Reflections on a giant of brain science

How lucky we are having Walter J. Freeman as our beacon in cognitive neurodynamics research

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Abstract Walter J. Freeman was a giant of the field of neuroscience whose visionary work contributed various experimental and theoretical breakthroughs to brain research in the past 60 years. He has pioneered a number of Electroencephalogram and Electrocorticogram tools and approaches that shaped the field, while “Freeman Neurodynamics” is a theoretical concept that is widely known, used, and respected among neuroscientists all over the world. His recent death is a profound loss to neuroscience and biomedical engineering. Many of his revolutionary ideas on brain dynamics have been ahead of their time by decades. We summarize his following groundbreaking achievements: (1) Mass Action in the Nervous System, from microscopic (single cell) recordings, through mesoscopic populations, to large-scale collective brain patterns underlying cognition; (2) Freeman–Kachalsky model of multi-scale, modular brain dynamics; (3) cinematic theory of cognitive dynamics; (4) phase transitions in cortical dynamics modeled with random graphs and quantum field theory; (5) philosophical aspects of intentionality, consciousness, and the unity of brain–mind–body. His work has been admired by many of his neuroscientist colleagues and followers. At the same time, his multidisciplinary approach combining advanced concepts of control theory and the mathematics of nonlinear systems and chaos, poses significant challenges to those who wish to thoroughly understand his message. The goal of this commemorative paper is to review key aspects of Freeman’s neurodynamics and to provide some

handles to gain better understanding about Freeman’s extraordinary intellectual achievement.

Keywords Freeman neurodynamics · Mesoscopic neurodynamics · Electroencephalogram (EEG) · Electrocorticogram (ECoG) · Mass action · Intentionality

Prologue

Walter J. Freeman would give the following brief description of his background. He was born and raised in Washington, DC. He studied physics and mathematics at M.I.T., electronics in the Navy in World War II, philosophy at the University of Chicago, and medicine at Yale University, where he received his M.D. *cum laude* in 1954. He continued with internal medicine at Johns Hopkins and neuropsychiatry at UCLA. He joined the University of California at Berkeley in 1959, where he stayed for the rest of his life teaching brain science. During his years at Berkeley, he has been the Chair of the Department of Anatomy and Physiology (1967–1972), which later became the Department of Molecular and Cell Biology. He maintained very active research till the very end of his life as Professor of the Graduate School and most recently as Professor Emeritus at the Division of Neurobiology, Department of Molecular and Cell Biology (Fig. 1).

Freeman has been an extremely influential neuroscientist. He has earned the highest respect all over the world for his revolutionary ideas on neurodynamics, which transformed the field. He received many awards and distinctions, including the Bennett Award from the Society of Biological Psychiatry (1964), Guggenheim Fellowship (1965), the Chaire Solvay, Université Libre de Bruxelles (1974), the MERIT Award from National Institute of Mental Health (1990), the Pioneer Award from the Neural Networks Council of the

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Fig. 1 Walter Jackson Freeman III (January 30, 1927–April 24, 2016)

IEEE (1992), the Spinoza Lectures, Amsterdam (1995), the Helmholtz Award of INNS (2005), and Lifetime Achievement Award, University of Salerno, Italy (2012). He was President of the International Neural Network Society (1994), President of the Pavlovian Society (1997), Life Fellow of the IEEE “For the development of biologically realistic neuro-engineering models based on non-convergent dynamics,” and fellow of the International Neural Network Society. He has been Honorary Professor of Fudan University, Shanghai, and Zhejiang University, Hangzhou, China.

Clearly, Walter Freeman has been a highly accomplished world-class neuroscientist, with many awards and recognitions to his credit. He has authored over 500 articles and 6 books: “*Mass Action in the Nervous System*” (Freeman 1975); “*Societies of Brains*” (Freeman 1995), “*Neurodynamics*” (Freeman 2000a), “*How Brains Make Up Their Minds*” (Freeman 2000b); “*Imaging Brain Function with EEG*” (Freeman and Quian-Quiroga 2013); and “*Cognitive Phase Transitions in the Cerebral Cortex*” (Kozma and Freeman 2016). Freeman has been a celebrity all over the world; still his pioneering vision was not fully appreciated by many of his fellow neuroscientists. Some were unwilling to face the intellectual challenge posed by his revolutionary approach or simply could not understand him and remained puzzled by his vision. We can honor his legacy by following through his major achievements, step by step, and provide clues to understand his message.

The journal of “Cognitive Neurodynamics” is especially well suited to carry on Freeman’s legacy for several reasons. The profile of “Cognitive Neurodynamics” and its major goals are closely resonating with the basic concepts of Freeman’s neurodynamics. Moreover, Freeman has been a founding member of the Journal’s Editorial Board and he fully supported its activities at many levels until his death. I am honored to be able to summarize Walter Freeman’s achievements in this commemorative review.

Freeman’s legacy as a launch pad in exploring neocortex

For over 60 years, Walter Freeman has been an extremely prolific researcher, thus it is not an easy task to describe his achievements in a concise way. As a starting point, we can rely on his own words and the helpful pointers to key areas he considered crucial to his legacy. In his talk at the Brain Network Dynamics Conference in January 2007 in Berkeley, which has been organized to celebrate his 80th birthday, he welcomed the audience with these words:

“Fifty years ago EEG was widely regarded as noise, the roar of a crowd. It still is, advisedly, because cortical neurons form great crowds, and the task of systems neuroscience is to comprehend them. I perceived EEG as an opportunity to make a contribution. I chose to study three-layered allocortex in the olfactory system as simpler than neocortex yet closer to the senses than the hippocampus. I began by pulsing it with pairs of electric shocks in order to identify a small-signal near-linear range, in which I could model the dynamics with linear equations. From the patterns of relaxation on perturbation—evoked potentials—I modeled the system with differential equations, evaluated the parameters, solved them to simulate the evoked potentials, and deduced the mechanisms of stabilization. I summarized 20 years of linear analysis in my 1975 book, from which I concluded that I had reached the limits of linear analysis. Trying to understand brain function that way was like trying to cross an ocean in a dugout canoe. I conceived a boundary in the imaginary axis of the complex plane. Contemplating that, I felt as Isaac Newton felt, playing with pebbles on a seashore. In the following 30 years I have explored the design of foundations for ocean crossings” (Freeman 2007).

