Andreas Steck
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Brain and Mind

Subjective Experience and Scientific Objectivity

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Foreword

I am not aware of any other book like this one. It represents a serious attempt to review the findings of contemporary neuroscience in broad brushstrokes—theoretical, empirical, and clinical—and to integrate them in a way that is both relevant and accessible to psychoanalytic psychotherapists (and other practitioners) working at the coalface of the mind–brain relationship.

By "coalface" I am referring to the *lived life* of the mind, and in particular to that aspect of it that we call mental suffering. The difficulties which bring people to psychotherapy are inevitably shaped partly by individual experiences and partly by biological universals—thus almost always by the interaction between these two. However, after the early works of Sigmund Freud which introduced such seminal concepts as libidinal drive and the Oedipus complex, and the like, psychoanalytic psychotherapists have by and large fallen woefully out of touch with developments in our understanding of the universal mechanisms that shape the mind—and therefore mental suffering.

This book seeks to redress this situation.

The authors are sensitive to the huge gulf that still separates the theoretical findings of the bench neuroscientist from the practical tasks facing the working psychotherapist, but they have sought to bridge the gap in the best possible way: via *clinical phenomena*. Also especially useful is their emphasis on development. The authors show how the new perspectives introduced by contemporary neuroscience provide practitioners with deeper understanding of the clinical and developmental problems they confront at the coalface.

I strongly recommend this book to every psychotherapist who acknowledges that there has been relevant progress in our knowledge of human biology since

Freud first published his *Three Essays on the Theory of Sexuality* more than a century ago. If you wish to acquaint yourself with this knowledge, I can think of no better place for you to start than with this book.

Mark Solms
President
South African Psychoanalytical Association

Chair of Neuropsychology
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Groot Schuur
South Africa

Preface

Our view of the human brain has been profoundly influenced by major developments in neuroscience. The goal of understanding the human brain always bears the inherent risk of biological or psychological reductionism. We present a perspective of the human mind in which personal history and subjective experiences are embedded in a framework that allows equal standing of the brain and the mind. To explain thoughts, feelings, and behavior, we have to be able to map mental representations in their full complexity. This mapping of brain structure and function is not new; today—due to the unprecedented development of technological innovations—links between physiological knowledge of the brain and features of the mind are conceivable. However, achieving a comprehensive theory of the mind and the brain is not yet within reach.

Jean-Pierre Changeux was one of the first neurobiologists to translate the basic facts of the neuronal structures and functions of the brain to the much broader scope of understanding mental functions. He advances the theory that the brain attains its adult and full pattern of connectivity by a process involving genetic and epigenetic factors. This model is at the base of our current understanding of brain plasticity—where remodeling on the one side and stabilization on the other are the two underlying functional aspects of the mind and brain throughout life—and at the root of neuronal and molecular mechanisms of learning and memory. Gerald Edelman presented a similar theory explaining the development and organization of higher brain functions based on an adaptive selection process of neuronal ontogenesis.

More recently, neuroscientists are taking advantage of the possibility to study and map large-scale neuronal networks investigating problems that were so far beyond the realm of neuroscience, such as the biological basis of consciousness. This theoretical approach—coupled with the incredible progress in neuroimaging—has revolutionized our way of considering the different stages of altered or diminished states of consciousness in clinical practice. While the centers, pathways, and neurotransmitters regulating alertness and awareness are well described and understood, fully translating what psychologists or philosophers call our conscious space or our lived mental experience in neuronal terms is still a formidable task.

The representational capacity of human memory grants us the many symbolic activities that characterize our mental lives and our many skills, including foremost language. Neuronal representations are not only widely distributed across brain regions but also depend on dynamic interactions between regions. Language—one of the most complex mental activities—is dependent on conceptual knowledge stored in vast regions of the brain, associated with sensory and motor control. Language and executive functions should not be separated but considered as part of a larger cognitive network. Language permits to communicate, exchange ideas, and establish contact with other persons. Language is related to conscious or unconscious content of the past, the present, or the future and contains shared realities and affects.

