

Chapter 2

Binding Problem of Consciousness

This chapter describes several candidate mechanisms that might explain the binding of distributed macroscopic patterns of neuronal activities into a coherent whole. According to current findings, this problem is still unresolved and represents a fundamental problem in neuroscience related to brain coding and integration of distributed neural activities during processes related to perception, cognition, and memory (the “binding problem”). The theory of feature binding originated in the concept of distributed coding and states that neurons involved in the processing of a single object will tend to synchronize firing. This neural activity occurs synchronously across brain regions and likely underlies the integration of diverse brain activities. Together, these findings indicate that the solution to the binding problem may lie in the fundamental problem of consciousness in modern neuroscience. The predominant opinion is that consciousness emerges from a dynamical nucleus of persisting reverberation and interactions of neural groups. Other approaches to the binding problem include nonconventional hypotheses related to various physical theories, such as the complexity theory and the chaos theory.

According to a recent growing body of evidence, the neural correlate of consciousness is related to the processing of distributed information that is represented by integration through levels of neural synchronization among multiple brain regions, which is in turn related to large-scale integration, or “binding.” A seminal contribution to discussions about mechanisms of large-scale integration was made by Crick and Koch (1992, 2003), who proposed that the problem of binding cannot simply be resolved as a simple consequence of synchronization among large groups of neurons. As a basis for this opinion they emphasize the binding problem of distributed information represented by different modalities (such as form, motion, color, smell, sound). Processing information related to the perceived object produces synchronous activities in separate areas of the brain, but there is no evidence of the spatial convergence in the brain that would represent the neural correlate of consciousness. The hypothetical center for information convergence was termed “Cartesian theater” (Crick and Koch 1992; Dennett 1991), but recent neuroscience has not located a distinct place in which information distributed in the brain comes together. Recent findings suggest that a candidate mechanism for the integration

or binding of distributed brain activities might be the “gamma activity” (most frequently high-frequency oscillations of about 40 Hz). Although there is growing evidence that EEG gamma waves enable different neuronal circuits to enter into synchrony with the perceptual information and oscillate together during transient periods of synchronized firing, there is no explanation of what mechanism is behind this synchronization and information convergence, integrating various percepts, memories, and associations. From this point of view the phenomenon of synchronization and functional integration presents evidence that information convergence is successfully achieved, but what is behind this process of synchronization remains a puzzle.

As already stated above, a solution to the binding problem may be found within the fundamental problem of consciousness. For example, Tononi and Edelman (2000) emphasize that consciousness is the re-entry of neural signals via changes in complexity and entropy in the central nervous system. Libet (1998) suggests that subjective experience might represent a field emerging from neural synchronization and coherence, and is not reducible to any physical process (see also John 2002). In accordance with Libet, Squires (1998) maintains that consciousness can be understood to be a primitive (irreducible) component of the world, and includes specific qualities of subjective experience (*qualia*) that cannot be reduced to any other physical quality (see also Duch 2005; John 2002). According to Freeman (1991, 2000, 2001), the image of the world that we have emerges as a consequence of creating order from nonlinear chaotic activity of large groups of neurons. These nonlinear chaotic processes represent a consequence of high system complexity, when the system involves a large number of complex interlinked and simultaneously active neural assemblies and runs in a desynchronized mode of parallel distribution that can lead to self-organization (Freeman 1991, 2000, 2001; Velazquez et al. 2003) and typical dynamical instabilities in mental phenomena (Atmanspacher and Fach 2005).

2.1 Consciousness and Complexity

Detailed studies on the mechanism of consciousness, binding mechanism, and complexity were reported by Tononi and Edelman (1998) and in later studies by Sporns et al. (2000, 2002). In contrast to conventional approaches to understanding consciousness, which are generally concerned with the contribution of specific brain areas or groups of neurons, Tononi and Edelman (1998) instead found out what kinds of neural processes represent the key properties of conscious experience. They applied measures of neural integration and complexity, and proposed the dynamic core hypothesis with regard to the properties of the neural substrate of consciousness. In agreement with the usual evidence, Tononi and Edelman (1998) postulated that conscious experience is integrated (i.e., each conscious scene is unified) but also highly differentiated by a huge number of differently experienced states of consciousness. They provided tools for the measurement of integration linked to functional clustering and differentiation representing neural complexity, which can be applied to actual neural processes.