Before describing the tools towards deeper understanding of brain functions, or in Freeman’s words to “cross the ocean,” it is very illustrative to elaborate on his powerful analogy between the roar of the crowd and EEG. For the external observer, EEG signals and the roar of the crowd both may seem as random noise, but they are not, Freeman contends. This analogy is illustrated in a cartoon describing Keystone Cops in a football stadium, Fig. 2. The task of brain monitoring using external devices seems to be a virtual impossibility according to the view of many experts. “External devices, such as brainwave-reading skull cap ... have none of these risks [... due to invasive techniques...]. But because their sensors are so far removed from the individual neurons, they are also far less effective. They are like Keystone Cops trying to eavesdrop on a single conversation from outside a giant football stadium (Marcus and Koch 2014).

Fig. 2 Illustration of the analogy between the roar of the spectators in a football stadium and EEG measurements. The roar of the crowd at a football game is not the sum of thousands of conversations (like those between Keystone Cops); rather it is a collective action of spectators engaged in a social ritual. Similarly, millions of neurons form collectives that transcend pairwise synaptic exchanges (illustration by Vladimir Taytslin); from (Kozma and Freeman 2015)

This misguided simile shows the lack of appreciation of large-scale collective brain dynamics. In Freeman's view, the roar of the crowd at a football game is not the sum of thousands of conversations. It is a collective action of spectators engaged in a social ritual, for which the stadium was built at enormous expense. The crowd has convened with extensive planning in advance, to enjoy participation in the realization of social solidarity. Comparably, millions of neurons form collectives that transcend pairwise synaptic exchanges (Quiroga et al. 2005). The collective that they form has the power of numbers in synchronized discharges sweeping through the basal ganglia and brain stem. Undeniably, there must be private conversations among neurons, but they are not the whole story. Collective actions take precedence, and they are observable using noninvasive techniques (Kozma and Freeman 2015).

Freeman's lifelong research played a pivotal role in the interface between computational neurobiology, mathematics, biophysics, and neuro-engineering. In this review, we discuss his five major achievements; the references listed are selected for illustration out of his over 500 publications:

1. The discovery of the role of spatio-temporal oscillations in vertebrate brains to create perception (Freeman 1975, 1991, 1992). His ECoG measurements in animal sensory cortices identified neural activity patterns and showed that perception occurs by the construction of spatial amplitude modulated (AM) oscillatory patterns in the gamma range carrier wave (Barrie et al. 1996; Freeman and Barrie 2000). His original work had focus on olfaction (Viana Di Prisco and Freeman 1985; Skarda and Freeman 1987), which in the past decades has been extended to other senses, including visual,

auditory, and somatosensory cortices, as well as multisensory Gestalts (Kay and Freeman 1998; Ohl et al. 2001). In recent years, many of these results are validated in noninvasive EEG measurements, as well (Pockett et al. 2009; Ruiz et al. 2010).

2. Development of mathematical-engineering models of the neuroscience findings using nonlinear dynamical oscillations and chaos (Freeman 1975, 1987; Chang and Freeman 1996); the corresponding models are called Freeman K (Katchalsky) models. One of the key features of these discoveries lies in the mathematical models utilizing a system of coupled ordinary differential equations with distributed parameters. The nested hierarchy of Freeman K models (K0, KI, KII, KII, and KIV) describes brain dynamics from microscopic, through mesoscopic, to macroscopic structures and characterizes the corresponding cognitive functions (Kozma and Freeman 2001, 2003; Kozma et al. 2003, 2007).
3. Development of the cinematic theory of cognition (Freeman 2006b). According to Freeman, the cortical code consists of repetitive spatial frames of meta-stable amplitude modulation (AM) patterns (Freeman 2000a, b, 2003, 2004a, b, 2005, 2006b; Freeman et al. 2000, 2003a, b; Freeman and Rogers 2002). In this model, the AM patterns are the movie frames, while the rapid transition from one AM pattern to the other acts as the shutter (Freeman and Quian-Quiroga 2013; Davis et al. 2013; Kozma and Freeman 2014). This work extends attractor theory in the presence of self-organizing, far-from-equilibrium thermodynamics, following Haken's synergetics and Prigogine's 'dissipative structures' that feed on energy (Freeman 2007, 2008).
4. The role of phase transitions on cortical dynamics. Phase transitions can be described using various tools. One option is using the concept of criticality in statistical physics and Erdos-Renyi random graph theory (RGT) to describe the switch between organized and disorganized states as neuroperturbation (Kozma et al. 2005; Freeman et al. 2009; Freeman 2015; Kozma and Freeman 2015). Quantum Field theory (QFT) is another potential tool describing dissipative brain dynamics, which has been explored by Freeman and collaborators (Freeman and Vitiello 2006; Freeman and Cao 2008; Capolupo et al. 2013).
5. Philosophical issues of intentionality and consciousness were fascinating Freeman thorough his life. He produced many valuable contributions, especially to intentional neurodynamics (Freeman 1995, 1997, 2000a) and the traditions of Thomism (Freeman 2009, 2016). His philosophical work is related to the concept of embodied cognition, linked to Dreyfus critique of representationalism, along the traditions of Heidegger and Merleau-Ponty

(Núñez and Freeman 1999). He has crucial contributions to answer Von Neumann's question on the language of the brain and to offer a solution of the notorious symbol-grounding problem.

All of these areas are important on their own rights, and they contribute necessary insights on specific research issues regarding the operation of brains. Taken together they provide a launch pad for vehicles to new discoveries across the ocean of nonlinear brain dynamics before us! Freeman concludes: "Like other true explorers, we don't know what we will find, and we don't yet have the proper framework in which to describe whatever is there. This broad view from an open mind is my legacy" (Freeman 2007).

Mass action in the nervous system (MANS)

ECoG studies of mesoscopic brain dynamics and the discovery of the meaning of amplitude modulation (AM) patterns

Freeman studied medicine at Yale in the 1950s under the supervision of John Farquhar Fulton, Professor of Physiology, founder of the Journal of Neurophysiology and author of the first textbook of neurophysiology (Fulton 1938). His mentor was Sir Charles Sherrington (recipient of Nobel Prize in 1932 for discoveries on the functions of neurons), who thus was Freeman's 'scientific grandfather'. In addition, Freeman considers Warren McCulloch and Karl Pribram as two of his teachers with extraordinary vision who were the most influential in his career choice.

McCulloch with the first cybernetics model of the neuron (McCulloch and Pitts 1943), and Pribram with his field approach to brain dynamics (Pribram 1969) have strong impact upon Freeman's intellectual development. Clearly, the roots of Freeman neurodynamics go back to his time at Yale, and after more than 20 years culminating in his book on the Mass Action in the Nervous System (MANS) (Freeman 1975). More than 40 years later, MANS is still a leading example of the successful integration of electrical circuit designs with control theory, in order to describe the physiology of neural assemblies.

