

The emergence of mind and emotion in the evolution of neocortex

L'emergenza della mente e dell'emozione nell'evoluzione della neocorteccia

WALTER J. FREEMAN

Department of Molecular & Cell Biology,
University of California at Berkeley

SUMMARY. The most deeply transformative concept for the growth of 21st Century psychiatry is the constellation of the chaotic dynamics of the brain. Brains are no longer seen as rational systems that are plagued with emotional disorders reflecting primitives inherited from our animal ancestors. Brains are dynamical systems that continually create patterns by acting intentionally into the environment and shaping themselves in accord with the sensory consequences of their intended actions. Emotions are now seen not as reversions to animal behaviors but as the sources of force and energy that brains require for the actions they take to understand the world and themselves. Humans are unique in experiencing consciousness of their own actions, which they experience as conscience: guilt, shame, pride and joy. Chaotic brain dynamics strives always for unity and harmony, but as a necessary condition for adaptation to a changing world, it repeatedly lapses into disorder. The successes are seen in the normal unity of consciousness; the failures are seen in the disorders that we rightly label the schizophrenias and the less severe character disorders. The foundation for healthy unity is revealed by studies in the evolution of brains, in particular the way in which neocortex of mammals emerged from the primitive allocortex of reptiles. The amazing facts of brain dynamics are now falling into several places. The power-law connectivity of cortex supports the scale-free dynamics of the global workspace in brains ranging from mouse to whale. That dynamics in humans holds the secrets of speech and symbol utilization. By recursive interactions in vast areas of human neocortex the scale-free connectivity supports our unified consciousness. Here in this dynamics are to be sought the keys to understanding and treating the disorders that uniquely plague the human mind.

KEY WORDS: chaotic dynamics, emotions, consciousness, connectivity.

RIASSUNTO. Il concetto trasformativo che più profondamente ha segnato la crescita della psichiatria del XXI secolo è la costellazione della dinamica del caos del cervello. I cervelli sono stati visti per molto tempo come sistemi razionali che erano stati invasi da disturbi emozionali e che riflettevano aspetti primitivi ereditati dai nostri antenati animali. I cervelli sono sistemi dinamici che continuamente creano pattern agendo intenzionalmente nell'ambiente e formando se stessi in accordo con le conseguenze sensoriali delle loro azioni volitive. Le emozioni sono ora viste non come un ritorno a comportamenti animali ma come una sorgente di forza e di energia di cui i cervelli hanno bisogno per le azioni che svolgono, al fine di comprendere il mondo e se stessi. Gli esseri umani sono gli unici ad avere un'esperienza cosciente delle loro stesse azioni, che essi esperiscono come coscienza: la colpa, la vergogna, l'orgoglio, la gioia. La dinamica del caos cerebrale si sforza sempre per l'unità e l'armonia, ma come una condizione necessaria per l'adattamento ai cambiamenti del mondo, ripetutamente ritorna nel disordine. I successi si vedono nella normale unità della coscienza; i fallimenti si vedono nei disturbi con cui regolarmente etichettiamo le schizofrenie e che meno severamente caratterizzano i disturbi. Il fondamento per una unità salutare si rivela dagli studi sull'evoluzione dei cervelli, particolarmente nel modo in cui la neocortex dei mammiferi emerge dalla primitiva allocortex dei rettili. I fatti sorprendenti della dinamica cerebrale sono ora visibili in diversi settori. Il power-law della connettività della corteccia supporta la dinamica scale-free dello spazio di lavoro globale nei cervelli nella scala evolutiva dal topo alla balena. Quella dinamica, negli uomini, mantiene i segreti del linguaggio e dell'utilizzazione del simbolo. Dall'interazione ricorsiva di vaste aree della neocortex umana, la connettività scale-free mantiene la nostra coscienza unificata; in questa dinamica, devono essere cercate le chiavi per comprendere e curare i disturbi che peculiarmente invadono la mente umana.

PAROLE CHIAVE: dinamica del caos, emozioni, coscienza, connettività.

