

Brains Create Macroscopic Order from Microscopic Disorder By Neurodynamics in Perception

Chapter 7 in:
Disorder versus Order in Brain Function
Essays in Theoretical Neurobiology

P. Århem, C. Blomberg, H. Liljenström (eds.)
Singapore: World Scientific Publishing Co., 2000.
pp. 205-219.

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11 July 1998

Abstract

The essential task of brain function is to construct orderly patterns of neural activity from disorderly sensory inputs, so that effective actions can be mounted by the brain, a finite state system, to deal with the world's infinite complexity. Two schools of thought are described, that characterize distinctive sources of the order within brains, one passive, the other active. These schools have profoundly influenced ways two groups of contemporary neuroscientists design their experiments and process their data, so that they have very different perspectives on the roles of noise and chaos in brain function.

Introduction

The world we all perceive is infinitely rich in patterns of light, sound, chemicals, fluxes of gases and liquids, moving objects. Yet another infinity of people share our world, and we continually interact with them at many levels of complexity. We are constantly bombarded with fields of energy and matter that we believe to be highly structured in space and time. Yet the sensory apparatus we use to perceive these structures does

not give us the fields directly, but only microscopic samples of them at the receptor cells.

Each of our sensory ports contains an array of receptors, which are microscopic transducers that convert the kinds of incident energy for which they are specifically sensitive to trains of action potentials. Their axons transmit these pulse trains into the brain. All of the information we get from the sensory arrays is in the form of point processes, that is, pulse trains that signal only the intensities and/or rates of change of types of energy at points in or on the body over brief time intervals. Everything that we know or infer about the structures of the energy fields that impinge upon us has come from these point processes. The individual receptors cannot send images of objects or processes extending in time and space. The arrays of receptors can and do send the raw sense data as spatial distributions of time series, but those data must be transformed and integrated in space-time, in order to yield patterns in the brain that simulate the patterns in the world.

Here is the central problem of brain function. Given what the American philosopher psychologist William James is reported to have described as "the blooming, buzzing confusion of the world", how do brains make order out of disorder? How do they process the infinitely complex flow of incoming information, given the finite capabilities they have for creating orderly dynamic states? Two main classes of answer have been offered by theorists over the past two millennia. The class that is identified with the tradition of Plato views perception as passive. The other class deriving from the tradition of Aristotle views perception as active. My aim in this essay is to contrast these two views in the context of contemporary neuroscience, and to comment on how the practitioners of these two schools of thought handle the intrusion of noise into sensory systems, and how they treat chaos when it turns up in the perceptual process. Both schools try to explain the emergence of order from disorder in brains, but with basically different premises, interpretations of data, and unsolved problems. The contrast illuminates where we are in our historic mission to understand brain function, and it indicates what directions we might best take, or avoid, in order to find solutions.

Perception as a Passive Process

Perception is regarded as passive when the beginning of the process is assigned to the impingement of a stimulus onto a receptor array, and the source of the subsequent order within brains is attributed to the form of the stimulus. In the ancient world, Plato described the process by a

metaphor. He wrote that the real world contains objects with ideal forms, which we do not see directly. We are denizens in a cave, and we see the shadows of these forms on the walls of our cave. The senses give us imperfect copies of the forms, from which we come to understand or approach the true forms by use of reason. In modern cognitive terms, the impact of a stimulus imports the information carried by the stimulus into the body, where it is transduced by the receptors and initially processed by neural networks in the spinal cord and brain stem. In the cerebral cortex the information is assembled to form a representation of the stimulus, which is stored in memory. The collection of representations comprises a world view. Each incoming stimulus evokes the retrieval of representations from the memory banks for comparisons, and that having a form most similar to the form of the stimulus serves to classify it.

