Freeman's Intentional Neurodynamics

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Abstract

In this commemoration of Walter Freeman's life and legacy, we review some his key contributions to the field of cognitive neuroscience. We elaborate on his groundbreaking contribution to neural aspects of intentionality, what he called intentional neurodynamics. We describe the conceptual framework of intentional neurodynamics and its neurophysiological manifestations. We conclude with the outline of Freeman K (Katchalsky) sets, a hierarchical model of brain structure, dynamics, and functions, which provide a suitable mathematical and computational framework to grasp essential aspects of intentionality.

1. Foreword – Freeman's Legacy

Walter Freeman's experimental and theoretical work revolutionized neurobiology and gave birth to the field of neurodynamics. He has been a scientific polymath and we can comfortably say that he wore many different scientific hats throughout his extensive academic career. His qualification to speak authoritatively across many sub-disciplines of neuroscience and science in general was widely acknowledged, as he studied math and physics at Massachusetts Institute of Technology, electronics in the Navy, philosophy at the University of Chicago, medicine at Yale and at Johns Hopkins, and neuropsychiatry at University of California at Los Angeles.

Freeman will most likely be remembered for his pioneering work in demonstrating how the brain uses chaos to make sense of the world. He was arguably the first neuroscientist to suggest that chaos played a pivotal role in cortical dynamics. His approach to chaotic brain dynamics has profound impact over cognitive neuroscience and it strongly influences the neuroscience community. From early on in his career, the theory of dissipative systems had key impact on his scientific approach (Glansdoff & Prigogine, 1971; Freeman 1975/2004). Based on his physics and experimental neurobiologist background, Freeman was able to quickly realize that the burgeoning field of chaos theory (Thom, 1981; Abraham and Shaw, 1983/2005; Garfinkel, 1983; Schuster, 1984; Gleick, 1987) has important implications to neuroscience and published with Christine Skarda a ground-breaking and comprehensive model of global cortical dynamics using the concept of chaos as the central driving mechanism of brain dynamics (Skarda and Freeman, 1987).

As groundbreaking as his dynamical systems and chaos approach to modeling cortical function was, it was only one of many similar interdisciplinary connections Freeman made between neurobiology, control engineering and other fields, which have enriched our understanding of what the brain does and how it does it; a blueprint of his cross-cutting approach is given in his first comprehensive monograph *Mass Action in the Nervous System* (Freeman, 1975). He taught us that, almost as equally as important as it is for the brain to learn is its ability to "unlearn." Unlearning is a process whereby coalitions of cortical units, called Hebbian cell-assemblies, that serve as memory traces demonstrating activities locked in rigid or stereotyped ways of thinking and behaving, are dissolved or washed away making room for new forms of thinking and behaving. In his popular book, *Societies of Brains* (Freeman, 1995), he goes into some detail as to how this unlearning is accomplished at the neurobiological level while at the same time relating to the reader that the new forms that replace the unlearned forms are largely forged through the "common sense" that individual brains and communities of brain's share in the participation of rituals. Some examples of such rituals that forge common sense between individuals range from singing traditional folk songs and signing in churches, and the sharing of common patterns of brain activation between two individuals when they learn to dance together.

Freeman had the uncanny ability to analyze the biological properties of interacting neurons at the microscopic, mesoscopic, and macroscopic levels, and relate them to everyday cognitive behaviors in a non-trivial way. His strong experimental neurobiology roots provided him with the foundations to become a convincing authority on the physiology, psychology, and philosophy of brains. What made Freeman such a pervasive presence in the neuroscience community was his ability to speak comfortably and authoritatively across interdisciplinary lines. He was the consummate *insider* in every discipline related to the brain and behavior and, because of his vast and disparate experience in each of these areas, he was always able to provide a deeper insight than most others to discussion in those areas.

2. The Experimental Paradigm of Mesoscopic Neurodynamics

What distinguished Freeman's research from other neuroscience investigators over the past half century was his focus on the importance of neuronal interactions at the population or mesoscopic level of organization. Many neuroscientists started with the premise that messages are transferred inside the brain in the form of a "code" represented in temporal and/or spatial distribution of spike trains of individual neurons. His approach is based on the recognition that there was no neural code in the brain in the sense of individual neurons, and perception and cognition are phenomena that are manifested at the level of cooperative actions of populations of neurons. In order to pursue this hypothesis, he took the electrode out from the interior of the individual neuron and placed it in the interstitial matrix between cells what is called electrocorticogram (ECoG) recording, where it could listen to not only one single neuron but to the collective effect of thousands of neurons in a local pool. What is captured from such an ECoG analysis is the so-called a local field potential, which represents the summed, collective behavior of upwards of 10,000 neurons in localized region of cortical neuropil, roughly reflective of a functionally integrated unit of cortical operation known as a cortical column (Freeman, 1975; Freeman, 1995; Mountcastle, 1997).