E-mail: d.freeman@calmail.berkeley.edu

INTRODUCTION

Studies of brain activity during perception by animals trained to discriminate olfactory, visual, auditory, or tactile stimuli (1) have led to the view that perception is a goal-directed action that is organized by large-scale neural interactions in the forebrain. Such action is intentional, in that it forms within a framework of brain dynamics that has been constructed from recent and remote experiences of action and its sensory consequences. Perception is “stretching forth” by thrusting the body into the world, in order to learn about the world by shaping the self through learning from whatever the senses encounter.

Brain scientists learned over a century ago that the necessary and sufficient part of the vertebrate brain to sustain autonomous intentional behavior for survival was the ventral forebrain, including the olfactory system and the hippocampus formed by three-layered allocortex. These components sufficed to support mechanistic patterns of intentional behavior in amphibia, fish and reptiles, but they did not support emotion and intellect. Those functions were shown to be provided by the neocortex, which is found only in mammals. The German physiologist Goltz (2) surgically removed all of the six-layered neocortex of the forebrain of dogs and demonstrated that the dogs retained the autonomous behaviors of integrated locomotion and orientation seen in reptiles but lacked all expression of emotion, despite having an intact limbic core. Similar results were found by Bures, Buresová and Krivánek (3), who chemically inactivated the neocortex bilaterally by chemical induction of spreading depression, which reversibly shut down the neocortex but left the limbic cortex and basal ganglia intact and functioning. In contrast, all intentional behavior was abolished by complete decortication, which removes both the neocortex and the three-layered allocortex of the hippocampus and the olfactory system and striatum. The procedures of Goltz and Bures (2,3) essentially converted the mammalian brain to the reptilian brain by neodecortication. The dogs and rats lost complexity, all capacity for playfulness, social behavior, and the expression of emotions. I conclude that the neocortex is the organ of emotion, not the limbic system, in which the core structures are allocortical.

All sensory areas of neocortex transmit to the allocortex, first to the superficial layer of the entorhinal cortex, which transmits through the perforant path to the hippocampus; they also receive from allocortex by relays through the subiculum to the entorhinal cortex. They also transmit to and receive from each other by long pathways. Therefore, every allocortical and neo-

cortical area must have the same dynamic code for the sharing and exchange of neural information. The properties of that code must have been developed in allocortex by evolution of the pre-mammalian species and then adapted to neocortex with the emergence of mammals.

The introduction of neocortex led to an enormous expansion of the surface area of brains, which is seen in the wrinkling of gyri and sulci. This expansion enabled brains to construct large numbers of neural circuits and networks, which brains use for homeostatic control of the internal environment, most notably brain temperature, which distinguishes mammalian and avian brains from those of extant reptiles. Neocortex provides not only the local circuitry in its Layers II, III and IV. It also provides the mechanism for global integration by the embedding of Layers I, V and VI. The neocortex in each hemisphere is a single, undivided neural organ, as shown by the phenomenon of spreading depression (3) and by the global coordination of the EEG (4). It is the organ of global integration.

CHAOTIC BACKGROUND ACTIVITY IN THE ALLOCORTEX AND NEOCORTEX AS SEEN IN THE EEG

The defining property of chaos is the genesis of signals that cannot be predicted, because they are not periodic, and they have never before existed. That is the meaning of the “infinite sensitivity to initial conditions”: a small change in starting point leads to a divergence from all previous experience. This property is essential for biological learning by trial and error under reinforcement, because it creates unforeseeable trials for testing. The property of chaos is not readily apparent in the nonlinear regulatory feedback mechanisms of brain reflexes. They determine the stability of brain function by keeping the internal environment of the brain at an optimal level in the process of homeostasis. Chaos becomes clear in modeling perception, which requires creative interaction with the external environment. Examples come from study of the patterns of neural activity in the olfactory bulb and cortex (**Figure 1**) (5), which are allocortex, and the visual, auditory and somatosensory cortices, which are neocortex. These semi-autonomous sensory systems interact among themselves and with other parts of the forebrain by both transmitting information and receiving regulatory feedback. Their basic functions are self-organizing. The chaotic activity of each area is self-organized by the synaptic interactions of all of the neurons in each area. This is important, because the patterns