Tononi and Edelman (1998) also proposed that consciousness is not a thing, but a process or changing stream on a time scale of fractions of seconds. In agreement with William James (1890), they emphasized that a fundamental aspect of consciousness is an integrated state, although at the same time there is evidence that distributed neural activity, particularly in the thalamocortical system, is essential for conscious experience (Edelman 1989; Picton and Stuss 1994; Newman 1995). Therefore, it is possible to suppose that interactions among neuronal assemblies in distributed brain areas might create a unified neural process corresponding to a multimodal conscious scene (Edelman 1989). In this context, Tononi and Edelman (1998) suggested that a key neural mechanism underlying conscious experience might be represented by interactions between posterior thalamocortical areas, which are involved in perceptual categorization, and anterior thalamocortical areas, which are related to memory processing and action planning. Furthermore, Tononi and Edelman (1998) suggested that such rapid interactions might be achieved through the process of re-entry, i.e., the ongoing, recursive, highly parallel signaling within and among brain areas. Using large-scale computer simulations, they showed that re-entry can achieve dynamical integration or “binding” of distributed and functionally specialized neuronal groups in a unified neural process without a single place – “Cartesian theater” (Tononi et al. 1992; Lumer et al. 1997; Tononi and Edelman 1998). In agreement with this current evidence changes in conscious experience driven by external stimuli, memories, mental images or dreams are also related to changes in the activity or deactivation of specific, widely distributed brain areas (Roland 1993; Frackowiak 1997; Tononi and Edelman 1998).

Some modeling studies suggest that a specific sign of effective re-entrant interactions might be short-term temporal correlations between the neuronal groups involved (Tononi and Edelman 1998). Other studies indicate that various kinds of cognitive tasks are related to short-term temporal correlations among distributed populations of neurons in the thalamocortical system (Bressler 1995; Tononi and Edelman 1998). In addition, reported magnetoencephalographic study of binocular rivalry indicates that awareness of a stimulus is related to increased coherence among distant brain regions (Tononi et al. 1998a). This condition of fast, strong, and distributed neural interactions related to binding may explain why feeble, degraded, or short-lasting stimuli are often not consciously perceived, even though they may produce a behavioral response, such as perception, without awareness (Marcel 1983; Merikle et al. 2001).

Tononi and Edelman (1998) applied methods of functional clustering and found that a subset of distributed elements within a system gives rise to a single, integrated process in cases where these elements interact significantly more strongly among themselves than with the other parts of the system. This interaction means that they form a functional cluster that can be measured by mutual information as a level of integration (Tononi et al. 1998b). When the level of integration calculated among all neurons within the subsystem is higher than the level of integration that the same neurons of this subsystem have with neurons outside of the subsystem, then the subsystem presents the functional cluster (Papoulis 1991; Tononi and Edelman 1998). For example, it is possible to compare levels of synchronous firing among cortical regions and between the cortex and thalamus (Tononi et al. 1992; Lumer

et al. 1997; Tononi and Edelman 1998). Functional clustering also enables system complexity to be defined as a number of its parts (i.e., number of clusters) that have a higher level of integration within the subsystem than a level of integration that neurons within this subsystem have with neurons outside of the subsystem. In this context, high values of complexity reflect the coexistence of a high degree of functional integration, which form the “dynamic core” within a system (Tononi and Edelman 1998).

This concept of complexity can be applied to neurophysiological data and enables the degree to which neural processes are integrated and/or differentiated to be evaluated (Friston et al. 1995). It is also possible to compare the values of neural complexity in different cognitive and arousal states or empirically test the relationships between brain complexity and levels of conscious experience (Tononi and Edelman 1998). Because consciousness is related to a high level of functional interaction among neurons, it is possible to predict that the complexity of the dynamic core might correlate with the conscious state of the subject. For example, neural complexity is likely to be higher during waking and REM sleep than during the deep stages of slow-wave sleep, and it is possible to expect that complexity might be extremely low during generalized epileptic seizures (Tononi and Edelman 1998).

