The theory of the whole-brain-work

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Abstract

The theory of the whole-brain-work basically explains the oscillatory dynamics of the human and nonhuman brain during cognitive processing. The theory is based on principles according to which brain functions are represented by the oscillatory activity. Oscillatory activity in a given frequency band performs multiple functions since they vary on a number of response parameters. There is selective cooperation in the stimulated brain; this produces super-binding between neural populations and super-synergy in the whole brain. The concept of super-synergy thus includes super-binding and, additionally, entropy and the role of EEG-oscillations as control parameters in brain’s responsiveness. In super-synergy, spatial integration occurs through the selective cooperation of brain structures. Temporal integration occurs in line with the principle of superposition of oscillations in which the comparative polarity and phase angle are critical for forming the function-specific configurations. Extension of the theory of whole-brain-work to cognitive processing proposes that there is a constant reciprocal activation within the subprocesses of attention, perception, learning and remembering and this leads to an APLR-alliance. In such a context, all brain functions are inseparable, for instance, from memory function and, in turn, memory states have no exact boundaries along the time space; memory states thus evolve in the APLR-alliance. The theory claims that the reentry and the dynamic behavior of oscillations during the reciprocal activation in APLR-alliance are among the causal factors for brain dynamics and for cognition.

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1. Introduction

Science seeks for causes. With the exception of the conventional analysis of neural activity which uses single unit recordings, the concept of causality has somewhat been overlooked in neural sciences and the need for rules and theories have thus been overlooked. This has generally been the situation for also EEG-oscillation analysis.

In all natural sciences, the general questions and problems on the concept of causality are based on or are derived from Newtonian dynamics. According to the first law of motion in Newtonian system, “free motion” is uniform motion in a straight line. When a force is applied to a body, it causes the body to deviate from this free motion. All observed motions could be analyzed into two components: a free component (inertia) and a component due to the acting force. The second law states that the force acting on a body is always proportional to the product of its mass and acceleration. Newton (1687/1726) never regarded the word “force” just as a name for this mathematical product. However, as a natural scientist, he eschewed speculation in dealing with the nature of forces and, for scientific purposes, he thought it sufficient to calculate and observe the effects of these forces.

Furthermore, Isaac Newton (1687/1726) was interested not only in descriptions pertaining to motions of planets, but he also wanted to find the mechanism of gravitation between the planets. Likewise, Galileo Galilei did not only observe the oscillations of clocks, but he also wanted to learn about their machineries. Albert Einstein was interested in describing tracks of the molecules as in the case of Brownian motion, but he also analyzed the causes of Brownian motion. Furthermore, Einstein was searching for causes of gravitation, but he also wanted to...
understand the causes of dissipating energy. To establish what has happened in the galactic system, Einstein predicted the existence of “black holes” from not only the facts about astrophysical events, but also from a combination of accumulated data on the motion of stars and laws of physics. Einstein thus offered *descriptions and explanations* pertaining to the nature of stars and the galaxy, including those that were not visible to conventional observations, i.e. the black holes.

Due to its breadth and impact, Newtonian dynamics has become the metaphor of all natural sciences. The relevance of the prestimulus EEG as a causal factor in attention, perception, learning and remembering has important parallels with Newton’s (1687/1726) first law of motion where the state of a moving body is a causal factor for the further evolution of its movement. The application of this law to electrophysiology is the following: The state of the brain as reflected in the prestimulus EEG is the causal factor for the later brain responses.

The trajectories (EEG signals) reflecting the activity of neuronal populations can also be analyzed as somewhat similar to the analysis of motion. As the expression “brain dynamics” implies, we intend to also elucidate the causes or mechanisms that give rise to the trajectories of the electrical signals in the brain. Similar to trajectories of missiles, or trajectories in Brownian motion, EEG trajectories is already providing most useful information on neural mechanisms that give rise to different transitions. The EEG seems to serve as a fundamental trajectory that is causally related to memory building and integrative brain function. The application of the Newtonian perspective or Einstein’s approach when searching for the mechanisms behind EEG trajectories has already started.