Freeman measured microscopic pulse trains, the conversion of pulses to dendritic currents, and vice versa; see Fig. 3 (Freeman 2000a, b). The input at synapses and output at trigger zones are by microscopic pulse trains. The pulses trigger dendritic currents, which flow in closed loops. Crossing at the trigger zone causes a potential difference that determines firing rate. The same current causes the extracellular ECoG, but it is the macroscopic sum from $\sim 10^4$ neurons in the neighborhood that contribute to cortical output by pulse time-multiplexing. He postulated two state variables, namely, the pulse density and wave density of currents, and described the conversion between these variables. The pulse-to-wave conversion in a neuron is realized using an experimentally determined asymmetric sigmoid function, while the wave-to-pulse conversion has an essentially linear gain until a maximum threshold, above which it drops to zero level (Freeman 1975).

One of Freeman's most fundamental contributions to neuroscience is the discovery that dynamical, spatio-temporal oscillations are utilized by vertebrate brains to create perception. He has measured neural activity patterns in sensory cortices and shown that perception occurs by the

Fig. 3 The input at synapses and output at trigger zones are by microscopic pulse trains. The pulses trigger dendritic currents, which flow in closed loops. Crossing at the trigger zone causes a potential difference that determines firing rate. The same current causes the extracellular ECoG as the macroscopic sum from $\sim 10^4$ neurons; from Freeman (2000b)

construction of spatial patterns of oscillations in the gamma range, which he called amplitude modulation (AM) patterns. AM patterns embody the meaning of the stimuli to the animal (Freeman 1992). They are not frozen, thus they are not representations in any sense; rather they change reflecting changes in the animal's expectations and goals (Barrie et al. 1996). Freeman's first AM results have been achieved by studying olfaction (Freeman 1975; Viana di Prisco and Freeman 1985; Kay and Freeman 1998), which later have been extended to other sensory cortices as well, including auditory, visual, and somatosensory areas (Freeman and Barrie 2000; Freeman 2000b; Ohl et al. 2001). An example of visual AM patterns for reinforced and unreinforced visual stimuli (A and B) are shown in Fig. 4 (Kozma and Freeman 2015). AM patterns reflect the meaning of the stimulus in the context of the animal's past experience, present state, and its future goals. AM patterns are measurable neurodynamic features, which manifest neural correlates of cognitive functions. In particular, AM patterns have been clearly identified for learning and discrimination tasks in animals and humans.

Theoretical models of mass action: Freeman K (Katchalsky) model

Freeman's MANS monograph (Freeman 1975) outlines the fundamentals of a mathematical model which he named Kachalsky (K) model, in honor of Aharon Katzir

Kachalsky, an early pioneer of emergent collective behaviors and dynamic patterns in chemical and biological systems (Katchalsky et al. 1974). Freeman K sets are prominent examples of population models with microscopic, mesoscopic, and macroscopic levels of granulation. Freeman K sets describe a physiologically substantiated hierarchy of neural populations that underlines the observed neurodynamic behaviors, including convergence to zero and non-zero population activity, as well as oscillations in narrow frequency bands. The solutions of higher-order K sets are governed by a landscape of chaotic attractors, each corresponding to a class of learned stimuli, thus solving the problem of generalization over equivalent stimuli (Freeman 1987). Dynamics have been employed in machine learning before, but Freeman's work goes far beyond those developments (Skarda and Freeman 1987; Freeman 1991). His revolutionary approach to nonlinear dynamics and chaos played leading role in using chaos theory to explain brain function (Aihara et al. 1990; Borisyuk and Borisyuk 1997). Since their inception, Freeman K-sets have been used successfully as dynamic memory architectures (Chang and Freeman 1996; Kozma and Freeman 2001; Xu and Principe 2004; Harter and Kozma 2005; Ilin and Kozma 2006), as well for describing the dynamic operation of sensory cortices and the formation of multisensory percepts, Gestalts (Kozma et al. 2007).

The brief overview of the K sets follows; for visual illustration, see Fig. 5. The K0 set represents a non-

Fig. 4 Amplitude modulation (AM) patterns obtained over the visual cortex of a rabbit, by an array of 8×8 electrodes, electrode spacing is 1 mm. The *left* plot illustrates the ECoG traces of the 64 electrodes over a 1 s window. The *right* plot combines the AM patterns for stimulus A and B in the first and second column, respectively. The three frames in both columns give the snapshot of the AM pattern in consecutive time steps; from (Kozma and Freeman 2015)

Fig. 5 Illustration of the hierarchy of Freeman K models, including K0, K1, K2, K3, and K4 sets of increasing complexity (Kozma et al. 2007)

interacting collection of neuron population of about 10^4 neurons. It models dendritic integration in average neurons and a sigmoid static nonlinearity for axon transmission. They are described by a state-dependent, linear, 2nd order ordinary differential equation (ODE). The K0 set is governed by a point attractor with zero output and stays at equilibrium except when perturbed. A K1 set represents a collection of K0 sets, which can be either excitatory or inhibitory units. If K1 has sufficient functional connection density, then it is able to maintain a nonzero state of background activity by mutual excitation (or inhibition). K1 typically operates far from thermodynamic equilibrium. The stability of the K1 set under impulse perturbation is demonstrated using the periglomerular cells in the olfactory bulb (Freeman 2000b). A K2 set represents a collection of excitatory and inhibitory K1 units. Under sustained excitation from a K1 unit, the K2 set is governed by limit cycle dynamics. K2 has the main function to generate narrow-band oscillations in the gamma band.

The K3 set consists of several interconnected K2 sets, and it models a given sensory system in brains, e.g., olfactory, visual, auditory, or somatosensory modality. K3 can be used as an associative memory, which encodes input data into meta-stable, chaotic spatio-temporal patterns. A K4 set is formed by the interaction of 3 K3 sets. It is used to model the interactions of the primordial vertebrate forebrain in the genesis of simple forms of intentional behavior in the limbic system. Finally, the KV set consists of interacting K4 and K3 sets in the undivided neocortical neuropil embedding the primary sensory and motor areas with the limbic system.

