Brain dynamics: Neural correlates of mental activities

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It is natural for us to think about how we think and be curious about mind–brain relations. Some amount of education in science gives one confidence to address these problems scientifically in a reductionistic fashion. Among scientists, theoretical physicists have a weakness (or fascination) to think about the brain from their own perspective, handicapped with ignorance of the complex field of neurobiology. Experimental physics on the other hand, has contributed immensely and has made brain research what it is now, through techniques such as positron emission tomography (PET), functional magnetic resonance imaging (fMRI), magnetoencephalography (MEG), electroencephalography (EEG), etc.

Before I begin I should make some clarifying remarks about the title of this article, borrowing from recent literature. Neural correlates refer to electrical activity of the brain from the level of neurons onwards that exists in various 'mental states'. Individual neurons can be studied by micro-electrodes and gross electrical activities of small regions of the brain (a volume of 1 cc of brain contain nearly 10^7 neurons), can be measured by non-invasive methods such as PET, fMRI or MEG. The chemical, biochemical, electrical and magnetic phenomena associated with the functioning of neurons are, in principle, measurable by the available scientific methods. The 'mental phenomenon' or 'mental state' is hard to define very precisely; for example the state of being conscious or self-awareness are personal and difficult to quantify or measure. While we can compare notes about such things among individuals, there are no quantifiers. However, there are broad agreements about various mental states; for example, being attentive or shifting the focus of attention, being awake, etc.

Two recent articles from *Nature*[1,2] that reported some interesting experiments on brain prompted me to write this commentary. The choice of these papers did not come out of my professional familiarity or deep involvement with the field: I simply chanced to read these two interesting papers and they opened a window and I got a glimpse of some of the fascinating activities that are current in neuro science, which I normally do not come across.

Briefly, the two papers discussed the following. The first paper[1] entitled 'Attention modulates synchronized neuronal firing in primate somatosensory cortex' studied neuron firings in the relevant parts of the brain (SII) of monkeys, using micro-electrodes, when a monkey switches 'attention' between a visual task and tactile (touching) discriminating task. The finding was that two separate neurons in the same region fired in synchrony when the attention changed. This was tested by analysing about 400 different pairs of neurons in the same region.

In the second paper[2] entitled 'Temporal patterns of human cortical activity reflect tone sequence structure', the subjects were human beings, who listened to several unfamiliar one-minute long 'tones', whose quality was changed (in a quantifiable manner) from pleasing ones (having melody-like statistical properties) to noise. The idea was to study the temporal neural correlates of complex auditory sequences (such as speech or music) which engage multiple brain areas as perception unfolds in time. The neural activity was measured using MEG.

In this experiment[2] the tone was also given a 40 Hz amplitude modulation. Weak time-varying magnetic fields, arising from the electrically active brain inside, are measured at various places in the scalp by a biomagnetometer. In particular, the experimentalists looked for the 40 Hz modulation in the magnetic signal. Sure enough there was the 40 Hz modulation in the enhanced electrical activity following the hearing of the tones. The exciting finding was that when the 'tone' had a pleasing character, the input modulation and the modulation of the electrical activity of the brain were in phase. The amount of phase correlation decreased as the music turned into more of a noise. Moreover the electrical activity between the recording region (sites over the left posterior hemisphere) and the rest of the brain was also in synchrony when one listened to a pleasant tone. As the tone became less pleasant, the phase modulation in different regions became less synchronous.

A brief digression about measuring biomagnetism of the brain. In MEG, a biomagnetometer measures the sum total of the tiny neuro magnetic signals (arising from the electrical activities of the neurons in the brain) near the scalp. Like fMRI and PET, MEG is also non-invasive. It uses a superconducting quantum interference device (SQUID) that is capable of detecting feeble magnetic fields of the order of femto Tesla (10^{-15} T). The evoked response from the brain produces magnetic fields of the order of pico Tesla (10^{-12} T) near the scalp. These tiny fields should be compared with the earth's magnetic field which is of the order of milli Tesla (10^{-3} T). These are very specialized and expensive equipments. Thanks to a recent successful fabrication of SQUID at the Materials Science Division of Indira Gandhi Centre for Atomic Research, Kalpakkam, it is possible to build this machine in India for clinical and research purposes; time is ripe for some action.

These two state-of-the-art experiments reported in *Nature* give the neuroscientists some more clues about the functioning of the brain from different points of view. The first experiment gives one of the neural correlates of the cognitive process, namely shifting the attention focus; that neurons will fire in synchrony during change of attention is very plausible, but there are more subtle facts one can infer, as discussed in the paper. The second experiment is more complex in some sense – it tells us about the synchronous response of the brain as a whole to what is 'pleasing' to us or some thing that we are already familiar with. Between-site phase coherence does indicate synchronized activity between brain areas.

As mentioned earlier, while it may become an endless debate if one wants to sharpen the definition and meaning of words like 'consciousness', 'self-awareness', etc., it is meaningful to ask the question, what happens to the activities of the neurons when I am conscious of something (like looking at a beautiful picture) or during the variety of possible mental activities? One can make certain hypothesis, based on a body of available experimental facts about the neuronal correlates and make some predictions that can be experimentally tested.