The brain does not function independently of the body, and this is especially true for emotions. There is an intense interest in understanding emotions and how they influence and affect our mental life. While the original definition of the limbic system and its boundaries laid down by James Papez and later by Paul McLean has been lately disputed, it is one of the most important parts of the brain controlling our emotions. Work on the limbic system remained for a long time in the hands of scientists studying animal behaviors like fear, aggression, and sexual arousal states. Psychiatry and neurology are increasingly looking at the role of the limbic system and its associated cortical and subcortical structures to understand behavioral and emotional disorders. Research on emotions boomed in the last two decades and has transcended the clinical and basic neuroscience fields. New models attempt to integrate neurobiological substrates to understand feelings and how we cope with fear and stress. Antonio Damasio has proposed that feedback from the body guides our behavior and eventually our decision-making abilities. Our reasoning and decision-making process is instinctive and influenced by our emotional evaluations. Rationality is always to some extent grounded in our bodies.

Jaak Panksepp, who has extensively studied neural mechanisms of emotions in animals, has joined forces with Mark Solms to lay the groundwork for a new discipline called neuropsychoanalysis. This scientific field is in fact not new, since it is what Sigmund Freud envisioned more than a century ago, when he proposed the basis of psychoanalytical theory. At this time however, neuroscience was in its infancy and could only provide limited answers to explain functional disorders of the nervous system. Neuropsychoanalysis seeks to connect psychoanalytical and neuroscientific perspectives of the mind and aims at advancing our understanding of scientific objectivity and subjective experience in mental life.

The results of infant research and the concepts of Anna Freud, Donald Winnicott, Wilfred Bion, Thomas Ogden, and many more greatly expanded the field of psychoanalytical interventions. The issue of childhood adversities in the development of mental disorder is a topic of considerable interest. Distress- and turmoil experiences of infants and young children have great impact on developmental structures and functions of the brain. Infant- and children's research show the importance of the quality of the early emotional relationship between infant and mother. Parents or primary caregivers' sensitive receptiveness to their infant and child's spontaneous expressions will shape his unique personality. Therefore, it is essential to focus

attention on the child's inner world of desires and imagination, for which psychoanalytic understanding has greatly contributed. In child and adolescent psychiatry, it is fundamental to combine individual developmental changes, neurobiological endowment, unconscious mental life, interactive dialogues, subjective experience, and personal meaning. A child's desire for exchange with his primary significant caregivers motivates the creation of mental representations, which underlie his understanding of feelings, believing, and behaviors of other persons. The evolution of these processes reveals complex interactions between constitutionally determined capacities and environmental experiences; if these exchanges are impaired, disturbances of intrapsychic, interpersonal, and social relatedness ensue. Resilience research arose from an effort to better protect children, adolescents, and young adults of the impact of adverse life experiences. Critical life events find expression in sensations of pain, in coping- and grieving processes; they are always related to the subjective perception of an individual in the context of his biography.

Psychoanalytic psychotherapy is a treatment method intending to meet the needs of patients with mental health problems and patients with neurological or other somatic disorders. Psychoanalytic therapy tries to gain access to the subjective experience and personal meaning of a patient in his pain. Thanks to neuroscientific research, a lot has been learned about the important differences between various types of memories. Patients undergoing psychoanalytical treatment very often suffered traumatic experience in their personal history. The discovery of the different memory encodings has contributed to explain why some patients are unable to remember traumatic events; they were not explicitly encoded and therefore appear as affective memories in dreams, bodily sensations, and fantasies. The interpersonal exchange—a significant dialogue in a sustainable relationship—opens a window to the (un)conscious mental life of an individual. Especially for children suffering from developmental psychopathologies, the therapeutic aim—with respect to the anguish of the patient and his family—has to foster the child's developmental progression, helping him to experience a sense of coherence and personal continuity over time. The emergence of his self, his inner reality with feelings and fantasies, the frontier to his outer world, finally define a child's personal experience, his inner freedom, and creativity.

Neurologists, psychiatrists, psychotherapists, and psychologists are increasingly involved in neuroscientific research, creating very successful interdisciplinary fields such as affective neuroscience and neuropsychoanalysis. We are aware that there are huge gaps between neuroscience and psychotherapeutic disciplines with regard to their history and scope. But it is only the combination of clinical experiences with scientific facts that will help us better understand the brain–mind relationship. The authors' interest focuses on the complexity and interplay between neurobiological science, clinical manifestations, developmental aspects of disorders, and the individual's mind. Clinical vignettes are presented to illustrate our current understanding of the brain and mind couple as they demonstrate the complexity of a subject's mental functioning.