However, recent developments on the dynamics of quantum physics and the new approach on chaos certainly brought a different understanding to the Newtonian causality. In his highly popular book on chaos, Gleick (1987), an advocate of the new science, went so far as to say: “Twentieth-century science will be remembered for just three things: relativity, quantum mechanics and chaos.” Chaos is the century’s third great revolution in the physical sciences. Like the first two revolutions, chaos cuts away at the tenets of Newtonian physics.

Can these developments be useful and have the great impact that the systems of Newton, Galilei and Einstein’s has had. The new development, “chaos in brain function”, is certainly fascinating. However, in the period of 1985–2000 during which findings on chaotic EEG were obtained, noteworthy progress was also occurring in the study of oscillatory phenomena and neural network resonance at the cellular level. Fruitful findings were also obtained upon application of the concept of entropy to brain processes (Rosso et al., 2001, 2002). The slogan, “EEG is not simple noise”, was formulated and this represented the conceptual renaissance in brain electrophysiology. Interpreting their findings, the neurophysiologists stated: “EEG is not noise, but is a quasi-deterministic signal.” All these empirically derived approaches were in fact favorable to chaotic dynamics of brain function.

Meanwhile, with a few exceptions, prediction and mathematical description of brain behavior has not been in the mainstream of brain research. Influential ideas such as those of John von Neumann and Burks (1966) may have had their share in this neglect: “...logics and mathematics in the central nervous system, when viewed as languages, must be structurally essentially different from those languages to which our common experience refers.” Therefore, the “big bang” of applying chaotic dynamics to brain activity has struck brain scientists all too early, when they were not yet prepared to use these concepts. Accordingly, studies that attempt to explain the brain through chaotic dynamics could not gain the status of a coherent research endeavor.

The present section presents a theory on brain function that basically follows Newton’s, Galilei’s and Einstein’s pathway. In this theory, the language brain uses is the brain waves. The oscillations in the different frequency bands are like the phonemes in languages. Superimposed oscillatory responses are the words. The selectively distributed parallel processing pathways are the syntagms of the brain language. And the whole-brain-work that follows the super-synergy is the sentences and the discourse in the language of the brain.

### 2. The theory of the whole-brain-work: an approach to brain function by means of EEG-oscillations

Chronological evolution of our conceptual framework evolved in the last 20–25 years. The development in the last 5 years has especially been fast. At its present state, the theory of the whole-brain-work represents the extension of the previously formulated neurons-brain theory.

#### 2.1. Basic principles

The theory assumes that functions of the brain, especially those in cognitive processing, are based on EEG and field potentials, shortly, the oscillatory activity. The theory rests on four basic principles.

**Principle 1.** Brain functions are represented by its oscillatory activity. It is to be noted that this activity is the paradigm change that Mountcastle (1998) had announced for brain sciences toward the end of the last century.

**Principle 2.** There is cooperation between distant structures of the brain and these can be measured by means of coherence and phase differences. The whole brain is activated during cognitive processing. Thus there is a super-synergy in the brain during all percept-and memory-related processes.

**Principle 3.** The cooperation between brain structures is selective. The selectivity may be demonstrated in the selective distribution of the coherence functions over various brain structures with values that vary between 0 and 1. The demonstration of the principle of selective cooperation requires the analysis of oscillations in several neural populations and in several frequency windows. Such analyses and the related findings have been instrumental in the further refinement of the concepts pertaining to “whole brain” and “cooperation”.

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Karl Lashley (1929) had concluded that the brain operates as a “whole”. Oscillations that are selectively distributed in the whole brain may be the mechanism whereby this wholistic operation is achieved. The new tools and concepts that are used in the analysis of brain electrical activity during sensory-cognitive processing may also provide new interpretations on Lashley’s (1929) and Hebb’s (1949) statements on brain functioning.

**Principle 4.** The machinery the brain uses for super-synergy consists of an ensemble of sub-mechanisms. These sub-mechanisms act in synergy when stimulated by sensory and/or cognitive input.

### 2.2. The theory in extended form: mechanisms in the whole-brain-work

The theory of the whole-brain-work proposes that integrative brain function is based on the coexistence and cooperative action of many interwoven and interacting sub-mechanisms. In its extension, the theory includes mechanisms which consist of super-synergy, superbinding and reciprocal interaction of attention, perception, learning and remembering (APLR-alliance). These mechanisms were grouped in the theory under four structural and/or functional levels.