In this context, the concept of complexity provides a very useful and promising tool for consciousness research that might be of significant assistance in finding a scientific explanation for the specific biophysical processes related to the dynamic integration of large-scale information processing in the brain.

2.2 Mechanisms of Consciousness and Chaos Theory

The concept of dynamical chaos was first developed by the French mathematician, Henri Poincaré (1854–1912), who studied predictability in system behavior and found that chaotic pseudo-randomness is caused by high system sensitivity leading to disproportionate changes as a response to stimuli that influence system behavior (Poincaré 1908/1998; Peterson 1993). As a consequence, the sensitivity significantly decreases the ability to predict system behavior, which leads to information loss about later system development. In his work *Science and method* (p. 68) Poincaré (1908/1998) wrote: “A very small, unnoticeable cause can determine a visible very large effect; in this case we claim that this effect is a product of random However, even if the natural laws were perfectly known, we will never be able to know the initial conditions with some approximation. If this allows us to know the future with the same approximation that is all we want. We will say that the phenomenon is foreseeable, that it is governed by laws; however this is not always the case, it is possible that very small initial differences lead to very large ones in the final state”

Although the nonlinear mathematical approach to the “chaotic phenomena” and complexity in nature has its roots in Poincaré’s work in the latter years of the nineteenth century, its application to the field of psychology and neuroscience is

relatively new. The purpose of using this method is the understanding of relatively short periods in the behavior of a system that are extremely sensitive to very small changes (the “sensitivity to initial conditions”). At critical times, this sensitivity characterizes the initiation of new trends in the system’s evolution, which may later emerge as very different macroscopic patterns of neural activity and mental processes (Elbert et al. 1994; Freeman 1983, 1991, 2000; Birbaumer et al. 1995; Kantz and Schreiber 1997; Meyer-Lindenberg et al. 2002; van Putten and Stam 2001; Faure and Korn 2001; Globus and Arpaia 1994; Korn and Faure 2003).

Several authors proposed that chaotic transitions might emerge in a wide variety of cognitive phenomena and might be linked to specific changes during the development of mental disorders, such as depression or schizophrenia (Pediaditakis 1992; Schmid 1991; Barton 1994; Gottschalk et al. 1995; Huber et al. 1999; Melancon and Joannette 2000; Korn and Faure 2003; Paulus and Braff 2003; Bob 2007; Bob et al. 2009a, 2009b), and might underlie psychological hypersensitivity to outside stimuli and the pathological processing of these stimuli.

Because of this sensitivity and unpredictability these nonlinear dynamical systems, although they might be deterministic, exhibit complex and random-like behavior. As experimental research indicates, values of the measured properties of many biological systems look random and their determinants are frequently unknown because of the high complexity of factors that influence the state of the living organism (Elbert et al. 1994; Freeman 2000; Dokoumetzidis et al. 2001; Korn and Faure 2003). The concept of randomness relies on evidence that every complex system has a large number of degrees of freedom that cannot be directly observed and manifest through the system’s fluctuations (Elbert et al. 1994; Dokoumetzidis et al. 2001; Freeman 1991, 2000, 2001). Recent research shows that the chaotic, deterministic, dynamical systems display random-like behavior that is often indistinguishable from truly random processes (Elbert et al. 1994; Dokoumetzidis et al. 2001). However, there is evidence that chaotic dynamics tends to produce a spontaneous order and patterns of organization – self-organization (Elbert et al. 1994; Freeman 2001; Dokoumetzidis et al. 2001; Korn and Faure 2003). The self-organization patterns are typically linked to states of instability, which may result in new modes of behavior. The sudden phase transitions, called bifurcations, present a typical form of a system’s behavior that is deterministic and characterized by typical modes of behavior called the “attractor.” The attractor represents typical states of the system that describe its behavior, which is not random, and therefore it is compressed to a limited subset of all possible states in the “state space” (all the possible states that a system could have in principle) (Elbert et al. 1994; Freeman 2001; Dokoumetzidis et al. 2001). On the other hand, a random system has no restriction on its behavior (“it is random”) and there is no limitation to its behavior in the “state space.”