The act of placing ECoG electrodes over the cortical neuropil can yield important information on the collective behavior of cortical columns in a circumscribed region of cortex. In the visual cortex, for example, these cortical columns might represent the activity of a population of simple or complex cells that act to distinguish the orientation of a figure in the animal's fovea (Hubel & Wiesel, 1962). Understanding the importance of neurophysiological analysis at the population level, Freeman sought to extend that mapping over a greater-sized patch of cortex and created an 8x8 array of electrodes to capture the local field potentials from what may be roughly considered a 2-D array of 64 cortical columns. The result of such effort of arranging the 8x8 array was nothing short of spectacular, for it is at this mesoscopic level of the analysis of neurophysiological signals that Walter Freeman arguably broke the secret of how the brain works. Specifically, he found that the brain operates through the manipulation of spatially amplitude-modulated (AM) perceptual frames (Freeman, 2003). The AM pattern provide a "window" to the cognitive process of the subject as they express the meaning of the stimulus based on past experience and present intentions and goals (Freeman, 1997; Freeman, 1999). Moreover, the AM patterns form a sequence in a fashion much like the frames of a film reel project a temporally extended sensory "scenario" on to a projector screen. This experimentally supported model of cognition encompasses the action-perception cycle and it leads to the "cinematic hypothesis" of mammalian brain function (Kozma & Freeman, 2016).

After four decades of doing cutting-edge research in experimental neurobiology, Freeman could have decided to simply rest on his laurels and forgo getting into the burgeoning new fields of neuroimaging and neuroenergetics research. However, this was not to be. Instead, he dove in full force and sought to study how new brain imaging technologies such as functional Magnetic Resonance Imaging (fMRI) and Magneto-Encephalograms (MEG) worked together with Electro-Encephalograms (EEG) and ECoG. His goal was to provide a deeper understanding of how the brain constructs meaning and behavior in neural populations (Freeman 2000a; 2000b). What he found was that the metabolic interaction within neurons and between neuron-glia assemblies in the cortex was not only critical in the formation of perceptual and cognitive constructs manifested as amplitude modulated (AM) patterns, but that such interactions were associated with the changes in the regional blood flow within those areas manifesting the AM patterns.

Freeman incorporated the new insights from the fields of neuroimaging and neuroenergetics in a landmark paper on combining fMRI with EEG and MEG to monitor brain activity patterns related to cognition (Freeman, Ahlfors, Menon, 2009), and later in his comprehensive neuroimaging book with Rodrigo Quian-Quiroga (Freeman & Quian-Quiroga, 2013). Freeman brings his vast experience as a neurophysiologist to each of the major instruments of analysis, including single unit recordings, population (LFP) recordings, intracranial ECoG micro-array recordings, and non-invasive EEG, MEG, and fMRI. He provides a comprehensive analysis of the complementary ways, in which individual neurons, neuron populations, and their supporting glia and vasculature architectures support the cortical neurodynamics responsible for perception, cognition, and behavior in mammals. One of the primary new challenges faced when merging traditional EEG technology with the new fMRI is the problem of different temporal and spatial resolution scales in these disparate techniques. Specifically, EEG signals have excellent temporal resolution but poor spatial resolution due to issues such as volume conduction and cortical gyrification, which complicate the orientations of the dipole fields being measured. The fMRI signals, on the other hand, have excellent spatial resolution (in the mm range) but poor temporal resolution due to the slow time course of the vascular response to metabolic demand in local glia-neuron pools. Freeman offers to make compatible the analysis of data yielded by the different techniques by spatially coarse grain the EEG and temporally coarse grain the fMRI data using various spectral analysis tools so that the data could be analyzed on a common platform.

Freeman's contribution to the thermodynamic and neuroenergetic study of the brain provides key insights that have the potential of future high-impact developments in brain dynamics. Neuroenergetics aspects of AM pattern formation and the intentional action-perception cycle are crucial for better understanding and modeling brain dynamics. For example, a population model of interconnected neurons embedded within an astrocyte assemblage is being developed by (Noack et al., 2017), in which work the presence of a vascular feed has been incorporated as well. The initial goal is to establish a self-sustaining population of interacting neurons that vary their behavior in a predictable and controllable manner based on the input and output parameters such as glucose concentration, cerebral blood flow, and glutamate concentration. The next step is to connect such "mesoscopic" modules into larger hierarchical macroscopic networks and try to simulate the more hemispheres-wide cortical-dynamical model, which provides a link with the interpretation of fMRI imaging results.