#### 2.2.1. Level A: transition from single neurons to oscillatory dynamics of the brain

1. The neuron is the basic signaling element of the brain.
2. Since morphologically different neurons or neural networks are excitable upon sensory-cognitive stimulation, the type of the structural element does not play a major role in the frequency tuning of oscillatory networks. Research has shown that neural populations in the cerebral cortex, hippocampus or cerebellar cortex are all tuned to the very same frequency ranges (Eckhorn et al., 1988; Llinas, 1988; Singer, 1989; Steriade et al., 1990, 1992; Başar, 1998, 1999). These findings support the suggestion that all brain networks communicate by means of the same set of frequency codes of EEG-oscillations.
3. Intrinsic oscillatory activity of single neurons forms the basis of the natural frequencies of neural assemblies. Oscillatory activity of the neural assemblies or the brain consists of the gamma, beta, alpha, theta and delta frequencies. These frequencies are the natural frequencies and thus the real responses of the brain (Başar et al., 2001a,b,c).
4. Feature detectors (Sokolov, 2001), place cells and memory cells (Fuster, 1995) are empirically established constructs. However, a crucial turning point occurred with the “grandmother” experiments. These experiments showed that large groups of neural populations were selectively activated upon complex semantic and episodic inputs to the brain (Edelman, 1978; Bullock, 1992; Başar, 2004). These experiments and other similar studies replaced the neuron with the neural assemblies in attempts at describing the integrative functions of the brain (Başar et al., 2001a). The emphasis on neural assemblies differs Başar’s theory from Sherrington’s “neuron doctrine” and Barlow’s “new perception doctrine” (Barlow, 1995).
5. Sokolov (2001) has excellently described and also constructively criticized the role of feature detectors. However, integrative functioning of the brain needs the selectively distributed and selectively coherent neural populations in concert with the feature detectors.
6. The brain has response susceptibilities. These susceptibilities mostly originate form its intrinsic rhythmic activity, i.e. its spontaneous activity (Başar, 1980, 1983a,b, 1992; Narici et al., 1990). A brain system responds to external or internal stimuli with those rhythms or frequency components that are among its intrinsic (natural) rhythms. Accordingly, if a given frequency range does not exist in its spontaneous activity, it will also be absent in the evoked activity. Conversely, if activity in a given frequency range does not exist in the evoked activity, it will also be absent in the spontaneous activity.
7. There is an inverse relation between EEG and event-related potentials. The amplitude of the EEG thus serves as a control parameter for responsiveness of the brain which can be obtained in the form of evoked potentials or event-related potentials (Rahn and Başar, 1993; Başar, 1998; Barry et al., 2003; Başar et al., 2003).
8. The EEG is a quasi-deterministic or a chaotic signal and should not be considered as simple background noise. This characteristic and the concept of response susceptibility lead to the conclusion that the oscillatory activity that form the EEG governs the most general transfer functions in the brain (Başar, 1990).
9. Oscillatory neural tissues that are selectively distributed in the whole brain are activated upon sensory-cognitive input. The oscillatory activity of neural tissues may be described through a number of response parameters. Different tasks and the functions that they elicit are represented by different configuration of parameters. Due to this characteristic, the same frequency range is used in the brain to perform not just one but multiple functions. The response parameters of the oscillatory activity is as follows: enhancement (amplitude), delay (latency), blocking or desynchronization, prolongation (duration), degree of coherence between different oscillations, degree of entropy (Pfurtscheller et al., 1997; Başar et al., 1999a,b; Miltner et al., 1999; Schürmann et al., 2000; Kocsis et al., 2001; Rosso et al., 2001, 2002; Başar, 2004).
10. The number of oscillations and the ensemble of parameters that are obtained under a given condition increase as the complexity of the stimulus increases or the recognition of the stimulus becomes difficult (Başar et al., 1999a,b, 2001a,b,c). These were demonstrated not only through techniques of frequency analysis but also through recent techniques of time-frequency analysis (Rosso et al., 2001; Özdemir et al., 2005; Tağluk et al., 2005).
2.2.2. Level B: from superbinding of neural assemblies to super-synergy

According to the theory of whole-brain-work, super-synergy is obtained by way of the following submechanisms:

11. In simple binding, there is temporal coherence between cells in cortical columns. This has been demonstrated by several authors (Eckhorn et al., 1988; Gray and Singer, 1989).