The emergence of mind and emotion in the evolution of neocortex

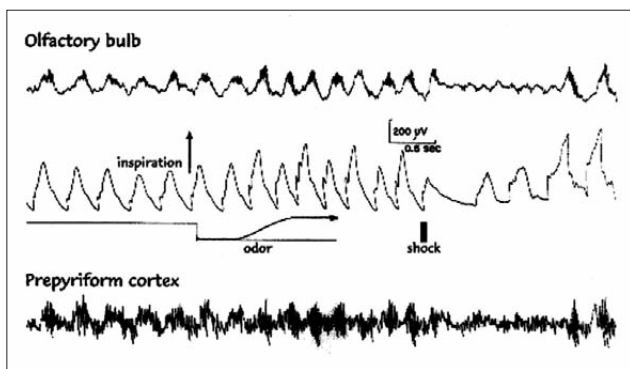


Figure 1. The background activity in every cortex is chaotic and resembles noise, because it contains all frequencies of the EEG spectrum. A brief input from the senses or from some other part of the brain causes a brief burst of oscillation in a narrow frequency band (here caused by inhalation). The frequency is different with every inhalation, but the dynamics is the same, that is, scale-free. From Freeman and Schneider (5).

that are recognized in perception are spatially distributed and characterized by relationships between each part and every other part of every pattern.

Each successive burst involves taking a sample from the environment by sniffing. The clearest demonstrations of the self-organization of complex spatiotemporal patterns of neural activity are presently found in simultaneous recordings of EEG activity from arrays of 16-64 electrodes placed on the sensory cortices of animals (**Figure 2**) (6).

In each burst the recordings reveal a shared waveform of oscillation in cortical potential over the entire array (7). The oscillation serves as a carrier wave in its

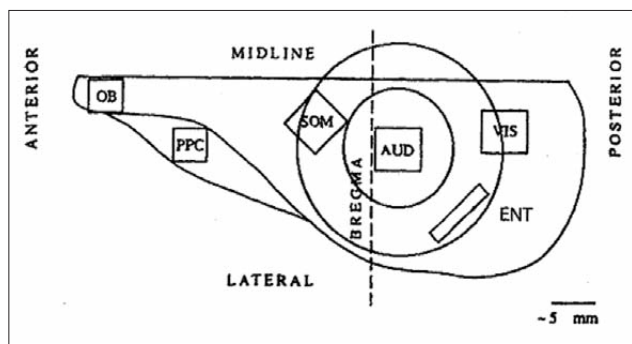


Figure 2. The left hemisphere of the rabbit brain is shown as if seen from above. Each rectangle shows the location and size of an array of 64 electrodes, most of them square (8x8, 5.6x5.6 mm). The circles show respectively the modal diameter and 95% inclusion diameter of surface domains of phase-locked oscillations of EEG potential. From Barrie et al. (6).

spatial pattern of amplitude modulation (**Figure 3**, left).

The center frequency and bandwidth of the carrier waveform are unpredictable, which reflects the chaotic dynamics of sensory cortices. The spatial patterns of amplitude do not show all the sensory information that a stimulus has delivered to the receptors or that the receptors have transmitted to the cortices over their sensory input pathways. The patterns reveal instead the generalization to the category across all prior perceptions of the stimulus (**Figure 3**, middle frames). What is categorized is the experiential content that has been associated with the stimulus during training to respond to the stimulus, in brief, the subject's knowledge about the stimulus. The simplest demonstration is by watching the evolution of the AM pattern over time with consolidation after initial learning (**Figure 3**, right frames), in which the conditioned stimulus (CS) is constant but the context changes (5). The result holds for both allocortex and neocortex (6).