Figure 5 shows the K-set hierarchy of neural populations progressing from cell level to hemisphere wide simulation, K0 through K4, following the organizational levels of brains. K0 is governed by a point attractor with zero output and stays at equilibrium except when

perturbed. K1 corresponds to a cortical column that has sufficient functional connection density between pure excitatory (or inhibitory) populations to maintain a state of non-zero background activity. K2 represents a collection of excitatory and inhibitory populations, which can exhibit limit cycle periodic oscillations at a narrow band frequency in the gamma range. K3 is formed by the interaction of several K2 sets through long axonal pathways with distributed delays. It simulates the known dynamics of sensory areas that generate broad-band chaotic oscillations. K4 is formed by the interaction of three (or more) K3 sets (Kozma et al. 2003). It models the hemisphere with multiple sensory areas and the genesis of simple forms of intentional behaviors with intermittent synchronization–desynchronization (Kozma and Freeman 2003; Kozma et al. 2007). The KV set is not shown in the diagram and its implementation is to be completed in the future. Table 1 summarizes the structure and dynamics of the hierarchy of K sets and also provides examples in the brain areas.

Preparing to cross the ocean: principles of intermittent state transitions in neurodynamics

Cinematic theory of cognition

Freeman has shown that the cortical code consists of repetitive frames of spatial amplitude modulation of a common aperiodic carrier wave (Freeman and Barrie 2000). These results lead to the postulation of the cinematic theory of cognition. ECoG measurements in a wide range of animals and human subjects provide experimental evidence of the cinematic theory of cognition in the form of amplitude modulation (AM) and phase modulated (PM) patterns (Freeman 2006a, b). According to the cinematic theory of perception, metastable AM patterns support the background cognitive state. These AM patterns act as movie frames sustained for a fraction of a second. They are ultimately destabilized and collapse for a brief transition period (10–20 ms), and this transition acts as a shutter. The collapse is demarcated by drastic desynchronization and phase dispersion in the form of a rapidly propagating phase gradients forming large-scale “phase cones.” After the brief transition, a new AM pattern emerges, which corresponds to the meaning of the new conditions/stimuli the animal faces.

The cinematic theory of cognition leads to the hypothesis that all sensory modalities share the same coding of their cognitive outputs and the same cinematic sampling of the environment. The cinematic synchronization of activity in diverse locations suggests that the transition that initiates the AM pattern does so by creating a field of nonsynaptic communication in the neuropil shared by all synchronized

Table 1 Overview of the hierarchy of Freeman K sets

Type of K sets	Structure	Dynamics	Examples of brain components
K0	Single unit	K0 represents a nonlinear I/O function	Building block of all higher level K sets
KI	Population of excitatory or inhibitory units	Fixed point convergence to zero or non-zero value	Basal ganglia, brain stem, dentate gyrus
KII	Interconnected excitatory and inhibitory populations	Limit cycle oscillations with frequency in gamma band	Olfactory bulb, anterior olfactory nucleus, prepyriform cortex, CA1, CA2, CA3 sections of hippocampus, amygdala, hypothalamus
KIII	Several interacting KII and KI sets	Chaotic oscillations	Cortex, hippocampal formation (HF), midline forebrain (MF)
KIV	Several interacting KIII sets	Spatio-temporal dynamics with global intermittent phase transitions	Hemisphere-wide cooperation of cortex, HF, and MF, coordinated by the amygdala
KV	Interacting KIV and KIII sets	Scale-free dynamics allowing rapid global integration and evolution	Undivided neocortical neuropil embedding the primary sensory and motor areas with the limbic system

cortical areas by which all local networks are coordinated simultaneously rather than by serial synaptic transmission among selected parts. The advantage is extremely rapid updating of the local memories to include associative contributions from all modalities within the time window defined by the duration of a global AM pattern (Freeman 2015).

Freeman has adopted Hilbert transform-based analysis for rapidly changing, non-stationary ECoG signals (Lachaux et al. 1999; Freeman et al. 2000; Freeman and Rogers 2002). Hilbert analysis provides the analytic amplitude (AA) and analytic phase (AP) of the band-passed signals, which are used to characterize intermittent phase transitions. Various indices have been introduced to quantitatively describe the transitions (Pikovsky et al. 2001), including the pragmatic information index, which implicitly takes into consideration the amount of work that is required to create knowledge expressed in meaningful actions (Freeman 2005). Pragmatic information index has been used to identify spatio-temporal singularities in ECoG, which have been interpreted as manifestations of the “Aha” moment of sudden deep insight, understanding, and decisions (Davis et al. 2013). Numerous examples of the beneficial and deleterious results of snap decisions have been recounted in psychological studies (Gladwell 2007).

The cinematic theory is schematically illustrated in Fig. 6. This image is based on a 64-channel intracranial experiment in rabbits, where the analytic amplitudes (AA) and analytic phases (AP) are obtained following Hilbert transformation of the beta-gamma filtered ECoG signals. The 64 analytic amplitudes are relatively large for a few 100 ms period, but they exhibit drastic reduction during the intermittent desynchronization (blue bars). These are the

null spikes (within the vertical blue bars), which are spatially and temporally localized. Intensive work has been conducted to describe dynamic transitions in cognitive processing as part of the action-perception. Recent scalp EEG studies evidence that AM and PM patterns are also observable by non-intrusive experimental techniques (Pockett et al. 2009; Ruiz et al. 2010).

The cinematic theory of cognition provides the framework for the intentional action-perception cycle. Intentional behavior from all vertebrates requires brief, repetitive and intensive synchronization of widely separated neurons in all parts of the limbic system. The intentional cycle starts with the individual who creates hypotheses on the external world in the context of his/her internal goals and desires. Based on the hypothesis, the subject makes an action, which is the intentional act of reaching out to the environment. As the result of the action and the ongoing sensory monitoring its own action, the hypothesis is confirmed or rejected. In both cases the resulting percepts are incorporated in the internal world-view of the individual, and the internal world model is updated. This completes the intentional cognitive cycle, which is ready to start again with a new set of actions.

The intentional action-perception cycle and its physiological manifestation in the cinematic theory (Freeman 2008) build on a wealth of research related to Prigogine's work on dissipative structures (Prigogine 1980) and Haken's synergetic approach to information processing (Haken 1983). Haken's ideas have been extended, including metastability of large-scale cortical structures and the whole brain (Kelso 1995; Bressler and Kelso 2001; Tognoli and Kelso 2014). Systematic overview of stability, metastability, and rapid transitions in brain activity is given

Fig. 6 Illustration of the cognitive cycle according to the cinematic theory of cognition. *Top:* 64 superimposed band-pass filtered ECoG signals. The amplitudes are high between the blue bars, and they correspond to the metastable AM patterns carrying the cognitive content. *Bottom:* During the shutter period with desynchronization and singularity (blue bars), phase cones convey the transition from microscopic disorder to macroscopic order (illustration by Chris Gralapp); from (Kozma and Freeman 2014, 2015). (Color figure online)

by (Le Van Quyen 2003; Stam et al. 2003; Werner 2009). Chaotic itinerancy yet another key theoretical concept (Tsuda 2001), closely related to Freeman view of complex brain dynamics.