12. Each function is represented in the brain by the superposition of the oscillations in various frequency ranges. The values of the oscillations vary on a number of response parameters (Principle 9). The comparative polarity and phase angle of different oscillations are decisive in producing function-specific configurations. Neuron assemblies do not obey the all-or-none rule that the single neurons obey (Karakaş et al., 2000a,b; Klimesch et al., 2000a,b; Chen and Hermann, 2001).

13. The superposition principle indicates synergy between the alpha, beta, gamma, theta and delta oscillations during performance of sensory-cognitive tasks. Thus, according to the superposition principle, integrative brain function is obtained through the combined action of multiple oscillations.

14. The response susceptibility of the brain activates resonant communications in the brain by facilitating electrical processing between networks (Başar et al., 1997a,b; Başar, 2004). This could be also interpreted as a general tuning process between neural populations and feature detectors (Sokolov, 2001).

15. Parallel processing in the brain shows selectivity. The selectivity in parallel processing is produced by variations in the degree of spatial coherences that occur over long-distances between brain structures/neural assemblies (Başar, 1980, 1983a,b; Başar et al., 1999a,b; Milner et al., 1999; Schürmann et al., 2000; Kocsis et al., 2001).

16. Temporal and spatial changes of entropy in the brain demonstrate that the oscillatory activity is a controlling factor in the functions of the brain (Graben et al., 2000; Graben, 2001; Quiroga et al., 2001; Yordanova et al., 2002).

As can be deduced from the foregoing explanations, the concept of superbinding collectively denotes the mechanisms of superposition, activation of selectively distributed oscillatory systems, and the existence of selectively distributed long distance coherences. The concept of super-synergy includes superbinding and, additionally, entropy and the role of EEG-oscillations as control parameter in brain’s responsiveness.

2.2.3. Level C: integration, alliance and interplay in memory

Extension of the theory of whole-brain-work to cognitive processing is governed by the following principles:

17. All brain functions are inseparable from memory function (Hayek, 1952; Fuster, 1995, 1997). Like in all integrative brain functions, memory is manifested as multiple and superimposed oscillations. A specific superposition of oscillations, each of which is characterized with the response parameters in Item 9, represents the configuration that is specific to the given type of memory.

18. Attention, perception, learning and remembering (APLR-alliance) are interrelated. As the grandmother-experiments demonstrated (Başar et al., 2003; Başar, 2004; Özgören et al., 2005), memory-related oscillations are selectively distributed in the brain. They have dynamic properties and evolve upon exogenous and endogenous input to brain. MEMORY states have no exact boundaries along the time space. There is a hierarchical order that takes place on a continuum but the boundaries of memory states merge into each other. Memory functions from the simplest sensory memories to the most complex semantic and episodic memories are manifested in distributed multiple oscillations in the whole brain.

19. In our theoretical framework, we introduced the expression “evolving memory” or “memory building”. The critical factor in memory building is the APLR-alliance. This concept represents a constant reciprocal activation within its sub-processes. Evolving memory has a controlling role in integrative brain functions (Edelman, 1978; Tononi et al., 1992; Barry et al., 2003). The hierarchy of memories is not manifested with separable states, since the memory manifests rapid transitions. Therefore we suggest using the term “memory states” rather than “memory stores”, a concept in which memory is considered to take place in successive stages. These explanations do not apply, however, to persistent memory which can be inborn or obtained through over-learned engrams or habits.

3. Causality in brain responsiveness

To discover the cause of an event is to discover something among its temporal antecedents such that, if it had not been present, the event would not have occurred. In the introduction of this section, causality was described as Newton, Galilei and Einstein conceptualized it. The present section considers causality as it pertains specifically to the responsivity of the brain. The theory of the whole-brain-work considers the following as the critical causal factors of brain dynamics.