In this sense, it is possible to use the term state space for various phenomena, from the position of a particle to states of the human mind (in many cases it may be useful to perform a graphical representation of the state space). Deterministic systems are in their behavior strictly limited, and the resulting behavior, such as movement of a very small body (for example, in a gravitational field), is precisely defined and predictable, which means that under a constant condition (of gravitation) the

body falls and then does not move. The behavior of such a system is strictly limited and defined in time and space (which together define the state space of the body). In this context, the state space can be visualized as a state space diagram, in which every possible state of the system corresponds to a unique point in the space. The number of dimensions or parameters of this space represents the degree of freedom of the system, and every dimension can be represented as an axis. Of course, in cases of complex behavior, it is difficult or impossible to imagine the state space, similar to the way in which we cannot imagine a cube or sphere that has more than three dimensions. Thus, the term multidimensional space presents an analogy to usual experience, which is used for the definition of mathematical terms. For example, the state space (which includes spatial and temporal dimensions) of the mechanical system can be described by all possible values of position and momentum or in the thermodynamic states or the phases of a chemical system, which may be described as a function of pressure, temperature or composition (Elbert et al. 1994; Dokoumetzidis et al. 2001).

What is specific to dynamical and chaotic systems is that they have limited behavior and a limited space of occurrence in the state space, similar to other deterministic systems, but their behavior has limited predictability, or rather it is unpredictable in space and time. A specific form of behavior of the chaotic system defined by the attractor includes the spatial and temporal dimensions of all its possible states in the past and future, which can be described as a “geometrical object” in the state space. In other words, this means that the dynamic and chaotic systems are neither deterministic nor random. Scientific description of a complex macrosystem, such as a living organism, may be defined by various complex “state functions,” such as temperature, blood pressure, blood flow or electrical activity, for example, EEG, ECG, electrodermal activity (EDA), and other physiological, behavioral or cognitive characteristics (Freeman 1991, 2000; Elbert et al. 1994; Globus and Arpaia 1994; Gottschalk et al. 1995; Huber et al. 1999; Melancon and Joannette 2000; Faure and Korn 2001; Meyer-Lindenberg et al. 2002; Korn and Faure 2003; Paulus and Braff 2003; Breakspear 2006; Bob 2007; Bob et al. 2009a, 2009b).

Seminal contributions to this field of research were made by Walter Freeman, who was particularly interested in exploring how the brain generates cognitive processing, intentionality, and meaning. His main body of research was focused on the EEG study of perceptual processing in rabbits. In his research, Freeman found that activity in the olfactory cortex is chaotic, and proposed that chaos might underlie the basic forms of collective neural activity in perceptual processing, including the ability to access memorized sensory patterns and learn novel sensory information (Freeman 1991, 2000, 2001; Skarda and Freeman 1987). Freeman also proposed that chaos might explain the brain’s ability to respond flexibly to the outside world and to generate novel activity patterns that are subjectively experienced as “novel” ideas, generated by unpredictable attractors that enable complex dynamic behavior of the brain and intentional behavior (Freeman 1991, 2000, 2001; Skarda and Freeman 1987). In this context, chaos theory enables understanding of the collective neural activity and brain functions as a global integrative process based on dynamic collections of attractors. These form an “attractor landscape” that is generated in the

web of synaptic connections and represent behavioral “intentional” patterns that can be modified by learning (Skarda and Freeman 1987; Freeman 2000).

Within this framework Freeman (1999) proposed that the linear view of the stimulus–response reflex determinism is not an appropriate concept for behavioral dynamics and suggested that it might be needed to study behavioral responses and intentional behavior as consequences of nonlinear chains of various stimuli and responses. Freeman (1999, 2000) also suggested that the chaotic and complex self-organization of multilevel interactions between microscopic neurons in assemblies and the macroscopic emergent states is not possible within the concept of “linear causality,” and must be replaced by “circular causality” (or reciprocal causality), which enables reflection upon the extensive relations among mutual dependencies, actions, and influences. Although the neurophysiological basis of these integrative processes is only partially understood, the concept of circular causality as a formal semantic description of brain dynamics related to chaotic self-organization and multimodal macroscopic patterns of neural activations may help to explain some of the functions of consciousness and intentional actions.