Phase transitions in cortical dynamics

Mathematical and physical theories are essential to describe and simulate the transitions in neural activity that might be consistent with the action-perception cycle. The most important operations are the phase transitions by which AM patterns form and diminish. This event involves a discontinuity in the analytic signal derived from brain wave recordings, which ushers in a new AM pattern and a new phase pattern having the form of a radially symmetric conic gradient in the phase of the carrier frequency (Freeman et al. 2003a, b; Freeman 2003; 2004a, b; 2005, 2006a, b). It is likely that neural phase transitions, which are so important in perception and decision, will play prominent roles in the operations performed by and on AM patterns. Freeman considered it a very important scientific challenge to develop adequate mathematical and physical approaches to describe cortical phase transition.

Specifically, he has been involved in two promising approaches: Random Graph theory (RGT) and Quantum Field Theory (QFT).

Neuropercolation is a family of probabilistic models based on RGT and probabilistic cellular automata on lattices. Neuropercolation is motivated by the structural and dynamical properties of large-scale neural populations. Neuropercolation extends the concept of phase transitions to interactive neural populations exhibiting frequent sudden transitions in their spatio-temporal dynamics. Neuropercolation develops equations for the probability distributions of macroscopic state variables using RGT as an alternative to differential equations (Kozma et al. 2005). Neuropercolation is a natural domain for modeling collective properties of interacting neural populations in brain networks, especially near critical states, when the behavior of the system changes abruptly with the variation of some parameter. It provides a convenient framework to describe phase transitions and critical phenomena in spatially distributed large-scale networks, in particular, in brain networks with transient dynamics.

Neuropercolation describes generalizations of random bootstrap percolations motivated by features of the

neuropil, the filamentous neural tissue in the cortex (Freeman 2008). The regular (monotonous) percolation model is generalized in neuropercolation, to describe complex oscillatory behavior (Bollobas and Riordan 2006). The dynamics of the interacting neural populations is inherently nondeterministic due to dendritic noise and other random effects in the nervous tissue and external noise acting on the population. Neuropercolation incorporates the following major generalizations over percolation models: (1) interaction with noise, i.e., inclusion of random effects characterizing critical phase transitions; (2) non-locality due to long axons, which play key role in the scale-free dynamics of the neural tissue, similarly to rewiring in small-worlds (Watts and Strogatz 1998; Albert and Barabasi 2002); (3) mutual excitatory and inhibitory effects, which contribute to sustained oscillations and scale-free dynamics.

Neuropercolation models have been established following the blueprint of Freeman K sets, whereas ODEs in the original formulation (Freeman 1975) have been replaced by equations for the probability distributions of macroscopic state variables. Multilayer neuropercolation models describe the 6-layer structure and dynamical properties of the cortex, including background activity (corresponding to KI sets), narrow-band oscillations in KII sets (Puljic and Kozma 2008), and broadband oscillations in KIII sets. Input-induced and spontaneous transitions between states with large-scale synchrony and without synchrony exhibit brief episodes with long-range spatial correlations, replicating Freeman's experimental findings (Kozma and Puljic 2015).

Neuropercolation is a dynamic pattern-based computing paradigm based on Freeman neurodynamics and it goes beyond symbol manipulation by a given rule set, as specified by the Turing computing principles. Table 2 summarizes components of neuropercolation computing in comparison with Freeman neurodynamics and Turing computing. Neuropercolation has the following main features: (1) the computing sequences are self-organized through frequent phase transitions between synchronized and desynchronized states; (2) the symbols are not fixed but dynamically emerge in the form of spatially distributed,

metastable AM patterns; (3) there is no predefined instruction set telling how to switch from one pattern to the other, rather the system follows a dynamic trajectory in a high-dimensional state space, modified by learning experience.

Freeman emphasized the importance of field effects in cortical dynamics and anticipated the potential role of dissipative quantum field theories (QFT) in symmetry breaking and in reassertion of symmetry in neural populations (Freeman and Vitiello 2006; Freeman and Cao 2008). The proposed QFT approaches explore the feasibility of interpreting phase transitions in ECoG data in terms of many-body physics, using concepts of energy dissipation, genesis of multiple ground states in the cortex, and pattern selection by spontaneous symmetry breaking (Capolupo et al. 2013; Werner 2013).

The QFT interpretation of brain dynamics starts with Freeman's observation that the mesoscopic neural activity of the cortex consists of dynamically changing spatially extended neural AM and PM patterns, in which cooperation among neural populations supports metastable, synchronized oscillations. This behavior resembles the picture outlined in QFT of condensed matter physics, when information is carried by some ordered pattern maintained by long range correlations mediated by specific quanta (Umezawa 1995). In other words, memory is embodied as an ordered pattern supported by long-range correlations. This leads to the following apparent paradox: if neural information is transmitted via well-defined pulses and dendritic currents through specific synapses, then how can neural fields exist, transmissions maintained and being organized in large-scale patterns of activity without apparent regard to specific pathways in the cortical tissue (Vitiello 2009). Pribram addressed similar questions using his holographic theory of brain operation (Pribram 2013).

According to the QFT interpretation of brain dynamics, the brain as a dissipative system has a collection of co-existing and overlapping ground states. The brain as an open system exchanges energy with the environment and it may occupy any of the multiplicity of ground states, or it may be in a state that is a superposition of these ground states. In response to stimuli, the brain state may shift from

Table 2 Comparing freeman neurodynamics and computational paradigms. Adopted from (Kozma and Puljic 2015)

Main features	Freeman neurodynamics	Neuropercolation by freeman K sets	Symbolic computation by turing machines
Patterns	Mesoscopic cortical patterns (frames) (100–200 ms)	Metastable (long) synchronized AM patterns	Predefined symbols e.g., binary patterns control state
Switches	Transitions between cortical patterns (shutter) (10–20 ms)	Phase transition (rapid) with desynchronization between AM patterns	Rules and operations write symbol move head change state
Sequence	Cinematic sequence of cortical states	Self-organized sequence of irregular steps	Regular deterministic cell sequence on a tape

one ground state to the other, where the given stimulus acts as control parameter. This means that the brain undergoes a sequence of phase transitions, manifesting in a sequence of wave packets as dissipative structures (Prigogine 1980). QFT has a great potential to model experimental results observed on field effects in brain dynamics, which provides many potential avenues to be explored in future studies.