In 1984, Francis Crick[3] proposed a 'searchlight hypothesis' for thalamocortical interaction specified in terms of testable hypothesis at the cellular level. Crick wrote, 'What do we require of a searchlight ? It should be able to sample activity in the cortex and/or the thalamus and decide 'where the action is'. It should then be able to intensify thalamic input to that region of the cortex, probably by making the active thalamic neurons in that region fire more rapidly than usual. It must then be able to turn off its beam, move to the next place demanding attention and repeat the process . . .'. Apparently the nature of the reticular complex (of the thalamus) and the behaviour of the thalamic neurons fit this hypothesis rather neatly. Various metaphors that generalize the searchlight hypothesis, such as a 'global worksplace' hypothesis have been made.

In spite of the seemingly chaotic neuronal firings, there are organized and periodic signals that emerge from the brain: the well-known α, β waves. Various authors have suggested that awareness might be correlated with particular states of the brain involving coherent oscillation in the 40–70 Hz range and which should serve to bind together percepts pertaining to a particular conscious moment.

There are also interesting problems that border philosophy, of 'qualia' – the 'what it is like' character of mental state; the way it feels to have mental states such as pain, seeing red, etc. This is also called a 'hard problem': understanding the manner in which subjective experience arises from cerebral processes. Some philosophers argue that problems such as 'qualia' are outside the purview of science.

There is the remarkable 'binding problem': how do diverse systems in the brain cooperate together to give us an unified experience? It is well established that different aspects of the visual field are analysed by very different regions of the brain at different times, later leading to the spectacular visual consciousness we all possess. The binding problem is striking when a part of consciousness gets 'broken apart', for example when some aspects of visual consciousness get suppressed (such as not being able to see the colour or not being able to recognize the object even though we see it etc.) when some parts of the brain get damaged. There are very many clinical examples such as blind vision and anosognosia. Clinically routed approach to the problem of consciousness is a very fruitful and perhaps the only way we could get crucial clues about brain functioning. While the binding problem is a challenging fact to neuroscientists and computational neuroscientists, I believe that this is one problem where theoretical physicists could make meaningful contribution.

On one extreme we have philosophers who question everything (according to Crick and Koch, 'neuroscientists should listen to the questions philosophers raise, but should not be intimidated by their discussions'), on the other extreme, we have what I call as quantum speculators, a popular example being Penrose with his ideas of the electromagnetic modes inside microtubules being q-bits (a majority of physicists vehemently argue that when we come to processes in the neural networks such as the firing of neutrons in the warm and wet brain, quantum coherence is completely lost and what we are left with are essentially 'classical processes'). There are a spectrum of people and ideas in between. The attitude as expressed by Crick and collaborators is very pragmatic, less speculative and seems one natural way to build a hard science: to discover a hierarchy of basic notions and mechanism using experiments at every stage to build the fabric of the mind–brain relation.

A look at the literature on consciousness-related issues in published works reveals very many debates, discussions and ideas bordering philosophy, which is not the strength of physicists in general. The strength of hard science like physics is to infer powerful general laws behind complex phenomena with help from experiments, modelling, laying mathematical foundations and thereby make quantitative predictions. Without going to questions of philosophy, there seems to be enough complexity, richness, surprises in various aspects of brain dynamics, understanding of which should, at a much later stage, embolden one to ask questions like why physical systems with a particular architecture give rise to feelings and qualia?

In this context, Crick and Koch make a remark which is worth thinking about, '. . . you cannot explain the 'livingness' of living things (such as bacteria, for example) by the action of 'dead' molecules . . . . It is entirely possible that the very elaborate nature of neurons and their interactions, far more elaborate than most people imagine, is misleading us, in a similar way, about consciousness'. That is, once we find the neural correlates of various mental phenomena, it will enable us to discover the general laws governing the dynamics of the brain and at the same time the detailed knowledge one has gained may even make some of the questions such as qualia meaningless.

The profound properties of the biological brain emerging out of communication of electrical signals among the seemingly chaotic biological cells (neurons), at various length scales and time scales make brain dynamics unique, attractive and formidable at the same time. Brain, in very elementary terms, is a neural network, an expert system, an image processor, a speech synthesizer, etc.; but at a profound level gives me, my minds 'eye' and mind's 'I'. My recent encounter with the brain leaves me with a feeling (like several others have) that the wealth of data coming from PET, fMRI and other experiments makes the time ripe for some of the physicists to look into the fascinating and the most challenging of all problems, to understand ourselves, in our own (limited?) scientific terms.

1. Steinmetz, P. N., Roy, A., Fitzgerald, P. J., Hsaid, S. S., Johnson, K. O. and Niebur, E., *Nature*, 2000, **404**, 187.
2. Patel, A. D. and Balaban, E., *Nature*, 2000, **404**, 80.
3. Francis Crick, *The Astonishing Hypothesis: The Scientific Search for the Soul*, Touchstone Books, 1995.
4. The following web sites contain useful information and research articles one can down-load free. Through this, one can also get connection to many sites related to neuroscience. 1) http://www.u.arizona.edu/~chalmers/online.html; 2) http://assc.caltech.edu/; and 3) http://cogprints.soton.ac.uk

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