The categories are revealed by presenting sets of AM patterns in frames from discriminative conditioning. For example, a subject who can discriminate two CS, one reinforced (CS+) and the other not (CS-), an AM pattern forms for both CSs and for the control condition – background odor. The 64 amplitudes in an AM pattern are expressed as a column vector that specifies a point in 64-space. When the points are displayed in a plane by step-wise discriminant analysis, they form 3 clusters that give the three patterns in summary form (**Figure 4**). When the reinforcement is switched, both AM patterns change. The CSs are the same, but the meaning is different. This distinction between sensory information and perceptual knowledge holds for all sensory cortices (1,8,9). The information is found in the pulses of individual neurons; the knowledge is found in the waves collectively generated by masses of neurons.

When observed during time spans of minutes to hours, the dynamic mechanisms are robustly metastable (10,11) over a wide range of amplitudes. They are regulated by neurochemical modulators from other parts of the brain, which mediate the onsets of sleep and arousal, and with institute the synaptic modifications that are required for learning to categorize new classes of input and embed them in the existing knowledge base during consolidation. These and related phenomena emphasize the role in neurodynamics of regulatory biases from other parts of the brain onto self-exciting populations in neural system control. The learning takes place in rapidly repeated small steps, which cumulatively give the appearance of a trajectory