One major challenge dealing with various disciplines is the meaning of words and phrases that may carry different significance in interdisciplinary discussions.

There is no consistent universally agreed lexicon between disciplines. One way to escape these language formalisms is to avoid theoretical concepts that cannot be translated into every day terms. By leaving unnecessary complexities aside, this book attempts to bring a coherent picture of both the experimental and clinical neuroscientific fields. Our hope is to foster a dialogue between the different areas of the sciences of the mind and brain and to connect the interdisciplinary efforts that are needed to better help those who suffer from mental health- or neurological disorders.

Epalinges and Evolène, Switzerland

Andreas Steck
Barbara Steck

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Barbara Steck expresses her sincere gratitude to all patients who shared their personal experiences with her. Thanks to their confidence and responsiveness they allowed her to gain insight in their individual biographical history and their emotional life.

For simplification and readability we use mostly the male form. All names of the clinical vignettes have been changed.

About the authors

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Part I

Chapter 1
Consciousness

The Problem of Consciousness

Historically, consciousness was defined by the English philosopher John Locke (1690, 1997) as "the perception of what passes in a man's own mind." The French philosopher René Descartes (1644, 1911) identified the mind with consciousness and, in his proposition of dualism, argued that the mind is independent from the body. René Descartes used the term "conscientia," which in modern terms means conscience or primarily moral conscience.[1] While for philosophers of mind the question of whether consciousness can be understood in a way that does not require a dualistic distinction between mental and physical entities remains an issue, the monist solution to the mind–brain problem, calling to an end of the division between mind and body, has come from the field of natural sciences, biology, and medicine.

For a long time, consciousness was a research topic avoided by most neuroscientists, because the experimental tools allowing exploration of a phenomenon that is classically defined in subjective terms were lacking. In the 1980s, an expanding community of neuroscientists began to address the question of consciousness giving rise to a stream of much acclaimed lay books[2] such as *Neuronal Man* by Jean-Pierre Changeux (1983), *The Remembered Present* by Gerald Edelman (1989), and *Descartes' Error* by Antonio Damasio (1995). In parallel, a considerable amount of

[1] John Locke (1632–1704) was interested in psychology and addressed topics such as the formation of self and consciousness. René Descartes (1596–1650) famously known for his statement "I think, therefore I am" shaped the philosophical discussion of the mind–body problem up to modern times.

[2] Jean-Pierre Changeux is a French neuroscientist who together with Dehaene is investigating the neuronal basis of cognitive functions. In his book *Neuronal Man* (*L'homme neuronal*), he proposes an elegant dialogue between the biological brain and the mind. Gerald Edelman is an American biologist (1929–2014) who turned late in his career to neuroscience. Influenced by his early work on the immune system, his model of the conscious brain is based on developmental selection. In a thoughtful book, *The Remembered Present,* he proposes an original biological theory of consciousnesses. Antonio Damasio is a neurologist who studies behavior, in particular emotions. In *Descartes' Error,* he calls for an end to the division between mind and body and contends that even our most rational decisions are rooted in emotions and feelings.

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new experimental work on consciousness was and is being published by neuroscientists, psychologists, neurologists, and psychiatrists in specialized journals.

More recently, neurologists have begun to look at the problem of consciousness by studying disorders of consciousness in patients with brain damage and disease states leading to an altered level of consciousness, using brain-imaging techniques such as functional magnetic resonance imaging (Owen 2008). With the development of the field of neuropsychoanalysis, the traditional matter of psychoanalysis, such as the unconscious, implicit processing, the self, and free will, is being reanalyzed, and attempts are being made to integrate psychoanalytical concepts with modern neuroscience (Solms and Turnbull 2002).

Neurobiology of Consciousness

Among the brain's properties, the most fundamental is the generation of consciousness. Consciousness can be viewed as an emerging property of the brain and as such is certainly one of the most complex biological phenomena.