3.1. Genetically fixed causal factors

There are in the brain, or in the CNS-ganglia genetically coded networks. The phylectic memory-networks that are inborn play essential roles in the responsiveness of neural populations. Accordingly, (a) occipital networks in the mammalian brain respond to light stimulation with enhanced 12 Hz oscillations (Başar, 2004). On the other hand, temporal auditory areas that do not react to light stimulation respond to auditory stimuli with 10 Hz enhanced oscillations. (b) The ray brain reacts with 10 Hz oscillations to electric stimuli (electroception); the human brain, on the other hand, does not have this ability (Başar, 2004). (c) Like alpha networks, there are selectively distributed gamma networks in the brain. These networks show obligatory responses to sensory stimuli (Karakaş and Başar, 1998). (d)
Reflexes are genetically coded. The so-called “prepotent responses” (Miller, 2000) in reflexive actions also partially represent this type of causality. (e) Results of Sokolov (1975) on the orienting response and the genetically fixed causal factors have to be emphasized: There are expectation cells, which fire upon expected input; sensory-reporting cells which fire in response to actual stimulus; and comparator cells which fire whenever there is a discrepancy between stimuli (Başar, 2004).

3.2. Dynamic causality due to reentry and to dynamic behavior of EEG-oscillations during reciprocal activation of the APLR-Alliance

Possible reentries (Edelman, 1978; Başar, 2004;), reciprocal activation of attention, perception, learning and remembering, recurrent inputs, and changes in prestimulus EEG-oscillations (Barry et al., 2003) change the causality of the brain response in a dynamic manner (Başar and Stämpfer, 1985).

The present behavior influences the immediately following future behavior. The plasticity in this adaptive behavior is demonstrated in the oscillations, showing that oscillatory plasticity is an additional causal factor in brain responsiveness. In auditory and visual memory task experiments, the EEG-oscillations manifest a high degree of plasticity: This is because neural networks have susceptibility for being activated with superimposed frequency codes, i.e., with multiple oscillations showing varied degrees of enhancements (Başar, 2004). The reciprocal activation of the APLR alliance (Başar, 2004) also affects the future responsiveness of the brain, attesting for the presence of oscillational plasticity in the higher cognitive processes.

The existence of a significant difference in the major operating oscillations in occipital or frontal areas gives strong support to the possibility that spontaneous, evoked or induced alpha rhythms or theta rhythms have fundamentally different functional roles. But during some functional states, major operating rhythms can change their functional roles. The nature of the experiment and the task conditions can influence the weight of the functional components on brain rhythms. This behavior of brain oscillations is another instance of the dynamic plasticity in brain responsiveness.

Recent results of Karakaş et al. (2003) showed that the early sensory gamma response showed individual differences and, further, the existence or nonexistence of the gamma response could be predicted from a battery of neuropsychological tests that measure attention, perception, learning and memory, in short, the APLR-alliance. Such complex cognitive processes are most probably multi-causal, including both the impact of genetic codes and the influence of environmental conditions. A recent study, however, showed that the presence of the early gamma response is not to be sought for in gender differences (in press).

4. To sum up

Why did we use the term “whole-brain-work” for our theory? This theory is based on principles and mechanisms according to which the integrative functions that involve EEG-oscillations are processed by the whole brain. The concepts of “all functions” and that of “whole brain” are therefore brought together in the present theoretical framework to produce the synthetic phrase, “all-works of the brain” or shortly, “whole-brain-work”.

The term “whole” indicates, first, the whole brain and the holistic functions that such a brain produces. Secondly, it indicates the fusion in function, space and time. Accordingly, the theory of the “whole-brain-work” is an explanation of the integration of all functions in the whole brain and the functional duration throughout, which the brain works. Such integration is more forcefully represented in the phrase “whole-brain-work” than in “integrative brain function”. The term “work”, on the other hand, indicates the additional dynamic component, one that is not implied in the term “function”.

Influential studies and explanatory findings on electrophysiology have mainly been on the spike potentials. The theory of the whole-brain-work explains brain function in cognitive processing on the basis of oscillatory activity. The very existence of a theory on the oscillations shows that EEG activity, be it spontaneous or evoked, needs special emphasis. The theory of whole-brain-work theory that this section presents provides the rules that are to be considered when dealing with the oscillatory dynamics of the brain.

References