Freeman WJ

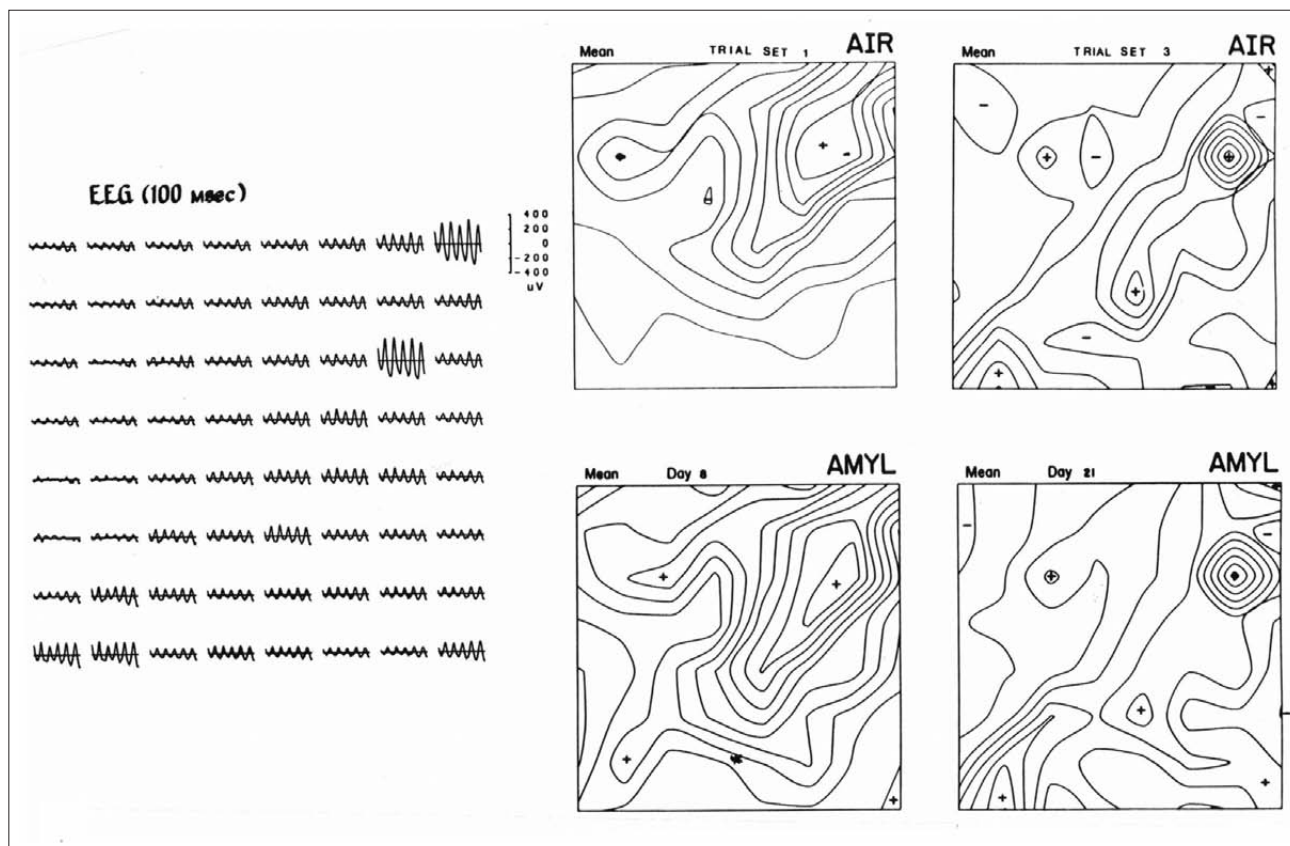


Figure 3. *Left:* a set of 64 EEG signals is shown after band pass filtering to extract the gamma oscillation. *Right:* the spatial patterns of amplitude modulation (AM) are shown as contour plots. The vertical change was imposed in each trial set by delivery of an odor conditioned stimulus; the horizontal change took place upon consolidation of the memory between training sessions that embedded the new category in the knowledge store of the sensory cortex.

in state space that never repeats itself. This is a manifestation of Tsuda's "chaotic itinerancy" (12).

THE ROLE OF PRAFFERENCE IN ATTENTION: CONSTRUCTION OF ATTRACTOR LANDSCAPES

A key concept in models of perception and motor control is that of *preaffference* (13), which is the process by which a copy of a motor command (also called corollary discharge) (14) is sent to the sensory cortices that adjusts their sensitivities to respond selectively to the expected sensory input that will result from an intended action (15). For example, if the oculomotor control system issues a command to move the eyes, the visual cortex is notified that a self-generated shift in visual field is about to occur, not a movement in the environment. So when a brain activity pattern that is generated by chaotic dynamics expresses an intent to move toward a goal, it has two facets. One is a motor

command that activates the descending motor systems. The other is a set of messages to all of the central sensory systems that prepares them for the impending changes in sensory input that will be caused by the motor action. Studies in vertebrate evolution (16) have shown that these neural activity patterns emerge through cooperation between the limbic system, a network of allocortex and subcortical nuclei in the forebrain that provide the basic drive, and the neocortex, which provides the patterning. As the limbic system initiates action into the world, the preafferent messages (corollary discharges) prime the sensory cortices to accept the sensory consequences of those planned actions by selectively activating the implementing attractor landscapes (17). The sensory consequences of behavior together with evolving sensory input, such as the retinal images that change from searching movements of the eyes while tracking a moving target, are fed back into the limbic system by way of the entorhinal cortex, where multimodal perceptual convergence

