carry out learning by providing the disorder that must precede the emergence of new order.

Figure 3.6. EEGs are shown from the olfactory bulb and prepyriform cortex to which the bulb transmits. The EMG (electromyogram) shows the performance of a CR (conditioned response) to a novel odorant after previous training to respond to an odorant CS (conditioned stimulus). The animal gave what is called a pseudoconditioned response to the unknown odorant, and the EEG showed the characteristic suppression of the burst activity, leading us to postulate the deep chaotic moat shown in Figures 3.4 and 3.5. Reproduced by permission from Freeman and Schneider (1982). © Cambridge University Press, 1982.

These synaptic modifications occur during the time duration of a single sniff, which is about a tenth of a second in rabbits and rats. But that only involves a single sample and a small fraction of the neurons that are used for reliable discrimination. Effective learning for generalization requires multiple samples, both with the target odorant reinforced, and without the target but with the background non-reinforced, which allows the animal to learn to discriminate the foreground that is important and to habituate to the background that is not. The acquisition of multiple samples of each odorant is necessary in order to construct a basin of attraction in the bulbar attractor landscape. Each sniff activates only a small subset of the receptors that are tuned to an important odorant, and the selection of the subset varies randomly over sniffs, owing to turbulence in the nose. The incremental formation of a Hebbian nerve cell assembly for that odorant provides for generalization, such that any combination of input from the relevant class of olfactory receptors, even if it never happened before, will put the system into its appropriate basin of attraction and give rise to the AM spatial pattern that conveys the required information to the animal.

3.6 Generalization and Consolidation of New Perceptions with Context

This phase of learning occurs rapidly because the required number of sniffs can take place within a minute or so, as the nerve cell assembly is developed and the AM pat-

terns emerge and are transmitted, reflecting the growth of the new basin of attraction and its chaotic attractor. However, this is only the beginning of the process of incorporation of the novel but now meaningful stimulus into the history of the organism. The consolidation of the learning means not only that a degree of permanence is achieved but, more importantly, that the new learning is knit together with all past experience. The fact that this occurs is revealed in studies of the AM patterns for multiple learned stimuli over periods of days and months. What we find is that whenever a new stimulus is learned and a new attractor forms, the AM patterns for all previously learned stimuli change as well, not by much, but by enough to show that the addition of a new wing to the global attractor jostles all of the others. Therefore, the AM pattern that is the message, which is extracted by the targets of bulbar transmission through a divergent-convergent axonal pathway performing a spatial integration, reflects in some part all of past experience. This is made clear by the progressive, relentless change in AM patterns for all stimuli as daily experience is accumulated. The AM patterns for invariant stimuli are themselves not invariant, because they reflect the changing history, context and significance of the stimuli. What is important for the animals is the meaning of a stimulus, not its particular form, which is constantly changing in any case with each new sample. So we don't have something like pattern retrieval or pattern completion, but instead pattern genesis, which leads now to the conclusion that what the bulb transmits outwardly to the rest of the brain is what it has constructed within itself on the basis of past learning. Another way of saying this is the only thing the nervous system can know about the olfactory environment is what it has created within itself. There is no direct infusion of information from the world.

The state space diagrams (Figures 3.4 and 3.5) summarize the levels of function of the olfactory system. To review, a point attractor is revealed by the suppression of EEG oscillations under deep anesthesia, which is equivalent to "brain dead". This is an open loop state with the gains of the positive and negative feedback set to zero. A point attractor that can be represented as a basin with a deep well, into which the system, if perturbed, will simply drop to inactivity. As the animal recovers to a state of waking rest, the point attractor bifurcates to a central repeller with a chaotic basin around it, in which there is continual flow of activity. With arousal to a motivated state, in which the animal is hungry, frightened, sexually aroused or combative, there is an expansion of this basin, with a change in the attractor landscape to reveal a broad central area within which the state moves in a restless chaotic trajectory.

Input from sniffing destabilizes the olfactory system and reveals the prior existence of a collection of small basins leading to near limit cycle attractors, corresponding to the wings of the global attractor. The input of a known odorant actualizes one of these potential basins, leading to the confinement of the system until the input terminates with exhalation. That is, with each inhalation there is a change in the attractor landscape, so that a collection of basins is made available and the selection of which basin the system will go to is made by the input. Further evidence for this global attractor structure is provided when a very intense electrical stimulus is given to the axonal pathway between the bulb and the cortex. Above a very high threshold, the artificial stimulus drives the olfactory system into an epileptic seizure, which is man-

ifested by an aperiodic spike at about 3/sec followed by a slow wave and a stereotypic burst. This form of epilepsy is well known in humans as a partial complex or petit mal seizure, and it is accompanied by an interruption of normal behavior known as "absence". The patients are temporarily unconscious, in that they do not respond to social contacts during the episode and afterward cannot remember anything that happened just before or during the seizure.