Referring to novel tools of RGT and QFT for modeling dissipative structures in brain dynamics, Freeman wrote: “Indeed this is the best of times to open this new continent for exploration with the mathematical and technical tools that seem extraordinarily complex and advanced from our present perspective, but which will appear to our descendants as quaint, in the way that we now see in museums the brass microscopes and telescopes that supported the collection of the knowledge that we now enjoy and project into our own futures” (Freeman 2009a).

Philosophical essays on intentionality and embodied cognition

Freeman has been fascinated by philosophical implications of his groundbreaking neurodynamics studies and produced highly influential results on intentionality, consciousness, and the unity of brain, mind, and body (Freeman 1997; Núñez and Freeman 1999). The dynamics of interactive neurons in the brain reach out to the environment with the intent to manipulate it. Each act of observation intends the gathering of information concerning the status of the brain and body with respect to expected possible future states that are anticipated from the context of past relations embodied in synaptic networks and the present relations that hold in the dynamic states of brain and body projected into the future. Collectively this sequence is known as the action-perception cycle (Freeman 2009).

Freeman’s description of the intentional action-perception cycle builds on the work of Aquinas (1272), suggesting that the physical body and particularly the brain is the vessel for subjective experience via intentionality. Freeman has observed three stages based on his records of ECoG from rabbits and EEG from human volunteers. Stage 1: experience of emotion and value before cognition—startle; Stage 2: union of the senses happens in Gestalts; and Stage 3: state of global coherence over the entire cerebral cortex. The intentional act of observation anticipates a collection of possible outcomes of the sensory consequences of each action. The consequences of the act are the selection of one of the predicted outcomes, and the updating of the selected cortical synaptic network in the brain. The updating of the network accommodates to the environment by incorporating the differences between expected and actual microscopic

sensory inputs. The cumulative changes in cortical networks continually expand and adapt the knowledge base in the brain (Freeman 2009).

Freeman’s intentional neurodynamics identifies the AM patterns that carry the meaning of the stimulus to the subject. AM patterns carry the meaning holistically, i.e., no specific location in the AM pattern is more relevant than another one. This observation is in line with Pribram’s prediction of the holographic principle in brains (Pribram 1969). Intentionality is the mechanism by which brains solve the symbol-grounding problem and construct the psychological “now” (Freeman 2016); Freeman was unable to deliver this Keynote Talk at The Science of Consciousness Conference due his death. Intentionality indicates that the brain is an open system with respect to energy and information but a closed system with respect to knowledge and meaning. Its unity is inviolate. It can predict the form of an object or event and test its predictions, but the form and information content of an object or event are not transferred through the microscopic sensory receptors and pathways into the brain.

It must be emphasized that AM patterns relate to the meaning of input stimuli but they do not have the status of symbols (Freeman 2009). Symbols lack the flexibility of instant reassignment and participation in multiple types of behaviors. The issue at hand is closely related to the dualist/symbolist view of human and machine intelligence, criticized by Dreyfus, following Heideggerian/Merleau-Pontian traditions (Merleau-Ponty 1942/1963; Heidegger 1975/1988; Dreyfus 1993). Dreyfus’ situated intelligence approach is a prominent example of a philosophical alternative to symbolism. Dreyfus ascertains that intelligence is defined in the context of the environment. Therefore, a preset and fixed symbol system cannot grasp the essence of intelligence. The resulting difficulties are formidable, but Dreyfus (2007) sees a hope for breakthrough based on Freeman’s intentional neurodynamics and its possible implementations in hardware domains. When discussing the relationship between brains and computers, Von Neumann (1958) pointed out that the language of the brains and its operational principles must be different from the logical operation of digital computers. Freeman has been fascinated with the question symbolic representations in brains and its implications on comparing the operation of digital computers and brains. Freeman argued against the mechanistic parallels between the cold logic of digital computers and complexity of our brains. He clearly opposed to the reductionism that considers brains as information processing units, transforming input data into output neural representations. Rather he considered brains as holistic organs in the unity of brain, mind, and body.

Fig. 7 Group photo at the NSF dynamic brain networks conference celebrating Walter Freeman's 80th birthday; University of California at Berkeley, January 27, 2007

Epilogue: carrying on Freeman's legacy

Walter has been a *Renaissance man*, as some colleagues characterized him, so rare in our overspecialized society. He had thorough knowledge of broad areas of neuroscience; it has been in his blood, by being the son of neurosurgeon Walter J. Freeman II, and the great grandson of William Keen, the nation's first brain surgeon. Contrary to typical neuroscientists with very specific focus of interest, he had the impressive command of broad science disciplines, such as math, physics, and engineering, and he has been well versed in humanities, too. Looking at his life path, such diversity has clearly rooted in his broad educational background, in math, engineering, literature and philosophy, medicine. He has been an extremely useful resource of almost any type of knowledge.

People were aware of his wisdom and appreciated his help in various ways. His intellectual depth was apparent when people met him, either one-to-one, in small groups, or in an audience of hundreds or thousands. He has been an extremely popular and effective speaker at all levels. What distinguished him from most other excellent scientists, what made him pioneer and visionary, is that he used his encyclopedic knowledge to discover new connections inside research disciplines, and between disciplines, which were far from apparent, in fact baffled most of his contemporaries. A good example of this is his first major book MANS (Freeman 1975). This book has been ahead of the

mainstream neuroscience by 50 years or so. Walter's work in the past 40 years is focused on spreading the word and extending the wisdom contained in MANS.

Walter was a great person to discuss with on various issues, science and beyond. All the same, he could become very defiant and combative when people criticized his work without properly absorbing the essence of it. In particular, he could identify in a split of a second the presence of any dogmatic view in his counterparts, pinpointed it without hesitation, and criticized it merciless. He applied this critical stand to himself, as well. He has been extremely open-minded, always looking for new ideas and developments and adjusted his own viewpoint if rigorous observations indicated that it was the prudent thing to do. The fact that his groundbreaking ideas stood the test of the time (for 50+ years), clearly indicates that those ideas are indeed extraordinary and deserve the highest recognition that can be bestowed to intellectual achievements.

We can honor his legacy by following his vision, and achieve a true breakthrough in science comparable only to the Newtonian revolution three centuries ago. He dreamed about "crossing the ocean" and we can indeed achieve this based on his example (Fig. 7).