The emergence of mind and emotion in the evolution of neocortex

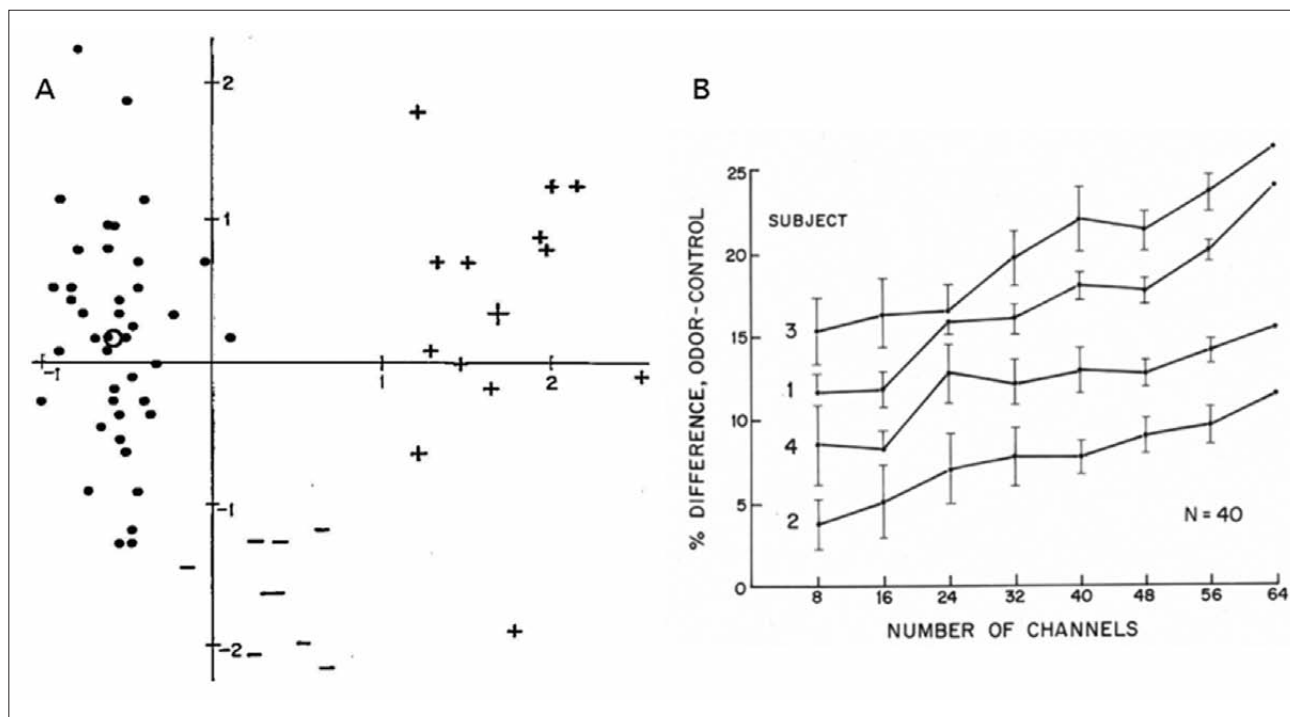


Figure 4. A. Categorization assay showing three clusters of AM patterns expressed as points in 64-space and projected into 2-space. Classification of individual AM patterns is by finding the nearest center of gravity of a cluster by calculating the Euclidean distance. B. The goodness of classification is reduced in proportion to the number of channels removed. No channel is more or less important than any other. From Barrie et al. (6).

takes place. The entorhinal cortex transmits the gestalt to the hippocampus, which is essential for the maintenance of spatial orientation (the cognitive map) (18) and temporal orientation (memory formation) (19).

PHASE TRANSITIONS IN PERCEPTION: CONVERGENCE TO AN ATTRACTOR IN GENERALIZATION

The output of each sensory cortex is a spatial pattern of amplitude modulation of the common waveform of the oscillation, which expresses the cooperative interactions of all of the bulbar neurons. This output is carried in parallel by millions of axons that transmit to the cortical targets. The pathways diverge, in that each local area of the cortex transmits broadly to the neurons in its target. Correspondingly, each local area in the targets sums the activity that it receives. By virtue of this spatial integration the only activity that is enhanced is that which has the same frequency of oscillation everywhere, which is the carrier. This is the cooperative activity that is the *signal* of the cortex. The local activities in the cortex that result from sensory in-

put, and which are the “raw sense data”, are smoothed and deleted as *noise* by summation and smoothing acting as a low pass spatial filter. In this way the cortex transmits its own created pattern and not the imprint on its activity that is driven by the sensory input.

The reason for this process is that the sensory environment is infinitely complex, and the neural mechanism for stimulus classification is finite. The same codes and modes of operation hold in the olfactory, visual, auditory, and somatosensory cortices (6). Since the output is not a processed image of the input but instead is a construction by the cortices from memory, the conclusion is that brains can only know the knowledge that has been constructed by their sensory cortices under their control and guidance (7).

The formation of a nerve cell assembly during training requires the modification of synaptic strengths. Associative learning is simulated by increasing the values of the excitatory feedback gains between neurons that are co-excited by input and excite each other on trials with reinforcement (20). Habituation is simulated by decreasing the strengths of excitatory output connections of neurons that are excited on trials without reinforcement. Learning takes place by modification of

Freeman WJ

synaptic strengths, which is an irreversible and cumulative structural change in the system, such that its behavior in the future is dependent on past experience.