In neurobiological explorations of the process, a stimulus is selected by the observer in the desired modality for delivery to an appropriate subject. For example, for studies of visual perception a geometric pattern of light is shown to a monkey. For audition, a frequency modulated tone or trill is given to a bird or a bat. A touch is applied to the whisker of a rat, or a chemical odorant is presented to a rabbit for inhalation. In each case the initial step is the perturbation of receptor neurons, that through a biochemical cascade or the modification of a resistance causes the release of generator currents. These currents initiate action potentials in so-called first order neurons in the peripheral nervous system, that excite second order neurons in the brain stem or spinal cord, typically by triggering one or more action potentials in them. They transmit to third order neurons located in the thalamus, which inject the information into the sensory cortex belonging to the modality of the receptors. An exception to this topology is olfaction, in which the receptors send their axons directly into the cerebral mantle of the forebrain.

The sensory receptors in large numbers form two dimensional arrays, and their axons run in parallel to their central targets, so that the stimulus-evoked activity is topographically mapped onto the arrays of second order neurons in the brain stem and spinal cord, next into the third order neurons in the thalamus, and then into the sensory cortices. In each sensory system the precise form of the mapping is modified by genetic instructions for building connections among neurons, developmental processes that make them, and learning that fine tunes them. By the matured networks the cortical neurons that are driven by a stimulus are made sensitive to selected aspects of the stimulus. These aspects are known as the features of the stimulus. In vision they are the contours, colors, and motions of objects. In audition they are the tones, frequency

or amplitude modulation (FM or AM), location of the sound source, and its rate of motion. In somesthesia they are the location and type of receptor for touch, pressure, vibration, temperature, pain, and so on.

The extraction of features is conceived as the third step of information processing, after transduction and central relay transmission. The fourth step is "binding" of the features into representations of the objects that possess the features. It is easy to conceive how features can be represented by repetitive firing of the feature detector neurons, but it is not so clear how the pulse trains can be combined to represent an object. The best available hypothesis for binding is that the pulse trains of the feature detectors become synchronized at a common phase and frequency in the gamma range ("40 Hz"), so that they sum under spatial integration in the cortical areas to which the feature detectors transmit. There is wide agreement among neurobiologists that the integration is done by neuron populations in areas adjacent to the primary sensory cortices, generally lying more anteriorly in the brain, in or in the direction of the frontal lobes of the forebrain. The frontal lobes are thought to be the sites of higher levels of organization of perceived objects into classes, preparatory to information processing by perception-based operations. These operations include association between inputs from all modalities, determination of meaning through logical operations, attachment of appropriate emotion, and the selection and execution of appropriate responses to the stimuli.

Noise in this passive view of perception has several sources. One source is in the individual neurons, which are seen as imperfect and unreliable pulse generators, partly due to thermal fluctuations in the membranes of their trigger zones, and partly due to their biochemical nature that makes them much more complicated than transistors. The remedy of engineers to the unavoidable unreliability of components is redundancy. By having numerous elements in parallel, a consensus can be found by averaging among them in order to extract a clean signal. Another source of noise is the endless and annoying background activity of brains, which can be suppressed by use of anesthetics and paralytics, or by surgical isolation of the sensory modules, in order to bring out the laws that govern the information processing. Another source is the background clutter in which perceived objects are embedded in the real world, such as the mixtures of shadows and overlapping objects in an aerial photograph, or the sounds of voices at a cocktail party. In engineering terms an object is recognized as foreground against background by formation of a store of images through learning in ideal noise-free circumstances. Recognition of an object is by template matching to an incoming stimulus, often by gradient descent in

artificial neural networks using least squares difference as a criterion for decision. Yet another source of noise is the unavailability of all but a fraction of the image of an object, such as a part of a face in a picture, a few phonemes in speech, or a malformed character in handwriting. Pattern reconstitution or completion is also done by use of templates in neural networks, which are said to be modeled on neural systems.

Chaos is not a desirable feature of neural networks, nor is it a useful property of the neural activity in models of feature binding in sensory cortices, because it is so difficult to define "phase" between chaotic time series (Rosenblum, Pikovsky and Kurths, 1996; Pikovsky, Rosenblum, Osipov and Kurths, 1997). The chaos in such aperiodic traces is treated as one among many types of noise in passive perception, one not deserving special study.