The current conception that "consciousness is entirely caused by neurobiological processes and realized in brain structures" (Dehaene and Changeux 2004) is widely shared by neuroscientists. Combining cognitive, neuroanatomical, neurophysiological, neuroimaging, and neurobiological methods, modern studies of consciousness describe its cognitive nature, its behavioral correlates, its possible evolutionary origin, and its functional role. By taking into account the many levels of organization on which the nervous system can be studied, from molecules to synapses, from neurons to local circuits, and from large-scale networks to the hierarchy of mental representations they support, neuroscientific research avoided the error to reduce consciousness to a low level of neural organization. While most models attempt to identify the neuronal base of consciousness, a complete theory will require new insights to explain how the neural events organize into larger-scale active circuits, how the circuits themselves carry specific representations and forms of information processing, and how these processes are ultimately associated with conscious reports. Hence, a cognitive neuroscientific approach to consciousness has to address both the architecture of mental representations and their neural implementation (Dehaene and Changeux 2011). A theory of consciousness should explain why some cognitive and cerebral representations are permanently or temporarily inaccessible to consciousness, the range of possible conscious contents, how they map to specific cerebral circuits, and whether a generic neuronal mechanism underlies them all.

A satisfactory scientific theory of consciousness is still beyond reach. However, different models relying on detailed biological, physiological, or clinical premises have been proposed. The models of consciousness presented here are part of the effort by neuroscientists to address an issue that until recently was considered beyond the scope of neuroscientific research. Inherent to all the proposed models

is a degree of abstraction as well as a subjective experience, which might frustrate some readers. It is clear that at present, no single model of consciousness appears sufficient to account fully for the multidimensional properties of conscious experience, and although some of the models have gained prominence, none has been accepted as definitive. However, even without a general model of consciousness, our current understanding of how the brain works and how psychiatric or neurological disorders affect brain functions allows us to access and understand how we become conscious.

Models of Consciousness

The Global Workspace Model

Changeux and Dehaene have proposed a theoretical framework for the understanding of conscious phenomena: in this model, neuronal networks link through "bridging laws" molecular, neuronal, behavioral, and subjective representations into a coherent form (Dehaene et al. 1998; Dehaene and Naccache 2001). Their theory can be best explained by studying the issue of conscious access. When a piece of information becomes conscious, it is broadly available for multiple processes including action planning and voluntary redirection of attention and memory. This cognitive model emphasizes reportability as a key property of conscious representations, and a mental state is considered conscious when it is verbally reportable or internally accessible.

Yet we should not forget that our brain constantly works unconsciously. Automatic or unconscious cognitive processing is determined by multiple dedicated processors or modules (Baars 1988). Basically these modules are specialized neural circuits that process specific types of inputs. They include, for example, orientation-selective cortical columns in the visual system or the special purpose devices recognizing phonemes in sensory speech areas. These brain circuits are organized into functionally specialized unconsciously operating subsystems and form the basis of the so-called automated modularity of brain functioning.

A given process involving several mental operations can proceed unconsciously if a set of adequately interconnected modular systems is available to perform each of the required operations. For instance, a masked fearful face may cause unconscious emotional priming,[3] due to dedicated neural systems in the superior colliculus, pulvinar, and right amygdala associated with emotional valence to faces (Morris et al. 1998). Multiple unconscious operations can proceed in parallel so uncon-

[3] Priming is a term used by psychologists to characterize an implicit memory effect in which exposure to one stimulus affects the response to another stimulus.

scious processing is not limited to low-level or computationally simple operations. High-level processes may also operate unconsciously as long as they are associated with functional neural pathways established by evolution, laid down during development, or automatized by learning. For instance, motor skills used by athletes or musicians, word and sentence reading, and postural and balance control all require complex computations, yet there is considerable evidence that they can proceed automatically, nonconsciously, using specialized neural subsystems. This has been particularly well studied in musicians where experimental evidence (Zatorre et al. 1998; Schneider et al. 2002) provides strong links between specialized skills and particular brain structures.

On the other hand, the human brain must function clearly beyond automated modularity; otherwise we would be lost in a chaotic and uncontrolled state of mind. Our brain can flexibly and seemingly effortlessly recombine all these specialized tasks: once we are conscious of an item, such as a sentence we read in a book, we can readily perform a large variety of operations, including evaluation, memorization, and verbal report.