References

- Atmanspacher H, Fach W. Acategoryality as mental instability. *J Mind Behav.* 2005;26:181–205.
- Barton S. Chaos, self-organization, and psychology. *Am Psychol.* 1994;49:5–14.
- Birbaumer N, Flor H, Lutzenberger W, Elbert T. Chaos and order in the human brain. *Electroencephalogr Clin Neurophysiol Suppl.* 1995;44:450–9.
- Bob P. Hypnotic abreaction releases chaotic patterns of electrodermal activity during dissociation. *Int J Clin Exp Hypn.* 2007;55:435–56.
- Bob P, Susta M, Gregusova A, Jasova D. Dissociation, cognitive conflict and nonlinear patterns of heart rate dynamics in patients with unipolar depression. *Prog Neuropsychopharmacol Biol Psychiatry.* 2009a;33:141–5.
- Bob P, Susta M, Chladek J, Glaslova K, Palus M. Chaos in schizophrenia associations, reality or metaphor? *Int J Psychophysiol.* 2009b;73:179–85.
- Breakspear M. The nonlinear theory of schizophrenia. *Aust N Z J Psychiatry.* 2006;40:20–35.
- Bressler SL. Large-scale cortical networks and cognition. *Brain Res Rev.* 1995;20:288–304.
- Crick F, Koch C. The problem of consciousness. *Sci Am.* 1992;267(3):153–9.
- Crick F, Koch C. A framework for consciousness. *Nat Neurosci.* 2003;6:119–26.
- Dennett D. *Consciousness explained.* Boston: Little, Brown; 1991.
- Dokoumetzidis A, Iliadin A, Macheras P. Nonlinear dynamics and chaos theory: Concepts and applications relevant to pharmacodynamics. *Pharmacol Res.* 2001;18:415–26.
- Duch W. Brain-inspired conscious computing architecture. *J Mind Behav.* 2005;26:1–21.
- Edelman G. *The remembered present.* New York: Basic Books; 1989.
- Elbert T, Ray WJ, Kowalik ZJ, Skinner JE, Graf KE, Birbaumer N. Chaos and physiology: deterministic chaos in excitable cell assemblies. *Physiol Rev.* 1994;74:1–47.
- Faure P, Korn H. Is there chaos in the brain? I. Concepts of nonlinear dynamics and methods of investigation. *C R Acad Sci III.* 2001;324:773–93.
- Frackowiak RSJ. *Human brain function.* San Diego, CA: Academic Press; 1997.
- Freeman WJ. The physiological basis of mental images. *Biol Psychiatry.* 1983;18:1007–25.
- Freeman WJ. The physiology of perception. *Sci Am.* 1991;264:78–85.
- Freeman WJ. Consciousness, intentionality, and causality. *J Conscious Stud.* 1999;6:143–72.

