

Brain Oscillations and Neural Networks

Arno Villringer, M.D.

*Berlin Neuroimaging Center and Department of Neurology,
Charité - Universitätsmedizin Berlin*

This lecture will give an introduction to basic brain function and organization. Rather than dwelling on examples or specialized functions, overall principals are being discussed.

Functional specialization versus integrated network

The controversy about the brain being *either* an un-separable “holistic” organ or a mosaic of many specialized areas is as old as the study of brain function. While Franz Gall’s phrenology indicated a heyday period for the latter notion, it was subsequently disregarded as a largely non-scientific endeavour. Indeed the phrenological notion of bony bumps being landmarks of underlying localized brain function was not sustainable, however, the underlying conceptual localizational approach seems now being revived by functional brain imaging. In most functional brain imaging studies, activated and/or deactivated brain areas are identified during certain conditions and/or performance of certain tasks. Thus, conceptually, it may be regarded as a neo-phrenological approach of the brain consisting of specialized modules, each of which is responsible for a certain role/function of the brain.

Today there is no doubt that certain areas of the brain have certain functional specifications. The lateralization of language function is a well known example, but also smaller highly specialized brain areas have been identified for example for face recognition and object shape. Despite increasing knowledge on the functional specialization of certain brain areas, it is also becoming increasingly evident that a purely topic approach cannot explain complex brain function and that only by the interaction of distributed brain areas such tasks can be performed. This notion is also supported by the clear anatomical evidence of an extremely high interconnection between different brain areas. In conclusion, it is now clear, that both functional specialization and integration of specialized areas into a larger functional network are present in the brain.

Subsequently, we will discuss some conceptual notions, how interactions between different brain areas may take place. Some of these notions are discussed in a “dialectic” fashion as pairs of concepts. Particularly for sensory processing, the notions of **top-down versus bottom-up processing** are of high importance. The notion of **sequential versus parallel processing** is of general interest for many parts of the brain, but can also be best exemplified for sensory systems. Another issue concerns the relevance/importance of **brain rhythms** which presumably are indicators of synchronized neuronal activity. Is synchronization of functional importance or is it only an epiphenomenon noticed in macroscopic EEG-recordings. Do the different types of synchronization serve different functions? Finally, for a given brain area for which a certain functional attribute has been obtained, the involvement in different networks opens the question of **fixed function versus pluripotency** of brain areas.

Top-down and bottom-up mechanisms

Our intuitive notion of processing of sensory information is that of a camera in which a “picture” is made of the environment which is subsequently “understood”, “recognized” etc. by “the brain” (**bottom-up** processing). This type of processing is well established and detailed pathways have been characterized: For example for the somatosensory system the pathway includes skin receptors, peripheral nerves, brain stem nuclei, thalamic nuclei, primary somatosensory cortex, secondary somatosensory cortex and transmodal cortical areas e.g. in parietal cortex.

However, sensory processing is not only a passive process. We all know, that attention towards a specific object, feature, sensation (e.g. pain) seems to allow for an easier identification of the respective thing. While it was first thought that attention acts like “moving a camera” towards a certain object, it is becoming ever clearer that attention also influences heavily the entire sensory chain. Such **top-down** effects can influence/manipulate neuronal processing even at the earliest level of the sensory system, i.e. preventing any “objective” or “unbiased” information about the environment.

Being universally present in the brain, using electrophysiological approaches and functional imaging methods, both aspects, top-down as well as bottom-up influences can be investigated systematically.

Evoked versus Background “Activity”

In contrast to the implicit assumption of many neuroimaging studies, usually there is no “stable” baseline condition when “no task” or “no stimulation” is performed, rather there is a constant up and down of a “background” activity. Even more relevant e.g. for averaging of subsequent stimulations in a functional imaging experiment, is the question whether background activity influences evoked activity by a (given constant) external stimulus. There is increasing evidence that this is indeed the case. This issue is closely related to the above discussed notion of top-down and bottom-up processing, since the influence on a baseline activity in a certain brain area may be one mechanism by which top-down processing can influence bottom-up processing.

Sequential versus parallel processing of information

Sensory systems are frequently viewed as consisting of a chain of sequential events. As mentioned above, this view is already modified by the conceptual framework of bottom-up *and* top-down processes, i.e. there are at least two directions of processing in one chain of sensory processing. In addition, however, there is not only one sequence, but frequently, there are several parallel ways of processing. Such parallel ways exist e.g. in the form of “shortcuts” between steps of the chain, e.g. direct connections from the thalamus to secondary somatosensory cortex (i.e. bypassing primary somatosensory cortex). Another form of parallel processing seems to serve different functional ends. An example for this are the two main pathways for processing in the visual system. The dorsal stream (occipito-parietal path) being involved mainly in guidance of action and a ventral stream (occipito-temporal path), being involved in processing during perceptual tasks. While parallel pathways exist, they seem not to be independent from each other, but rather full of mutual

interactions. Thus, the notions of parallel and sequential processing of information clearly can be applied to the brain, however, almost never in their purest forms, but rather as frameworks from which deviations are frequent.