3. Neural Basis of Intentionality

Freeman's intentional action-perception cycle builds on his deep insight on brain monitoring and cognitive neurodynamics. According to his approach, intelligent behavior is characterized by the flexible and creative pursuit of endogenously defined goals. Humans and animals are not passive receivers of perceptual information, rather they actively search for sensory input (Freeman, 2008). Freeman's action-perception cycle is described through the following steps: 1) stimuli from an animal's environment enters the animals sensory neocortices, 2) triggers a cell assembly there related to a given biologically relevant percept-memory, 3) projects to the frontal motor cortices where it triggers a related motor routine which in the past has produced reward in the animal, 4) executes that motor routine which changes the animal's proximate sensory environment which, 5) presents new information/stimuli back into the animal's sensory cortices whereby the process cycles again.

In intentional dynamical systems, meaningful knowledge is continuously created, processed, and dissipated in the form of sequences of oscillatory patterns of activity in sensory network distributed across space and time (Kozma & Freeman, 2003; Kozma, Freeman, Erdi, 2003; Kozma & Freeman, 2009). The oscillatory patterns can be viewed as representations of generalized symbol systems. However, these dynamical symbols are not rigid but flexible and they disappear very soon after they have been generated, at a rate of 4-5 patterns per second in human brains. Human cognition performs a granulation of the seemingly homogeneous temporal sequences of perceptual experiences into meaningful and comprehendible chunks of concepts and complex behavioral schemas, which are accessed during future action selection and decisions. The intentional dynamic model for the action- perception cycle has its closure through the environment; in this sense, the environment is part of the model (Davis et al., 2015).

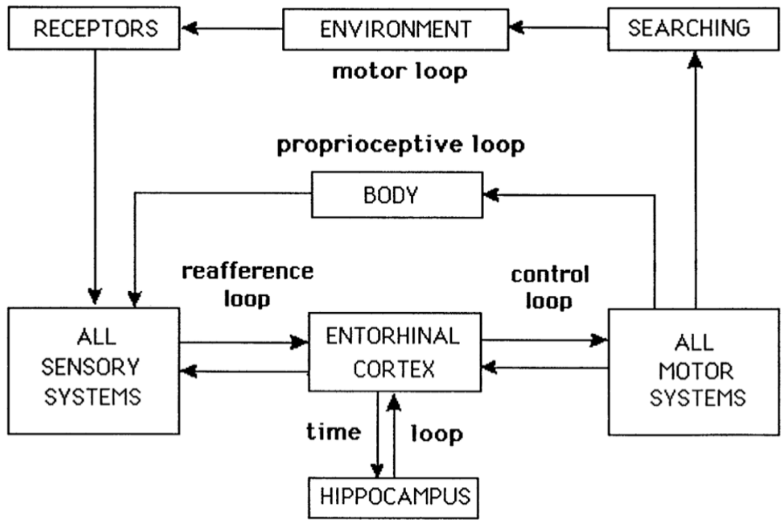

Figure 1. Illustration of Freeman's action-perception system in mammals; note the interconnected system of brain, body, and environment, including the proprioceptive, reafference, and motor control loops; from (Freeman, 1995).

The sensori-motor loop of information flow makes intuitive sense neuro-behaviorally and, in fact, was termed the "Perception-Action Cycle" by Juaquin Fuster (Fuster, 1985). While Fuster developed a detailed model of the cycle motivated by Uexkull (Uexkull, 1957), the underlying assumption in his formulation is that the Perception-Action Cycle (PAC) is *driven* by the perception. Freeman's "Action-perception cycle" is different from PAC by the way the primacy of intention, extending on the approach of his mentor, Karl Pribram (Miller, Galanter, Pribram, 1986). Freeman's formulation is similar to the PAC in the sense that the flow of information in the cortex is essentially from the posterior sensory cortices toward the frontal motor cortices, then out into the environment and back into the sensory cortices. The sophistication of Freeman's description exposes subtle but important distinctions. Specifically, while according to the PAC formulation the brain essentially "waits" for a stimulus to enter it's sensory cortices before the cycle becomes initiated, Freeman's formulation starts from *within*. Freeman's formulation dictates that the animal's brain issues an "efference signal" which, in the initial absence of guidance by sensory stimuli, causes the animal to *reach out* into its environment in the search for an important sensory stimulus that might initiate the cycle. It is the motor behavior of the animal re-orienting its bodily sensory apparatus in the effort to find a stimulus that comes first.