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References

- Aihara K, Takabe T, Toyoda M (1990) Chaotic neural network. *Phys Lett A* 144:333–340
- Albert R, Barabasi AL (2002) Statistical mechanics of complex networks. *Rev Mod Phys* 74:47–97
- Aquinas ST (1272) “*The Summa Theologica*.” Translated by Fathers of the English Dominican Province. Revised by Daniel J Sullivan. Published by William Benton as Volume 19 in the Great Books Series. Chicago: Encyclopedia Britannica, Inc., 1952
- Barrie JM, Freeman WJ, Lenhart MD (1996) Spatiotemporal analysis of prepyriform, visual, auditory, and somesthetic surface EEGs in trained rabbits. *J Neurophysiol* 76(1):520–539
- Bollobas B, Riordan O (2006) Percolation. Cambridge University Press, Cambridge
- Borisyuk RM, Borisyuk GN (1997) Information coding on the basis of synchronization neuronal activity. *Biosystems* 40(1–2):3–10
- Bressler SL, Kelso JAS (2001) Cortical coordination dynamics and cognition. *Trends Cognit Sci* 5:2–36
- Capolupo A, Freeman WJ, Vitiello G (2013) Dissipation of ‘dark energy’ by cortex in knowledge retrieval. *Phys Life Rev* 10(1):85–94
- Chang HJ, Freeman WJ (1996) Parameter optimization in models of the olfactory neural system. *Neural Netw* 9(1):1–14
- Davis JJJ, Kozma R, Freeman WJ (2013) Neurophysiological evidence of the cognitive cycle and the emergence of awareness. In: IEEE 2013 international joint conference on awareness science and technology and ubi-media computing (iCAST-UMEDIA), pp 149–157
- Dreyfus HL (1993) Heidegger’s critique of the Husserl/Searle account of intentionality. *Soc Res* 60(1):17–38
- Dreyfus HL (2007) Why Heideggerian AI failed and how fixing it would require making it more Heideggerian. *Philos Psychol* 20(2):247–268
- Freeman WJ (1975/2004) Mass action in the nervous system. Academic Press, New York. <http://sulcus.berkeley.edu/MANSWWW/MANSWWW.html>
- Freeman WJ (1987) Simulation of chaotic EEG patterns with a dynamic model of the olfactory system. *Biol Cybern* 56(2–3):139–150
- Freeman WJ (1991) The physiology of perception. *Sci Am* 264(2):78–85
- Freeman WJ (1992) Tutorial on neurobiology: from single neurons to brain chaos. *Int J Bifurc Chaos* 2(03):451–482
- Freeman WJ (1995) Societies of brains: a study in the neuroscience of love and hate. Psychology Press, Milton Park
- Freeman WJ (1997) Three centuries of category errors in studies of the neural basis of consciousness and intentionality. *Neural Netw* 10(7):1175–1183
- Freeman WJ (2000a) How brains make up their minds. Columbia University Press, New York
- Freeman WJ (2000b) Neurodynamics: an exploration in mesoscopic brain dynamic. Springer, London
- Freeman WJ (2003) The wave packet: an action potential for the 21st century. *J Integr Neurosci* 2(01):3–30
- Freeman WJ (2004a) Origin, structure, and role of background EEG activity. Part 1. Analytic amplitude. *Clin Neurophysiol* 115:2077–2088
- Freeman WJ (2004b) Origin, structure, and role of background EEG activity. Part 2. Analytic phase. *Clin Neurophysiol* 115:2089–2107
- Freeman WJ (2005) Origin, structure, and role of background EEG activity. Part 3. Neural frame classification. *Clin Neurophysiol* 116(5):1118–1129
- Freeman WJ (2006a) Origin, structure, and role of background EEG activity. Part 4. Neural frame simulation. *Clin Neurophysiol* 117(3):572–589
- Freeman WJ (2006b) A cinematographic hypothesis of cortical dynamics in perception. *Int J Psychophysiol* 60(2):149–161
- Freeman WJ (2007) My legacy: a launch pad for exploring neocortex. In: Keynote talk at the 2007 NSF brain network dynamics conference. Berkeley. https://archive.org/details/Brain_Network_Dynamics_2007-03_Walter_freeman. Accessed on 26–27 Jan 2007
- Freeman WJ (2008) A pseudo-equilibrium thermodynamic model of information processing in nonlinear brain dynamics. *Neural Netw* 21:257–265
- Freeman WJ (2009) The neurobiological infrastructure of natural computing: intentionality. *New Math Natural Comput* 5(01):19–29
- Freeman WJ (2015) Mechanism and significance of global coherence in scalp EEG. *Curr Opin Neurobiol* 31:199–205
- Freeman WJ (2016) What neural correlates of consciousness can tell us about its properties? Plenary talk (cancelled), the science of consciousness conference (TSC’16). Tucson. Accessed on 26 April 2016
- Freeman WJ, Barrie JM (2000) Analysis of spatial patterns of phase in neocortical gamma eegs in rabbit. *J Neurophysiol* 84:1266–1278
- Freeman WJ, Cao Y (2008) Proposed renormalization group analysis of nonlinear brain dynamics at criticality Chapter 27. In: Wang R et al (eds) *Advances in cognitive neurodynamics ICCN 2007*. Springer, Heidelberg, pp 147–158
- Freeman III WJ (2009) Nonlinear dynamics and intention according to Aquinas. *Mind Matter* 6(2)
- Freeman WJ, Quian-Quiroga R (2013) *Imaging brain function with EEG*. Springer, New York
- Freeman W, Rogers L (2002) Fine temporal resolution of analytic phase reveals episodic synchronization by state transitions in gamma EEGs. *J Neurophysiol* 87(2):937–945
- Freeman WJ, Vitiello G (2006) Nonlinear brain dynamics as macroscopic manifestation of underlying many-body field dynamics. *Phys Life Rev* 3:93–118
- Freeman WJ, Rogers LJ, Holmes MD, Silbergeld DL (2000) Spatial spectral analysis of human electrocorticograms including the alpha and gamma bands. *J Neurosci Methods* 95(2):111–121
- Freeman WJ, Burke BC, Holmes MD (2003a) Aperiodic phase resetting in scalp EEG of beta–gamma oscillations by state transitions at alpha–theta rates. *Hum Brain Mapp* 19(4):248–272
- Freeman WJ, Burke BC, Holmes MD, Vanhatalo S (2003b) Spatial spectra of scalp EEG and EMG from awake humans. *Clin Neurophysiol* 114:1055–1060
- Freeman WJ, Kozma R, Bollobas B, Riordan O (2009) Scale-free cortical planar graphs. In: Bollobas B, Kozma R, Miklos D (eds) *Handbook of large-scale random networks: Bolyai-Springer series on advanced combinatorics*. Springer, New York
- Fulton JF (1938) *Physiology of the nervous system*. Oxford University Press, London
- Gladwell M (2007) *Blink: the power of thinking without thinking*. Back Bay Books, New York
- Haken H (1983) *Synergetics: an introduction*. Springer, Berlin
- Harter D, Kozma R (2005) Chaotic neurodynamics for autonomous agents. *IEEE Trans Neural Netw* 16(3):565–579
- Heidegger M (1975/1988) *The basic problems of phenomenology* [rev. ed.]. Hofstadter A [trans.] Indiana UP, Bloomington
- Ilin R, Kozma R (2006) Stability of coupled excitatory-inhibitory neural populations application to control multistable systems. *Phys Lett A* 360:66–83
- Katchalsky A, Rowland V, Blumenthal R (1974) *Dynamic patterns of brain cell assemblies*. MIT Press, Cambridge