A modular view of the brain (Fodor 1983) is clearly not sufficient to account for the unified character of our conscious mental state. Baars (1988) proposed one of the first neurobiological models of consciousness that tries to fill this gap. Baars and Franklin (2007) described a "conscious access hypothesis" in a framework called "global workspace" (Fig. 1.1). This theory was conceived mainly from a cognitive psychological point of view and at first had little impact because the evidence was indirect and did not rely on anatomical or physiological bases. However, later developments in neuroimaging techniques broadly support his hypothesis.

The "Global Workspace" theory hypothesizes that a number of brain components constitute an integrative workspace that serves to reconcile the narrow momentary capacity of conscious contents by a widespread recruitment of unconscious brain functions, including long-term memory. Baars (1988), however, did not specify how the psychological construct of the conscious workspace was implemented in terms of neuronal networks. Different groups (Dehaene and Naccache 2001; Edelman and Tononi 2000; Edelman et al. 2011; Damasio 2010) have now integrated the theoretical framework into a neurobiological theory.

During decision making or discourse production, a subject brings to mind information conveyed from many different sources in a seemingly non-modular fashion. Furthermore, during the performance of a particularly difficult task, there is temporary automatic inhibition of some functions, allowing entry in a strategic or "controlled" mode of processing (Posner and Petersen 1990; Shallice et al. 2008). In order to establish a neurocomputational model of consciousness, it became clear that one had to postulate a distinct functional architecture, which goes beyond modularity and establishes flexible links among existing individual processors.

In recent years, the global workspace model has taken on an anatomical form (Dehaene and Changeux 2011). It emphasizes the role of groups of neurons with long-distance connections, particularly dense in prefrontal, cingulate, and parietal regions that are capable of interconnecting multiple specialized processors and broadcasting signals on a large scale in a spontaneous and sudden manner (Fig. 1.2).

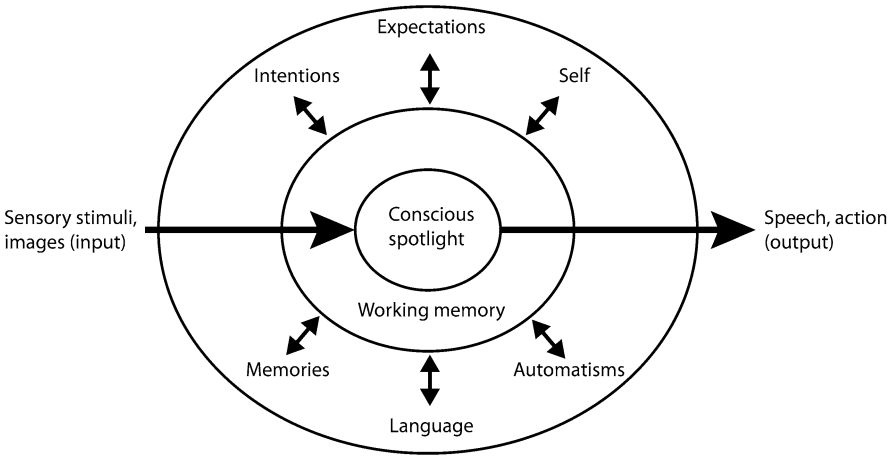

Fig. 1.1 The global workspace. The global workspace theory of Baars consists of a cognitive architecture and is based on the principle that conscious brain events evoke widespread cortical activity. Conscious contents (conscious spotlight) need unconscious working specialized processors that operate in the backstage and compete with each other to gain access to the workspace (working memory) (Adapted from Baars and Franklin 2007)

These neurons form, what was referred to by Baars, as the "conscious spotlight" (Baars 1988; Baars and Franklin 2007, Fig. 1.1). This spotlight breaks the modularity of the nervous system and allows information reporting to and from multiple neural targets. It creates a global availability that is experienced as consciousness and results in reportability. The neuronal workspace hypothesis posits that the workspace neurons are reciprocally connected via long-distance axons to many, if not all, cortical processors permitting locally available information to be brought into consciousness. These neurons may be more densely accumulated in some areas than others. Anatomically, long-range cortico-cortical tangential and callosal connections originate mostly from the pyramidal cells of layers II and III of the cortex, which give or receive the so-called association efferents and afferents. These layers are thicker in the dorsolateral prefrontal and inferior parietal cortical structures (Goldman-Rakic 1988). The high concentration of neurons with long-distance axons in these areas may explain why they frequently appear coactivated in neuroimaging studies of conscious effortful processing. This model predicts that long-distance connections have been the target of recent evolutionary pressure in the course of hominization and are particularly well developed in our species.