The unconventional nature of Freeman's formulation of the action-perception cycle, however, goes even deeper and it cuts to the heart of what was his principal contribution to the philosophy of neuroscience. It is his recognition that the brain is not an organ that passively waits for information and then acts on that information in the production of a corresponding behavior. Rather, the brain is a proactive organ that always creates and acts. Instead of *being used* by sensory stimulation, it *uses* sensory information to construct its concepts and behaviors. The property of the brain's function whereby it uses sensory stimuli to form its cognitive and behavioral constructions is referred to as "reaferrance," see Figure 1. Reafferance is a process that is driven by complex dynamics in global neural populations and fundamentally serves as the central driver of the action-perception cycle. Anyone that has confidently taken a sip out of what they thought was a cup of milk and it turned out to be orange juice has experienced reafferance in action. The process goes something like this: you are sitting around idly and your hypothalamus, through a cascade of chemical signals, tells you that you have a craving for a sip of milk. Now, all of a sudden, your neocortex begins to trigger a wide assortment of cell assemblies related to your previous experiences with milk such as grabbing, lifting, and drinking a cup of milk.

The triggering of these cell assemblies, in turn, creates a metastable state in the sensory and motor cortices, which manifests as an attractor landscape of loosely coordinated or high-dimensional chaotic attractors related to milk-associated objects and behaviors. It is the formation of this attractor landscape that identifies the property of reafferance. Reafferance can essentially be defined as a metastable state in cortical brain dynamics whereby a timely and relevant attractor landscape is established in the neocortex in order to prime a basin of attraction (Thom, 1981; Freeman, 1997; Freeman 1999), whereby an expected sensory stimulus can quickly and reliably send the state of cortical dynamics into an appropriate action-perception cycle state. That action-perception cycle is initiated once the expected stimulus is found or recognized.

Considering the previous example, the milk stimulus is found when you orient your eyes toward a table where you see a milk cup. At this point, the high-dimensional metastable attractor that manifested the reafferance now becomes low dimensional, constrained to a localized attractor valley, which characterizes a *specific* perceptual feature, in this case the image of the milk cup. The visual image of the milk cup reinforces a previously learned hierarchically organized sequential motor behavior in your frontal cortex as you proceed to reach out, grab, and lift that milk cup to your lips. However, in keeping with the initial scenario of accidentally taking a sip of orange juice from what was thought to be a milk cup, as you commence the behavior, the receptors in your tongue and nose send an orange juice signal to an attractor landscape in your brain that was prepared to accept a milk stimulus. Due to a mismatch between expectation and actual sensing, what ensues is utter chaos (sic) in your cortical structures, which results in an abrupt startle reaction. This is Freeman's model of reafferance and the action-perception cycle in action. Table I provides details of Freeman's intentional action perception cycle and the corresponding measurable neural signatures (Freeman, 2012; Davis et al., 2015).

Table I.
Neurodynamic Manifestations of the
Freeman Intentional Action-Perception Cycle

Intentional Action-Perception Cycle	**Neural Manifestations**
PREDICTING Form hypotheses about expected future states, anticipation. Express the hypotheses as goals.	EXPECTATIVE RESTING BRAIN DYNAMICS Maintain background brain state of readiness. Demonstrate habitual activity.
TESTING BY ACTION Formulate a plan of action and reach out to environment via action.	ACTIVATING SENSORY & MOTOR SYSTEMS Activate the motor system to execute action. Inform the sensory apparatus about the expected future input using the reafference process.
SENSING Manipulate the sense organs. Take information in the form of samples from all sensory ports.	TAKING NOTICE (“AWE”) & EXPLORATION Selection and transduction of stimuli, action potentials. Activate Hebbian cell assemblies in sensory cortices Explore chaotic memory traces and emergent AM patterns in search for meaning.
PERCEIVE Generalize, abstract, categorize. Form Gestalts and make decisions.	RECOGNIZING (“AHA” MOMENT) The emerging wave packet marks the identification of the searched clue. Form multisensory percepts in the limbic system.
ASSIMILATE & UPDATE Use the new data to verify or negate the hypotheses. Update the brain state and complete the intentional action-perception cycle.	LEARNING & ADAPTATION Employ plasticity for the integration of the new knowledge by adapting the chaotic attractor landscape. Ultimately return to basal background state of expectancy.

4. Modeling Intentional Neurodynamics – Freeman K-Sets

Walter Freeman understood that rigorous modeling of the experimentally observed complex neurodynamics is crucial to understanding and interpreting the measurements. These efforts lead to the development of the KIV model of intentional neurodynamics (Kozma & Freeman, 2003; Kozma et al., 2003). The KIV model is arguably the first and to this day only mathematical model that captures the integrated dynamics of neuron interactions at all levels of processing in the cortex, from single neurons to mesoscopic neuron pools to the macroscopic large-scale interacting brain systems known as "resting state networks (RSN)."