The EEG manifests a low dimensional attractor, which lasts several seconds and cannot be modified or interrupted by further perturbation, either electrical or behavioral. These properties of stationarity and autonomy allow the epileptiform to be modeled by a low dimensional deterministic chaotic attractor embedded in 3-space, having a fractal correlation dimension between two and three (Freeman, 1988), and a form that is consistent with a collapsed hypertorus (Kaneko, 1986). The epileptic state is also seen during induction of and recovery from the open loop state. The KIII model of the olfactory system indicates that the chaotic state is accessed not by period doubling but by the Ruelle-Takens route – two Hopf bifurcations and the collapse of the torus (Freeman, 1992). Observations on the abruptness of recovery from a seizure show that the state transition from the epileptic state to the normal brain state is by a single bifurcation to a higher dimensional state. The epileptic state is of further interest, in that learning that has taken place just prior to the onset of a seizure is prevented from going on into consolidation. This corresponds to the amnesia observed in human subjects with petit mal epilepsy. It offers further evidence that learning is temporary during the formation or modification of an attractor, and that the heavy work of compiling the fabric of memory is clearly done off-line in some form of batch processing. Many lines of evidence have shown that the hippocampus and related limbic structures in the medial temporal lobes are essential for that work, even though these structures are not the sites of memory storage, as the computer metaphor would hold.

3.7 The Central Role of the Limbic System

Brain scientists have known for over a century that the necessary and sufficient part of the vertebrate brain to sustain goal-directed behavior, a subclass of intentionality, is the ventral forebrain, including those components that comprise the external shell of the phylogenetically oldest part of the forebrain, the paleocortex, and the deeper lying nuclei with which that cortex is connected. These components suffice to support remarkably adept patterns of intentional behavior, after all of the newer parts of the forebrain have been surgically removed from dogs (Goltz, 1892) or chemically inactivated in rats by spreading depression (Bures et al., 1974). Intentional behavior is severely altered or disappears following major damage to the basal forebrain. Phylogenetic evidence for the limbic origin of intentionality comes from observing goal-directed behavior in salamanders, which have the simplest of the existing vertebrate forebrains (Herrick, 1948; Roth, 1987). The three parts are sensory (which is predominantly but not exclusively olfactory), motor, and associational, which contains

the primordial hippocampus with its associated septal, amygdaloid and striatal nuclei. The hippocampus is considered to be the locus in higher vertebrates of the functions of spatial orientation (the “cognitive map” of O’Keefe and Nadel, 1978) and temporal integration in learning (the organization of “short-term memory”). These processes are essential, inasmuch as intentional action takes place into the world, and even the simplest action, such as searching for food or evading predators, requires an animal to know where it is with respect to its world, when it got its last signal, where its prey or refuge is, and what its spatial and temporal progress is during a sequence of attack or escape.

The crucial question for neuroscientists is, how are the patterns of neural activity that embody the goals of intentional behavior created in brains? The answer can be provided by extending the models of the dynamics of the olfactory system to the visual, auditory, somatic and entorhinal cortices. The electrical activity of the primary sensory and limbic neocortices of animals that have been trained to identify and respond to conditioned stimuli (Freeman, 1975, 1992, 1995; Barrie et al., 1996; Kay and Freeman, 1998) are closely related to that of the various parts of the olfactory system. As in the case of the olfactory bulb and cortex, neocortical neurons are selectively activated by sensory receptors to generate microscopic activity, and by interactions among the cortical neurons, populations form that “bind” their activity into macroscopic patterns (Hardcastle, 1994; Gray and Singer, 1989; Singer and Gray, 1995). The brain activity patterns reflected in EEGs are macroscopic brain states that are induced by the arrival of stimuli. Each learned stimulus serves to elicit the construction in a primary sensory cortex of a stable pattern that is shaped by the synaptic modifications among cortical neurons from prior learning, and also by the brain stem nuclei that bathe the forebrain in neuromodulatory chemicals (Gray et al., 1986). As a dynamic action pattern it creates and carries the meanings of stimuli for the animal by incorporating the individual history, present context, and expectancy, corresponding to the unity and the wholeness of the intentionality. The patterns created in each cortex are unique to each animal and each experience.

All sensory cortices transmit their signals into the limbic system (Figure 3.7). Much the same kinds of EEG activity as those found in the sensory and motor cortices are found in various parts of the limbic system. This discovery indicates that the limbic system also has the capacity to create its own spatiotemporal patterns of neural activity. I predict that its patterns will be found to depend on past experience and convergent multisensory input but to be self-organized. The limbic system provides a complex array of interconnected modules, that might well serve continually to generate the neural activity that forms goals and directs behavior toward them. Anatomical evidence shows that all primary sensory cortices in mammals direct their transmissions to the entorhinal cortex, and EEG evidence shows that they have the same or similar dynamics. The similarity is essential for the assembly of the inputs deriving from the various specialized sensory ports into the unified Gestalts on which perception is based. Each Gestalt must occur by a dynamic phase transition, in which a complex assembly of neuron populations jumps suddenly from one spatiotemporal pattern to the next. Being intrinsically unstable, the limbic system must continually transit across states that emerge, spread into other parts of the brain, and then dissolve

to give rise to new ones. Its output controls the brain stem nuclei that serve to regulate its excitability levels, implying that it regulates its own neurohumoral context, enabling it to respond with equal facility to changes, both in the body and the environment, that call for arousal and adaptation or rest and recreation. I propose that it is the neurodynamics of the limbic system, modulated by other parts of the forebrain such as the frontal lobes and the thalamic and midbrain reticular activating systems, that appears as intentional behavior, and in particular that initiates the novel and creative behavior seen in search by trial and error.