The relative anatomical expansion of cortical areas rich in long-axon neurons, such as the prefrontal cortex, may have contributed to important changes in the functional properties of the workspace (Dehaene and Changeux 2004). Detailed anatomical studies of transcortical connectivity in the human brain revealed the presence of distant transcortical projections, which, for instance, directly link the right fusiform gyrus to multiple areas of the left hemisphere including Broca's and Wernicke's areas

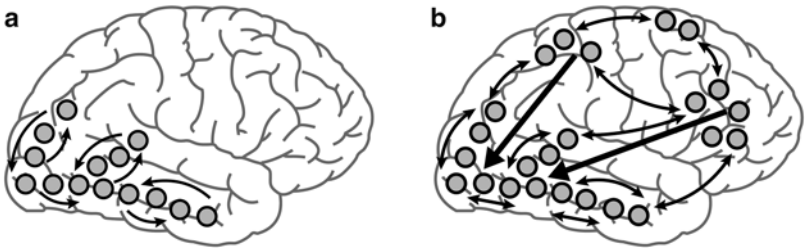

Fig. 1.2 Preconscious and conscious processing. The global workspace model proposed here takes an anatomical form. It shows that during preconscious processing (**a**) the activation pattern of the brain is confined to sensory-motor areas and does not reach higher parieto-frontal areas. During conscious processing (**b**), the parieto-frontal areas become activated. *Long arrows* illustrate top-down attention. There is a continuum of in between states that are not shown (Adapted from Dehaene et al. 2006)

(Di Virgilio and Clarke 1997). The direct connection between the inferior temporal cortex and Wernicke's and Broca's areas is part of a large network linking higher-order visual and speech areas, including largely spread intrahemispheric and interhemispheric connections. One can speculate that these key components of the verbal reportability system are connected to many cortical areas given the overwhelming role of language in naming and understanding percepts and concepts.

While this model emphasizes cortico-cortical connectivity, it should be noted that corticothalamic columns are also important processing units in the brain. According to Llinás et al. (1998), the key aspect of neuronal organization, central to global functioning, is the rich thalamocortical interconnectivity and, particularly, the reciprocal nature of the thalamocortical neuronal loops. The interaction between specific and nonspecific thalamic loops suggests that rather than a gate into the brain, the thalamus represents a hub from which any site in the cortex can communicate with any other sites. Thus, long-distance connections between thalamic nuclei are contributing to the establishment of a coherent brain-scale state. Llinás et al. (1998) propose that consciousness is more a case of intrinsic brain activity than of external sensory drive. Llinas suggests that consciousness is an oneiric-like internal functional state, modulated—rather than generated—by the senses. To illustrate, he tells the example of how, in childhood, the sound of a curtain fluttering in the dark evokes very worrying images, corresponding to an oneiric perception. However, as soon as the lights go on, the worrying images go away, pointing to the modulatory role of the senses; in this case, the visual input changes the perception. The internal events we recognize as thinking, imagining, or remembering are, for the most part, related to intrinsic activity. This concept is in accordance with the fact that a very large percentage of the connectivity in the brain is recurrent and that much of its activity is related to intrinsic connectivity, not necessarily linked to the immediacy of sensory input. The thalamocortical theory of consciousness developed by Llinas, a founding father of modern brain science, has been further developed by Edelman and Tononi (2000) into what they call the dynamic core model.

The Dynamic Core Model

The dynamic core model proposed by Edelman and Tononi (2000) and Tononi and Edelman (1998) emphasizes two basic properties of consciousness: conscious experience is integrated—each conscious scene is unified—and highly differentiated. At the same time and within a short period, we can experience a number of different conscious states. Neurobiological data indicate that neural processes associated with conscious experience are indeed highly integrated and highly differentiated. Changes in specific aspects of conscious experience correlate with changes in the activity of specific brain areas, whether the experience is driven by external stimuli, memory, or imagery and dreams. Conscious experience involves the activation or deactivation of widely distributed brain areas.