The most effective way to remove or attenuate noise is by averaging. The most common algorithm is time ensemble averaging, by which a stimulus is presented repeatedly, and records are kept of the neural responses to the stimulus on each trial. The records are aligned with respect to the time of onset of the stimulus, and the sum is calculated at each point in time over the trials, beginning before the stimulus and ending after the response. The sum of the traces is divided by the number of trials to give the average. Alternatively, a spatial pattern of the cortical response to a stimulus, as in mapping receptor fields, is calculated by repeating the stimulus and moving a single electrode to a new location in an area of cortex for each new presentation, or by fixing the electrode and moving the stimulus. These methods also give time ensemble averages, because the spatial patterns are derived by combining traces recorded at different times.

The use of time ensemble averaging is based in the concept of additive noise, which in turn derives from viewing perception as the extraction of forms from stimuli as if they were signals embedded in noise. Brains have no mechanisms for calculating time ensemble averages, though they are very good at getting spatial ensemble averages. The implication is that the knowledge about brain function that is acquired by time ensemble averaging may deeply distort the modeling that is derived from these data, because they produce artificial structures of neural activity that do not exist in brains.

Perception as an Active Process

In active perception the process begins not with the arrival of a stimulus at a receptor array, but with the emergence of a pattern of expectancy within the brain. The presence of a state of arousal and directed attention is one condition that distinguishes perception from sensation. It is not necessary or even desirable to postulate conscious experience or awareness as a basis for active perception. For example, in the study of conditioned reflexes an observer does not need to know, and with animals cannot know, whether the subjects are aware of the stimulus, only whether a contingent response occurs in conjunction with patterns of neural activity in the brain that are accessible to observation. Two implicit requirements for studies of perception by conditioning are (1) that a human or animal subject be trained to adopt what is called a desired "set", which is an orientation toward the conditions of the experiments, and (2) that the subject be adequately aroused (motivated) by use of appropriate punishments or rewards.

The philosophical foundation for this point of view stems from Aristotle, who distinguished two kinds of action. One is transitive, which consists of directing the body into the world, probing, cutting, burning and manipulating objects. Through these actions the world impacts on the sensory receptors, causing sensations that have not only been evoked by the transitive actions but actively sought and elicited by those actions. The other kind of action is intransitive, by which the sensations are constituted into knowledge. The medieval philosopher St. Thomas Aquinas (1988) synthesized this approach into his doctrine of intentionality, by which the self thrusts the body into the world (the Latin verb "intendere" means "to stretch forth") in search of stimuli, and by which the self changes itself to conform to the impact of the world. This process of learning he called "assimilation" ("adaequatio", which has given us the adjective "adequate", meaning close enough but not ideal), which meant to make the self into a likeness, not to include or incorporate an object from outside into the self. An example would be to shape one's hands into a hollow sphere so as to enclose and understand the shape of a ball, without bringing that spherical form into the hands or the brain. This conception is in opposition to the idea that information comes into the brain from objects in the world.

Several schools of thought have formulated this doctrine in modern terms. Piaget (1930) in studies of development in human infants and children found that the process of perception begins just after birth in the somatomotor phase, in which infants dynamically use their limbs to explore and assimilate to their worlds, learning how their movements impact on their sensations through visual, auditory and proprioceptive

feedback. In ecological psychology derived by J. J. Gibson (1979) from Gestalt psychology, the definition of an object is by its "affordance", that is, the information that it presents about how it can be used by an active perceiver. A chair is for sitting; chocolate is for eating; and so on. In terms of situated cognition the subject maintains a cognitive map of the world (Tolman, 1948),, which is a collection of internal representations that govern the search for external representations of objects, as they present themselves to the observer. In the study of embodied robotics (Clark, 1996) the devices are designed to explore their environments through their own locomotion, and to learn through their own actions by modifying their internal connections. The basis for future movements is not a map in the sense of cognitivists' use of the term. It is a collection of specifications on which direction to take from each point in the field of action that has been established by prior exploration (Hendriks-Jansen, 1996).