The transitions between the receiving and transmitting phases of the action-perception cycle do not involve a parameter change. They depend on input. Therefore, this change is not a bifurcation. One way to view the operation of responding to input is to postulate that each sensory cortex has a global attractor landscape that has multiple basins of attraction, one for each class of input that it can discriminate. The system is forced out of the basal state by receptor input with each sensory input, and if it contains a known stimulus, the cortex is constrained to oscillate in one of the basins of attraction, which provides for the generalization gradient in classifying repeated stimuli that are never twice the same in detail. The attractors and their basins are determined by the synaptic modifications in learning, and they are retrieved and brought on line during perception by the process of prefference.

This mode of brain function was put forth by the American pragmatists, most clearly by John Dewey (21) in his critiques of the conditioned reflex. It was further developed by Gestalt psychologists (22), who studied the impact on perception of objects embedded in environmental contexts, leading to the conception of a field of force, which resonated with brain dynamics. Koffka (23) expanded this concept to include interactions between fields of force in the environment and in the brain. Gibson (24) further conceived the role of behavior as composed of actions that were generated within brains. Objects in the environment were defined in terms of their affordances, by which he meant the uses that they offered to the subjects perceiving them. In his conception, the information was provided by the objects in the world and was incorporated by resonance of Gestalt fields that *in-formed* the brain. This process was similar to the *intentional arc* of Merleau-Ponty (25,26), but with the difference that an affordance was provided by information in an object, and the resonance transferred that information into the cortex, whereas in the view provided by chaotic dynamics, the intentional brain state defined the object in terms of a goal created in the brain, corresponding to Merleau-Ponty's *maximum grip*, with its unity of inner context. In the act of perceiving there was no bulk transfer of information, only a modification of the self as the result of learning from the results of action. The Gestaltist and Gibsonian theories are essentially passive, by virtue of the source of organization being attributed to objects and events in the world, whereas the dynamical theory attributes the structure of behavior to active self-organizing chaotic dynamics in brains

that provide novel modes of action and novel hypotheses for testing.

CONCLUSIONS

The allocortices that form the main components of the primitive limbic system came to full flower in the age of dinosaurs and may be construed to have developed the prototypic chaotic dynamics by which vertebrate brains cope with their environment. From the findings that fundamentally the sensory neocortices operate with very similar nonlinear chaotic dynamics in repetitive AM pattern formation adapted the neocortical dynamics in full and continuous coordination with the allocortex, which provides the basic energy (Mind Force, in the terminology advocated by Franco Orsucci) (27,28), while the neocortex provides the detailed content of thought and emotion within the energetic context that is provided by the allocortex. Of particular value for psychiatric treatment of anxiety and depression is an understanding of the brainstem control through neuroamines of the energy flow through the allocortex, with elaboration of the forms and structures through the self-organizing chaotic dynamics of the neocortex in forming worries, phobias, hallucinations, and delusions, which by their shared codes feed back into the brain stem.

A remarkable finding has been the evidence for scale-free dynamics in the neocortex (29,30). This property is evidenced by the discovery of self-similar AM patterns in scalp EEG that extend over the entire scalp (4) and at all frequencies in the beta and gamma ranges (31), as well as appearing in a 1 sq mm array on the right inferior temporal gyrus of a human subject under study for treatment of epilepsy (32). This property of self-similarity is becoming a core concept in the integration of allocortical-neocortical dynamics. The primary task of the brain is not information processing; it is thinking in patterns that have their own intrinsic logic, which we still don't adequately grasp. It is likely that local patterns are continually binding upwardly into larger patterns, and those are continually partitioning into smaller patterns, after they have incorporated the pre-existing contents, always with the possibility of emergence through chaotic dynamics of powerful new configurations.