- Kay LM, Freeman WJ (1998) Bidirectional processing in the olfactory-limbic axis during olfactory behavior. *Behav Neurosci* 112(3):541
- Kelso JAS (1995) *Dynamic patterns: the self organization of brain and behavior*. MIT Press, Cambridge
- Kozma R, Freeman WJ (2001) Chaotic resonance—methods and applications for robust classification of noisy and variable patterns. *Int J Bifurc Chaos* 11(06):1607–1629
- Kozma R, Freeman WJ (2003) Basic principles of the KIV model and its application to the navigation problem. *J Integr Neurosci* 2(1):125–146
- Kozma R, Freeman WJ (2014) On neural substrates of cognition: theory, experiments and application in brain computer interfaces. In: *Proceedings of the 2014 annals oak ridge national laboratory biomedical science and engineering center conference (BSEC2014)*. IEEE Press, pp 1–4
- Kozma R, Freeman WJ (2015) Cognitive phase transitions in the cerebral cortex-enhancing the neuron doctrine by modeling neural fields. Springer, Heidelberg
- Kozma R, Puljic M (2015) Random graph theory and neuopercolation for modeling brain oscillations at criticality. *Curr Opin Neurobiol* 31:181–188
- Kozma R, Freeman WJ, Erdi P (2003) The KIV model: nonlinear spatio-temporal dynamics of the primordial vertebrate forebrain. *Neurocomputing* 52:819–826
- Kozma R, Puljic M, Balister P, Bollobas B, Freeman WJ (2005) Phase transitions in the neuopercolation model of neural populations with mixed local and non-local interactions. *Biol Cybern* 92(6):367–379
- Kozma R, Aghazarian H, Huntsberger T, Tunstel E, Freeman WJ (2007) Computational aspects of cognition and consciousness in intelligent devices. *IEEE Comput Intell Mag* 2(3):53–64
- Lachaux JP, Rodriguez E, Martinerie J, Varela FJ (1999) Measuring phase synchrony in brain signals. *Hum Brain Mapp* 9:194–208
- Le Van Quyen M (2003) Disentangling the dynamic core: a research program for a neurodynamics at the large-scale. *Biol Res* 36:67–88
- Marcus G, Koch C (2014) The future of brain implants: How soon can we expect to see brain implants for perfect memory, enhanced vision, hypernormal focus or an expert golf swing? *Wall Street Journal*, Saturday Essay. 14 March 2014
- McCulloch WS, Pitts W (1943) A logical calculus of the ideas immanent in nervous activity. *Bull Math Biophys* 5(4):115–133
- Merleau-Ponty M (1942/1963) *The structure of behavior*. Fischer AL [trans]. Boston, Beacon
- Núñez R, Freeman WJ (1999) *Reclaiming cognition. The primacy of action, intention and emotion*. Thorverton: Imprint Academic
- Ohl FW, Scheich H, Freeman WJ (2001) Change in pattern of ongoing cortical activity with auditory category learning. *Nature* 412(6848):733–736
- Pikovsky A, Rosenblum M, Kurths J (2001) *Synchronization: a universal concept in non-linear sciences*. Cambridge UP, Cambridge
- Pockett S, Bold GE, Freeman WJ (2009) EEG synchrony during a perceptual cognitive task: widespread phase synchrony at all frequencies. *Clin Neurophysiol* 120:695–708
- Pribram KH (1969) *The neurophysiology of remembering*. Sci Am 220(1):73–86
- Pribram KH (2013) *The form within. My point of view*. Prospecta Press, Westport
- Prigogine I (1980) *From being to becoming: time and complexity in the physical sciences*. San Francisco. W. H. Freeman
- Puljic M, Kozma R (2008) Narrow band oscillations in probabilistic cellular automata. *Phys Rev E* 78:026214
- Quiroga QR, Reddy L, Kreiman G, Koch C, Fried I (2005) Invariant visual representation by single-neurons in the human brain. *Nature* 435:1102–1107
- Ruiz Y, Pockett S, Freeman WJ, Gonzalez E, Li G (2010) A method to study global spatial patterns related to sensory perception in scalp EEG. *J Neurosci Methods* 191(1):110–118
- Skarda CA, Freeman WJ (1987) How brains make chaos in order to make sense of the world. *Behav Brain Sci* 10(2):161–195
- Stam CJ, Breakspear M, van Cappellen AMVC, van Dijk BW (2003) Nonlinear synchronization in EEG and whole-head recordings of healthy subjects. *Hum Brain Mapp* 19:63–78
- Tognoli E, Kelso JAS (2014) The metastable brain. *Neuron* 81(1):35–48
- Tsuda I (2001) Toward an interpretation of dynamics neural activity in terms of chaotic dynamical systems. *Behav Brain Sci* 24:793–847
- Umezawa H (1995) Development in concepts in quantum field theory in half century. *Math Jpn* 41(1995):109–124
- Viana Di Prisco G, Freeman WJ (1985) Odor-related bulbar EEG spatial pattern analysis during appetitive conditioning in rabbits. *Behav Neurosci* 99:962–978
- Vitiello G (2009) Coherent states, fractals and brain waves. *New Math Nat Comput* 5:245–264
- Von Neumann J (1958) *The computer and the brain*. Yale UP
- Watts DJ, Strogatz SH (1998) Collective dynamics of ‘small-world’ networks. *Nature* 393:440–442
- Werner G (2009) Consciousness related neural events viewed as brain state space transitions. *Cognit Neurodyn* 3(1):83–95
- Werner G (2013) Consciousness viewed in the framework of brain phase space dynamics, criticality, and the renormalization group. *Chaos, Solitons Fractals* 55:3–12
- Xu D, Principe JC (2004) Dynamical analysis of neural oscillators in an olfactory cortex model. *IEEE Trans Neural Netw* 15(5):1053–1062