In neurobiological terms the Thomist process of assimilation begins with an act of exploration. The site or sites of origin of the exploratory act appear to lie in the components of the forebrain that comprise the limbic system. This system maintains self-organizing dynamics that generate goal-directed behaviors, which are commonly described as motivated, emotional, and intentional. It maintains the state of arousal and attention that characterizes exploratory actions. Under these conditions an alert subject anticipates the arrival of some form of stimulus, though the precise form usually is not and need not be predicted.

The neural basis for expectancy can be described as a set of attractor landscapes (Haken, 1983), that are maintained by the primary sensory cortices (Freeman, 1992). The limbic system appears to act onto the primary sensory cortices by modulating the attractor landscapes, so as to enhance selected basins of attraction. The selection process is called refference, because the initiation of exploratory behavior such as sniffing, orienting, or searching by movement of the head, eyes and ears is accompanied by corollary discharges that guide the sensory cortices to those classes of stimuli that are being sought (Freeman, 1995; Kay, Freeman and Lancaster, 1996).

The Neural Basis for Assimilation

The attractors are preferred modes of global activity, which are expressed in spatial patterns of amplitude modulation (AM) of an oscillatory wave form that is shared over the extent of each primary sensory cortex. The AM pattern of each attractor is shaped by the

multitudinous synapses between cortical neurons that have been modified (strengthened or weakened) during previous learning (Freeman, 1975, 1995). The basin of each attractor is determined by the collection of sensory stimuli of a certain kind, that were transmitted to the cortex during the time that that kind of stimulus was learned under reinforcement. Evidence has been found that this mode of nonlinear brain dynamics holds for visual, auditory, and somatosensory cortices as well as for the olfactory bulb and cortex (Barrie, Freeman and Lenhart, 1996). Access to a basin of an attractor is by a first order phase transition, which is elicited when an input destabilizes the sensory cortex by its impact (Freeman, 1992). The newly accessed attractor then leads the cortex into the AM pattern that is its trademark.

The AM pattern is a macroscopic form of activity, that is created by the microscopic activity of the cortical neurons, and that serves as an "order parameter" to constrain or "enslave" the microscopic activity of the same neurons (see Haken, Chapter 5). Because the AM pattern is formed after the phase transition induced by a sensory stimulus of a certain class, the AM pattern was upon its initial discovery thought to "represent" the stimulus in the brain (Freeman, 1983) That turned out not to be the case, because the AM pattern was found to lack invariance with respect to a constant stimulus (Skarda and Freeman, 1987). For example, in serial discriminative conditioning, when animals were trained to respond with the same conditioned response to a succession of stimuli, the return to a previously learned stimulus resulted in a new AM pattern, not a recurrence of the old AM pattern. We concluded that the AM pattern is the physical basis for the meaning of a stimulus, in terms of the context, history, and the action toward which it directs the individual having it as an expression of the brain state (Freeman, 1991).

Active perception is assimilation, which is the process by which the active perceiver changes itself to become similar to that which is being perceived. The process begins with the microscopic activity of receptor neurons, and it culminates in the formation of macroscopic AM patterns that constitute the elements of percepts. The attractor that mediates the assimilation and generates the AM patterns forms during learning. This is seen most clearly in olfaction. During a sniff an odorant chemical attaches to a randomly selected subset from that type of receptor which has a chemical affinity for it. There are at least 1,000 types among the 100,000,000 receptors in each nostril, but only a small fraction of the roughly 100,000 receptors is selected by each sniff. The selection forms a spatial pattern in the 2-D array of receptors, which is mapped directly into the olfactory bulb without interaction among the receptors. This

input simultaneously excites a subset of the roughly 100,000 projection neurons, the mitral cells, to which the receptor axons converge. The mitral cells do interact by reciprocal excitatory synapses. If the input is accompanied by reinforcement, then according to the Hebb Rule the synapses between co-active neurons are strengthened (Freeman, 1995).