Maps, fixed function versus pluripotency of brain regions

In order to orientate oneself within the brain, clearly some kind of “map” or “coordinate system” is needed. There are many ways of subdividing / mapping the brain into for examples “regions”, “areas”, “lobes”, “lobules”, “columns”, or “minicolumns”. Such subdivisions have been designed following different mapping rules. Thus, borders between different parts of the brain may be drawn according to macroscopic features (upon visual inspection), histological and cytoarchitectonic features, but also according to functional assignments as they are currently being accumulated especially through a plenitude of functional neuroimaging studies. The most well known subdivision into “areas” designed by Korbinian Brodmann used cytoarchitectonic features and divided the brain in (originally 47) areas. The most widely used co-ordinate system is currently the one designed by Tailarach. In many functional imaging studies, after having obtained areas of “activation / deactivation” it is attempted to assign “Tailarach”-coordinates to these “activations/deactivations” and to allocate them to the respective “Brodmann area”.

When reviewing such functional assignments of many studies, the following general observations regarding the relationship between anatomy and functional assignments are frequently made: (1) In many instances, there is overwhelming and converging evidence regarding the functional assignment of certain areas. For example, primary visual cortex is activated whenever there is visual perception. (2) In many other instances, quite similar functional tasks lead to different “maps of activation”, sometimes between studies, sometimes there is also significant inter-subject variability within one given study. These results seem to indicate that the brain can use different strategies (and different associated brain areas) to perform certain tasks, thus there seems to be – to a certain extent – some redundancy in brain function. (3) a third observation is that the very same areas of the brain are being reported to be “active” in quite different conditions/tasks and are being associated with different functions. Whether this observation is related to true “pluripotency” of a given area or to the fact that the different functional assignments made in different studies are “indicators” of the very same – perhaps more fundamental – underlying function, cannot be differentiated at the moment.

Such considerations seem to be of great importance, e.g. for studies on brain plasticity. What, for example, does it “mean” if the visual cortex is being activated in blind subjects? What are the chances for recovery of certain functions when certain brain areas are lesioned. Only when we truly understand the function and the “flexibility of function” of a certain brain area, will we be able to give answers to such questions.

Synchronous neuronal oscillations and brain rhythms

The first non-invasive method to assess brain function was actually the EEG, developed by Berger in 1929, and what was first detected in the EEG was an indicator of neuronal synchrony, the Alpha Rhythm. In the meantime many other brain rhythms have been identified, and oscillatory behaviour is now being regarded as a major feature of brain function. Brain rhythms which are the product of synchronous neuronal oscillations probably

serve several different goals. The low-frequency alpha rhythm is probably an example for a group of background rhythms indicative of a default state of a certain network of neurons. Rhythms of higher frequency in the Gamma range have been suggested to be the long sought for mechanism for the binding problem i.e. the integration of several features of an object, into one percept. Rhythmic activity of networks is probably also of crucial relevance for memory formation, consciousness, and alterations of the latter such as for example during sleep. Furthermore, synchronous behaviour of neurons seems also to play an important role in neural plasticity.

Thus, synchronous neuronal activity is a major mechanism of forming and maintaining functional networks in the brain. The fact that such rhythms can be depicted in non-invasive EEG and MEG recordings has significantly strengthened the importance of the latter methods and major efforts are being undertaken to combine EEG/MEG with MRI studies.

How does the brain work?

Above a number of different principles of neuronal processing and interactions were mentioned and briefly discussed. However, to know some fundamental principles does not explain yet how the whole brain functions. Indeed, we are far away from any overall model of brain functioning.

On the other hand, there is increasing evidence that the brain may be described as a “self-organizing system following certain basic principles”. If this is true, than it is indeed most crucial to understand these basic principles and how the application of these basic principals and their mutual interaction can develop the organ brain into such a complex organization associated with sophisticated behaviour.

What is the role of brain imaging?

Functional and structural imaging methods have to meet the requirements given by the basic principles of brain functioning. E.g. spatial resolution has to be ideally on the order of meaningful “functional units” of the brain, temporal resolution should keep up with the speed of neuronal processing and brain rhythms (the latter up to 600 Hz), and methods should be available to study the interaction (and ideally the direction of interaction) of different brain areas on the appropriate temporal scale.

Further Reading

- Friston K (2002). Functional integration and inference in the brain. *Prog Neurobiol.* 68:113-43.
- Amunts K, Zilles K (2001). Advances in cytoarchitectonic mapping of the human cerebral cortex. *Neuroimaging Clin N Am.* 11:151-69
- Buzsaki G, Draguhn A (2004). Neuronal oscillations in cortical networks. *Science* 304:1926-9
- Toga AW, Thompson PM (2001). Maps of the brain. *Anat Rec.* 265:37-53.