The limbic activity patterns of directed arousal and search are sent into the motor systems of the brain stem and spinal cord. Simultaneously, patterns are transmitted back to the primary sensory cortices, preparing them for the consequences of motor actions (Figure 3.7). This process has been called the "sense of effort" (Helmholtz, 1878), "reafference" (von Holst and Mittelstaedt, 1950; Freeman, 1995), "corollary discharge" (Sperry, 1958), "focused arousal", and "preafference" (Kay et al., 1996). It sensitizes sensory systems to anticipated stimuli prior to their expected times of arrival in the process of attention. Sensory cortical constructs consist of brief staccato messages to the limbic system, which convey what is sought and the result of the search. After multisensory convergence, the spatiotemporal activity pattern in the limbic system is up-dated through temporal integration in the hippocampus. Between sensory messages there are return up-dates from the limbic system to the sensory cortices, whereby each cortex receives input that has been integrated with the output of the others, reflecting the unity of intentionality. Everything that a human or an animal knows comes from this iterative circular process of action, preafference, perception, and up-date (Freeman, 2001).

The limbic system is clearly well situated for controlling the motor systems, because intentional action requires close integration of the central brain state with the conditions in the environment through immediate and close interactions (Taga, 1994; Clark, 1996; Hendriks-Jansen, 1996; Tani, 1996). Its output is directed immediately into two major descending pathways. The lateral forebrain bundle carries activity patterns from the amygdaloid nucleus to the musculoskeletal apparatus to implement overt actions. The medial forebrain bundle carries activity from the septal and accumbens nuclei into the hypothalamus, the head ganglion of the autonomic nervous system and the hypophysis. Moreover, these two descending pathways play major roles in feedback control of the aminergic and peptidergic nuclei in the hypothalamus and brain stem, which are crucial for regulation of affect, learning, and the levels of metabolic energy expenditure, and in oversight through the tract of Vic d'Azyr of the allocation of attention, orienting and awareness resources through the thalamus. In primitive vertebrates the limbic system is dominated by olfaction. Other senses in higher vertebrates have co-opted the basic mechanisms of self-organization. Evolution has also greatly expanded the preprocessing of information in vision, audition and somesthesia, particularly in thalamocortical circuitry, but the algorithms for forming spatiotemporal patterns of chaotic activity appear to have been derived from the olfactory anlage. In the most advanced vertebrates, the limbic system is a complex of interconnected cortical and subcortical structures in the base of the brain forming the medial temporal lobe, which is required for the formation of episodic

memories comprising the personal history of each individual, and for control of attention as well as intention (Clark and Squire, 1998).

Figure 3.7. In mammals all sensory input is delivered to the entorhinal cortex, which is the main source of input to the hippocampus, and the main target of hippocampal output. Goal-directed action must take place in time and space, and the requisite organ for these matrices is the hippocampus providing “short-term memory” and the “cognitive map”. The emergent pattern impacts the brain stem and spinal cord, leading to stereotypic searching movements that are adapted to the immediately surrounding world. Proprioceptive feedback from the muscles and joints to the somatosensory cortex provides confirmation that the intended actions are taking place. The impact of the movements of the body on sensory input is conveyed to the visual, auditory and olfactory systems. All of these perceptual constructs, which are triggered by sensory stimuli and are dependent on prior learning, are transmitted to the limbic system, specifically to the entorhinal cortex, where they are combined. In the genesis of behavior the flow of neural activity is through proprioceptive and exteroceptive loops outside the brain. Within the brain the flow of activity constitutes preafferece. When a motor act is initiated by activity descending into the brainstem and spinal cord, the same or a similar activity pattern is sent to all of the sensory systems by the entorhinal cortex, which prepares them for the impact of the movements of the body and, most importantly, sensitizes them by shaping their attractor landscapes to respond quite selectively to stimuli that are appropriate for the goal toward which the action has been directed. These preafferent patterns are the essence of attention as distinct from intention.

3.8 Conclusions

The interface between the finite state intelligent system and the infinite world is active, not passive. The process is self-organizing, by which sequential first order phase transitions lead to formation of complex spatial patterns covering large cortical

areas with millions of neurons. The requisite instability and anatomical basis for pattern formation is provided by the dense but sparse connectivity, such that each neuron interacts with its surround, not with small numbers of selected neurons. The trajectory of a perceptual act is not by packets of information that are transmitted from place to place in the brain, starting at sensory cortex and ending at sensory cortex. It is a sequence of phase transitions of cortical neuropil, that solicit the cooperation of varying numbers and sizes of domains in each hemisphere, depending on the complexity of the emergent goal that embeds the process. The process of learning requires chaotic activity as a form of endogenous noise that is subject to control by the limbic system of the brain.

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3.10 References

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