REFERENCES

1. Freeman WJ. How brains make up their minds. New York: Columbia University Press, 2001.

The emergence of mind and emotion in the evolution of neocortex

2. Goltz FL (1892). Der Hund ohne Grosshirn. Pflügers Archiv 2001; 51: 570-614.
3. Bures J, Buresová O, Krivánek J. The mechanism and applications of Leão's spreading depression of electroencephalographic activity. New York: Academic Press, 1974.
4. Ruiz Y, Pockett S, Freeman WJ, Gonzales E, Li Guang. A method to study global spatial patterns related to sensory perception in scalp EEG. J Neuroscience Methods 2010; 191: 110-8.
5. Freeman WJ, Schneider WS. Changes in spatial patterns of rabbit olfactory EEG with conditioning to odors. Psychophysiology 1982; 19: 44-56.
6. Barrie JM, Freeman WJ, Lenhart M. Modulation by discriminative training of spatial patterns of gamma EEG amplitude and phase in neocortex of rabbits. J Neurophysiol 1996; 76: 520-39.
7. Freeman WJ. The physiology of perception. Sci Am 1991; 264: 78-85.
8. Globus GG, Pribram KH, Vitiello G (eds). Brain and being: at the boundary between science, philosophy, language and arts. Amsterdam: John Benjamins, 2004.
9. Changeux J-P. The physiology of truth: neuroscience and human knowledge. Cambridge, MA: Harvard University Press, 2009.
10. Kelso JAS. Dynamic patterns: the self organization of brain and behavior. Cambridge: MIT Press, 1995.
11. Bressler SL, Kelso JAS. Cortical coordination dynamics and cognition. Trends Cogn Sci 2001; 5: 2-36.
12. Tsuda I. Chaotic itinerancy and nowhere-differentiable attractors in neural networks. Invited talk in the 1st Tamagawa International Forum on Brain. Tamagawa, September 1996.
13. Kay LM, Freeman WJ. Bidirectional processing in the olfactory- limbic axis during olfactory behavior. Behav Neurosci 1998; 112: 541-53.
14. Sperry RW. Some effects of disconnecting the cerebral hemispheres [Nobel Lecture]. Science 1982; 217: 1223-6.
15. Taylor JG. CODAM: a model of attention leading to the creation of consciousness. Scholarpedia J 2007; 2: 1598.
16. Herrick CJ. The brain of the tiger salamander. Chicago IL: University of Chicago Press, 1948.
17. Skarda CA, Freeman WJ. How brains make chaos in order to make sense of the world. Behav Brain Sci 1987; 10: 161-95.
18. Buzsáki G. Rhythms of the brain. Oxford UK: Oxford University Press, 2006.
19. Squires E. Conscious mind in the physical world. Bristol, UK: Adam Hilger, 1990.
20. Kozma R, Freeman WJ. Classification of EEG patterns using nonlinear dynamics and identifying chaotic phase transitions. Neurocomputing 2002; 44: 1107-12.
21. Dewey J. Psychological doctrine in philosophical teaching. J Philos 1914; 11: 505-12.
22. Köhler W. Dynamics in psychology. New York: Grove Press, 1940.
23. Koffka K. Principles of gestalt psychology. New York: Harcourt Brace, 1935.
24. Gibson JJ. The ecological approach to visual perception. Boston: Houghton Mifflin, 1979.
25. Merleau-Ponty M. The structure of behavior. Boston: Beacon Press, 1942.
26. Merleau-Ponty M. Phenomenology of perception. New York: Humanities Press, 1945.
27. Orsucci F. Changing mind: transitions in natural and artificial environments. River Edge, NJ: World Scientific, 2002.
28. Orsucci F. Mind force, human attractions. Singapore: World Scientific, 2009.
29. Sporns O, Honey CJ. Small worlds inside big brains. Proc Natl Acad Sci 2006; 103: 19219-20.
30. Bressler SL, Menon V. Large-scale brain networks in cognition: emerging methods and principles. Trends Cogn Sci 2010; 14: 277-90.
31. Pockett S, Bold GEJ, Freeman WJ. EEG synchrony during a perceptual-cognitive task: widespread phase synchrony at all frequencies. Clin Neurophysiol 2009; 120: 695-708.
32. Panagiotides H, Freeman WJ, Holmes MD, Pantazis D. Behavioral states may be associated with distinct spatial patterns in electrocorticogram (ECoG). Cogn Neurodyn 2011; 5: 55-66.