- Freeman WJ. Mesoscopes neurodynamics: from neuron to brain. *J Physiol Paris*. 2000;94:303–22.
- Freeman WJ. Biocomplexity: adaptive behavior in complex stochastic dynamical systems. *Biosystems*. 2001;59:109–23.
- Friston KJ, Tononi G, Sporns O, Edelman GM. Characterising the complexity of neuronal interactions. *Hum Brain Mapp*. 1995;3:302–14.
- Globus GC, Arpaia JP. Psychiatry and the new dynamics. *Biol Psychiatry*. 1994;32:352–64.
- Gottschalk AM, Bauer MS, Whybrow PC. Evidence of chaotic mood variation in bipolar disorder. *Arch Gen Psychiatry*. 1995;52:947–59.
- Huber MT, Braun HA, Krieg JC. Consequences of deterministic and random dynamics for the course of affective disorders. *Biol Psychiatry*. 1999;46:256–62.
- James W. The principles of psychology. New York: Holt; 1890.
- John ER. The neurophysics of consciousness. *Brain Res Rev*. 2002;39:1–28.
- Kantz H, Schreiber T. Nonlinear time series analysis. Cambridge: Cambridge University Press; 1997.
- Korn H, Faure P. Is there chaos in the brain? II. Experimental evidence and related models. *C R Biol*. 2003;326:787–840.
- Libet B. Do the models offer testable proposals of brain functions for conscious experience. In: Jasper HH, Descarries L, Costelucci VC, Rossignol S, editors. *Advances in neurology: consciousness at the frontiers of neuroscience*. Philadelphia: Lippincott-Raven; 1998. p. 213–17.
- Lumer ED, Edelman GM, Tononi G. Neural dynamics in a model of the thalamocortical system. I. Layers, loops and the emergence of fast synchronous rhythms. *Cereb Cortex*. 1997;7:207–27.
- Marcel AJ. Conscious and unconscious perception: an approach to the relations between phenomenal experience and perceptual processes. *Cogn Psychol*. 1983;15:238–300.
- Melancon G, Joannette Y. Chaos, brain and cognition: toward a nonlinear order? *Brain Cogn*. 2000;42:33–6.
- Merikle PM, Smilek D, Eastwood JD. Perception without awareness: perspectives from cognitive psychology. *Cognition*. 2001;79:115–34.
- Meyer-Lindenberg A, Zeman U, Hajak G, Cohen L, Berman KF. Transitions between dynamical states of differing stability in the human brain. *Proc Natl Acad Sci USA*. 2002;99:10948–53.
- Newman J. Thalamic contributions to attention and consciousness. *Conscious Cogn*. 1995;4:172–93.
- Papoulis A. Probability, random variables, and stochastic processes. New York: McGraw-Hill; 1991.
- Paulus MP, Braff DL. Chaos and Schizophrenia: does the method fit the madness? *Biol Psychiatry*. 2003;53:3–11.
- Pediaditakis N. Deterministic non-linear chaos in brain function and borderline psychopathological phenomena. *Med Hypotheses*. 1992;39:67–72.
- Peterson I. Newton's clock: Chaos in the solar system. New York: W.H. Freeman; 1993.
- Picton TW, Stuss DT. Neurobiology of conscious experience. *Curr Biol*. 1994;4:256–65.
- Poincaré H. Science and method. Londong: Thomas Nelson and Sons; 1908/1998.
- Roland PE. Brain activation. New York: Wiley-Liss; 1993.
- Schmid GB. Chaos theory and schizophrenia: elementary aspects. *Psychopathology*. 1991;24:185–98.
- Skarda CHA, Freeman WJ. How brains make chaos in order to make sense of the world. *Behav Brain Sci*. 1987;10:161–95.
- Sporns O, Tononi G, Edelman GM. Connectivity and complexity: the relationship between neuroanatomy and brain dynamics. *Neural Netw*. 2000;13:909–22.
- Sporns O, Tononi G, Edelman GM. Theoretical neuroanatomy and the connectivity of the cerebral cortex. *Behav Brain Res*. 2002;135:69–74.
- Squires EJ. Why are quantum theorists interested in consciousness. In: Hameroff SR, Kaszriak A, Scott AC, editors. *Toward a science of consciousness II: the second Tucson discussions and debates*. Cambridge: MIT Press; 1998. p. 609–18.
- Tononi G, Edelman GM. Consciousness and complexity. *Science*. 1998;282:1846–51.

- Tononi G, Edelman GM. Schizophrenia and the mechanisms of conscious integration. *Brain Res Rev.* 2000;31:391–400.
- Tononi G, Sporns O, Edelman GM. Reentry and the problem of integrating multiple cortical areas: simulation of dynamic integration in the visual system. *Cereb Cortex.* 1992;2:310–35.
- Tononi G, Edelman GM, Sporns O. Complexity and coherency: integrating information in the brain. *Trends Cogn Sci.* 1998a;2:474–84.
- Tononi G, McIntosh AR, Russell DP, Edelman GM. Functional clustering: identifying strongly interactive brain regions in neuroimaging data. *Neuroimage.* 1998b;7:133–49.
- Van Putten MJAM, Stam CJ. Is the EEG really “chaotic” in hypsarrhythmia. *IEEE Eng Med Biol Mag.* 2001;20:72–9.
- Velazquez JLP, Cortez MA, Snead III OC, Wennberg R. Dynamical regimes underlying epileptiform events: role of instabilities and bifurcations in brain activity. *Physica D.* 2003;186: 205–20.



<http://www.springer.com/978-1-4614-0435-4>

Brain, Mind and Consciousness
Advances in Neuroscience Research
Bob, P.
2011, VIII, 142 p., Hardcover
ISBN: 978-1-4614-0435-4