The transition between conscious controlled performance and unconscious automated performance is accompanied by a change in the degree to which neural activity is distributed within the brain. When tasks are novel, brain activation related to the task is widely distributed; when the task becomes automatic, activation is more localized. These observations suggest that when tasks are automatic and require little or no conscious control, the spread of signals influencing the performance of the task involves a more restricted and dedicated set of circuits which become "functionally insulated." This produces a gain in speed and precision but at the same time a loss in context sensitivity, accessibility, and flexibility, as Baars (1988) has suggested.

Tononi and Edelman (1998) propose that an underlying conscious experience does not extend to most of the brain but is restricted to varying subsets of neuronal groups. These neuronal groups constituting—on a time scale of hundreds of milliseconds—a unified neural process of high complexity are called the "dynamic core." By calling it the dynamic core, they mean to emphasize the function of integration (core) and the constantly changing activity pattern (dynamic). The dynamic core is a functional cluster: the participating neuronal groups are much more strongly interactive among themselves than with the rest of the brain. The dynamic core is tailored for high complexity: its global activity pattern must be selected within less than a second out of a very large repertoire. The dynamic core typically includes posterior corticothalamic regions involved in perceptual categorization, interacting with anterior regions involved in concept formation, value-related memory, and planning, although it is not necessarily restricted to the thalamocortical system. The term "dynamic core" deliberately does not refer to a unique invariant set of brain areas (such as the prefrontal or visual cortex), as the core may change in composition over time. The role of the functional interactions among distributed groups of neurons is more important than their local properties; the same group of neurons may at times be part of the dynamic core and underlie conscious experience, while at other times, they may be involved in unconscious processes. Since participation in the dynamic core depends on the rapidly shifting functional connectivity among groups of neurons rather than on anatomical proximity, the composition of the core can expand beyond anatomical limits and, in relation to particular conscious states, is expected to vary significantly. The dynamic core hypothesis

avoids the idea that certain local intrinsic properties of neurons have, in some mysterious way, privileged correlation with consciousness. Instead, this hypothesis accounts for fundamental properties of conscious experience by linking them to global properties of particular neural processes. It emphasizes the fact that the dynamic core is a process since it is characterized in terms of time-varying neural interactions. It should not be viewed as a "thing" in a particular location or a specific structure in a given anatomical site.

An important characteristic of the dynamic core is fast integration of neural activity. The selection between different integrated states must be achieved within hundreds of milliseconds, thus reflecting the time course of conscious experience. While all these criteria are in line with our subjective perception of what consciousness is about, an essential prediction for the accuracy of the hypothesis is that in cognitive activities involving consciousness, there should be evidence of a large but distinct set of distributed neuronal groups that interact much more strongly among themselves than with the rest of the brain over fractions of a second. Various electrophysiological measurements support this hypothesis showing that when separate cortical areas contribute to a particular content of consciousness, they exhibit enhanced synchrony in the gamma frequency band[4] (Engel and Singer 2001). This specific change in neuronal synchrony provides the temporal binding and thus represents the neural correlate of conscious awareness (Canolty et al. 2006). These areas and patches of synchronous activity can be widely distributed across and within the cerebral hemispheres.

Epilogue

All models describing the neural correlate of consciousness have in common the concept of a "global workspace," consisting of spatially dispersed, but interconnected neuronal groups in a widely distributed set of brain areas (Baars 1988; Edelman et al. 2011). Evidence also suggests that each separate area functions to process a distinctive feature of the overall conscious scene and that synchrony serves to "bind" these features together into an apparently seamless whole (Engel and Singer 2001). For example, it is possible to analyze the temporal distribution of neural activity generated in a subject's cortex using brain-imaging techniques, e.g., functional magnetic resonance imaging (fMRI) (Norman et al. 2006) or magnetoencephalography (MEG) (Srinivasan et al. 1999). From this information, we can deduce how mental states are represented in the brain; conscious perception of a visual stimulus is associated with a significant increase in coherence between distant cortical neuronal populations measured by MEG recordings. These data suggest that during conscious perception, there is increased synchrony among distinct and distant neuronal groups.[5]

[4] Gamma waves are fast neural oscillations around 40 Hz. They are thought to be important in determining neuronal synchrony.

[5] New techniques such as optogenetics, so far limited to animal experimentation, offer both wide spatial coverage and high temporal resolution. They are helping to establish how mental representations map onto patterns of neural activity (Deisseroth 2014).