In the Freeman K model, each K-set represents a particular hierarchical scale of neuronal structure and dynamics in the cortex. The K0 set represents the lowest or microscopic level of individual neurons, while KI describes a population of excitatory or inhibitory neurons interactions, which may exhibit non-zero fixed point convergence. KII incorporates several interacting KI populations with excitatory and inhibitory connections. Due to the negative connections, limit cycle oscillations may form, which are the source of narrow-band gamma frequencies in the cortical tissue. KIII sets represent intermediate or mesoscopic interactions between oscillatory KII populations. KIII can exhibit chaotic dynamics and correspond to various sensory systems. KIV sets represent global-cortical interactions between KIII sets as cooperative behavior of cortical RSNs. KIV sets can exhibit intermittent changes between synchronous and non-synchronous oscillations that are hallmarks of intentional dynamics, which reflect the cooperative behavior of cortical RSNs. Continuing Freeman's vision, we are currently developing the KV model by connecting multiple KIV sets to describe higher cognitive functions in the human brain.

The KIV framework for modeling cortical behavior has shown successes in implementing an autonomous control and navigation systems for NASA SRR-2K Rover prototype to explore outer solar system planets such as Mars (Kozma et al., 2008). Successful hardware implementations include a VLSI silicon chip platforms at Principle's Lab (Principle et al, 2001). Freeman also developed a high-density array to be used on the exposed cortex of human subjects undergoing surgery for intractable epilepsy for data analysis and that may prove useful in the burgeoning new technology of brain-computer interfacing (BCI). Freeman and colleagues have developed advanced methods of non-invasive brain monitoring as well, using high-density EEG array signals recorded from human scalp electrodes (Freeman, 2007; Kozma et al., 2016).

5. Afterword

Walter Freeman passed away on April 24, 2016 at the age of 89. He continued to study, write, and advance the field of neuroscience up until his final days. He has written over 450 peer-reviewed articles and 8 books. His very last book *Cognitive phase transitions in the cerebral cortex*, coauthored by Robert Kozma, yielded his swan-song treatise

(Kozma, Freeman, 2016). In a scene reminiscent of Copernicus receiving a printed copy of his book *De revolutionibus orbium coelestium* on his deathbed, his phase transitions book appeared shortly before his passing. Understanding fully in his final days that the end was near, he heroically called upon his friends and scientific collaborators to continue his legacy.

Indeed, today that legacy is being carried forward at institutions and by many researchers around the world that have been inspired by Walter Freeman. For example, at the Biologically Inspired Neural and Dynamical Systems (BINDS) Lab at the University of Massachusetts, Amherst, we are developing models to describe how brain metabolic states affect individual neurons and glia-neuron networks spanning the entire micro-meso-macroscopic brain hierarchy. At the Center for Large-Scale Integration and Optimization Networks (CLION), the University of Memphis, we develop intelligent systems based on the hierarchy of Freeman K sets. Furthermore, various contributions to this special issue clearly demonstrate the broad impact of Freeman's legacy.

If one could think of a single label to define Walter Freeman it would be that of a scientific *polymath*. In a talk he gave on his chaotic neurodynamics at the 2003 Association for the Scientific Study of Consciousness (ASSC) Conference, at one point he made a deflective, self-effacing response to a mundane question from an audience member that went something along the lines of, *"I don't know, I'm just an old biophysicist."* He was much more than a biophysicist; he uncannily demonstrated an almost equal expertise in disparate fields such as psychology, philosophy, poetry, politics, as well as in engineering and physical sciences. It was undoubtedly his ability to abstract knowledge from each of these disparate academic disciplines that fostered his capacity to make significant and pioneering advancements in experimental and cognitive neuroscience.

In a final anecdote, let us recount a story from the 2008 Toward a Science of Consciousness conference in Tucson, Arizona. During an informal discussion with a close collaborator of Freeman, one of us (R.N.) made the quip: "You know, the only thing that disturbs me about Walter Freeman is that he always seems to be one step ahead of me. Just when I think I've read everything he's written and I've finally caught up with him, he comes out with something new and completely out of the blue." Characteristically, the response I received was along the lines: "Only one step behind? Be thankful for that, I often feel like I'm always *two* steps behind him!" This might be the most important lesson we can take from Walter Freeman's legacy - that is to push yourself, push yourself, and always push yourself to be on the forefront in whatever your passion in life is.

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