Here is the essence of assimilation in terms of neuron dynamics. A pair of mitral cells is changed by learning to fire together just as the pair of receptors fired together, but with the difference that in later sniffs that pair of mitral cells will again co-fire, even if only one of the two receptors is activated. That is generalization over equivalent stimuli. Typically each sniff excites thousands of pairs of receptors, and learning strengthens the connections among hundreds of mitral cells. On successive sniffs there is overlap of the selection from the type that is sensitive to the odorant, so as Koenderink (1988, 1993) has shown, the pair-wise activation is generalized to the formation of a Hebbian nerve cell assembly. Any selection from the members of the sensitive type activates the entire assembly, whether or not that combination of receptors in its spatial pattern was ever previously selected. The assembly by itself is insufficient to shape the entire bulbar output. Its role is to guide the entry of the entire bulb into a basin of an attractor during the first order phase transition, by which the bulb generates an AM pattern as the outcome of the sniff.

The similarity of form does not exist between an odorant chemical and an AM pattern of neural activity, because there are multiple processes that contribute to the pattern formation, including the entire past history of the individual with respect to all perceived odorants, the state of arousal mediated by brain stem neuromodulators, and the corollary discharges from the limbic system in the process of reafference that bring attention to focus. The AM pattern is not a representation of the stimulus. It is a carrier of the meaning, value and significance of the stimulus for the individual, that is created by brain dynamics. The similarity of form begins at the interface between the co-activity of receptors (contingent on the odorant) and the co-activity of mitral cells (contingent on learning). This is also an interface between the infinite world and the finite brain, and between the world's microscopic disorder and the brain's macroscopic order. The assimilation extends into the realm of action in respect to an odorant, which involves tracking it to its source, and then taking action either to find and attack prey, or to run and hide from a predator, or to approach and assimilate to a sexual partner. The self that is shaped includes all aspects of the brain and body.

These same considerations should apply to assimilation in the visual, auditory and somesthetic systems, because they have similar dynamics as manifested in the spatiotemporal patterns of their EEGs (Barrie, Freeman and Lenhart, 1996).

The Genesis of Noise and Chaos

An outstanding characteristic of normal brains is their background, basal, so-called spontaneous activity. This is a biological necessity, because neurons are not like transistors, that have their longest life sitting inactive in a box on a shelf. Neurons must continually emit pulses, or they atrophy and die. The pulse trains among arrays of neurons must be aperiodic, or else sooner or later the pulses of all the neurons would entrain, and the synchrony would be manifested in epilepsy.

The mechanism for generating the basal activity has been demonstrated in explants of neurons in tissue cultures to be excitatory interaction. About 85% of cortical neurons are excitatory, and the preponderance of their synaptic input is from other excitatory neurons, only 10% coming from neurons outside the cortex. The anatomical connection density supports the potential for positive feedback gain exceeding unity, so that each neuron has the connections to receive more than one pulse from other neurons for every pulse that it gives to them. The recurrence pathway through the thousands of neurons that each cortical neuron connects with can be modeled as a one-dimensional diffusion process (Freeman, 1975). Each neuron drives itself by positive feedback through other neurons to whatever mean firing rate that it can sustain, given the requirement that it recover from each of its pulses during its relative refractory period. At that mean rate it finds a stable point attractor. The outcome for the 2-D array of cortical neurons is a field of white noise, uniform in density, with the pulse train of each neuron uncorrelated with the pulse train of any other, and having the statistical properties of a Poisson process with a refractory period. The stability of this state is demonstrated by the trajectories of its return to the point attractor following a broad range of perturbations.

The 15% of cortical neurons that are inhibitory provide negative feedback, which is apparent in the emergence of sustained oscillations. In some isolated parts of the brain the oscillations have been observed to approach periodicity, suggesting that small domains can maintain limit cycle attractors. This is unusual. The great majority of records from the intact brain show aperiodic oscillations having power spectra with linear decrease in relation to the increase in a power of the frequency. These

oscillations have common wave forms and spectra with phase coherence over domains of cortex one or more centimeters in diameter, indicating that the spatially distributed interactions of neurons in the cortical populations give rise to a spatially coherent chaotic attractor. The basal state provided by a strange attractor in the absence of motivation or arousal provides the context from which ordered states of behavior are self-organized. It is chaos from which order emerges (Prigogine and Stengers, 1984). Its temporal patterns can be simulated with networks of ordinary differential equations (Kay, Shimoide and Freeman, 1995), but in stable states only with the introduction of low-level additive noise (Freeman, 1996; Freeman et al., 1997).

The field of noisy chaos is the foundation for perception, because the distributed interactions among cortical neurons that arise in nerve cell assemblies "enslave" the mass of cortical neurons. They lead to symmetry breaking of the white noise upon the formation of AM patterns by phase transitions. Sequential phase transitions give rise to chaotic itinerancy (Tsuda, 1991), which expresses preferred or habitual trajectories of behavior. This type of chaos is indeterministic, because it feeds on noise. The models for deterministic chaos derived from low dimensional systems, such as the Lorenz, Rössler and Chua attractors based in reaction-diffusion equations and twist-flip maps, for which the Grassberger-Procaccia and Guckenheimer algorithms have been developed to calculate embedding and correlation dimensions, are inappropriate for the analysis of non-autonomous, non-stationary, noisy brain chaos.

The mechanism for readout of cortical AM patterns facilitates the extraction of those patterns as "signals" from background "noise". Unlike the topographic mapping by which sensory input patterns are injected from receptor arrays into primary sensory cortices, the output of cortex is typically by divergent/convergent pathways (Freeman, 1992). Each projection neuron diverges its pulses to many target neurons. With convergence, each receiving neuron sums the dendritic currents triggered by neurons broadly scattered over the transmitting cortex. This is how brains do spatial ensemble averaging. No storage of traces is required.

The only activity that survives this spatial integration is that which has the same instantaneous frequency and phase over the spatial extent of the integration. The activity that has this property is the common carrier wave generated by the cortical interaction, which conveys the AM patterns. The cortical activity that is driven by the sensory receptors does not have the required spatial coherence, so it is attenuated by spatial integration. The consequence is that the raw sense data, which can be

regarded as a representation of each particular stimulus, is deleted by the brain as noise, and the self-organized AM pattern is accepted as the signal, that is, the meaning for the individual of the class of the particular stimulus.

Conclusions

The essential difference between the theories for passive versus active perception comes down to the source of the order created from disorder. In the passive view, the order is derived from a postulated "object" that exists outside the brain, so the form that is constructed within the brain is called a "representation" of the object. In the active view, the form that results from exploratory action into the world outside is constructed inside the brain by a learning process of generalization. The construct embodies the meaning of an experience with an "object", so it cannot be said to represent the object. The reason that brains must work this way is that the world is infinitely complex, whereas brains are finite state systems. The "objects" that occupy the world shared by all observers are different for every observer, and the delineation of each object on every presentation is never quite the same. This is the main lesson to be learned from the half century of failure of Artificial Intelligence to achieve its goal of simulating Biological Intelligence using rule-driven symbol manipulation. That approach fails to acknowledge and deal with the infinity of the world, which even primitive animals and small children can do by assimilation.

Noise is the substrate from which chaos emerges. Efforts to distinguish brain chaos from colored noise were based on models of low dimensional chaos that had no noise, and for this reason they failed when applied to brain dynamics. A better model for brain states and phase transitions is the laser (Haken, 1983), which more readily gives chaotic light than coherent light. Noise is essential for maintaining the health of neurons, and it provides the unstructured pre- and post-synaptic co-activity that is required to form new attractors with Hebbian learning, instead of merely reinforcing existing attractors. When noise is regarded as unclean and undesirable, the natural recourse is to attenuate it by smoothing, particularly by use of time ensemble averaging over trials. Brains cannot do this. This is ironic, because in the spatial ensemble averaging that brains can do, that which is saved is the endogenous component that has the common temporal frequency over a neural population, whereas the stimulus-locked activity that is not spatially coherent is washed away. The irony is that the neurobiologists who use time ensemble averaging remove what the brain keeps for its use, while they save and study what

the brain removes as trash. The patterns that are extracted by time ensemble averaging do not and cannot exist in brains, and the forms of the averages can mislead us in our attempts to learn how cortex functions.

Acknowledgement

This work was supported by grants from the National Institute of Mental Health, and from the Office of Naval Research.

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