

Title:

A continuum approach to modelling cognitive disorders

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Summary:

At the present time, the dominant conceptual framework in neuroscience views neurons as discrete information processing units. While this framework has undoubtedly been successful at explaining phenomena at the single cell level, it has had less success in explaining large-scale neural phenomena such as cognitive disorders. An alternative conceptualization of brain function is in terms of a energy continuum, where energy is an abstract variable modelling the flow of electrochemical activity between neurons. Using this energy (E) model, large-scale phenomena may be incorporated within a single conceptual framework. This framework can in turn be related to the underlying biochemistry. The E model also generates testable predictions, and should prove quantifiable using differential equations. These claims are illustrated with simple examples from the spectrum of cognitive disorders.

INTRODUCTION

Despite many attempts in recent years, e.g. (1-4), there is still no generally accepted theory of many large-scale neural phenomena, such as sleep, the EEG and cognitive disorders like schizophrenia and bipolar disorder. One reason for this is that the currently dominant information processing approach is essentially functional in emphasis, e.g. (5), and determining the functional significance of many large-scale phenomena has proved unexpectedly problematic. A second more important reason is that treating neurons as discrete information processors when modelling large-scale phenomena leads to a combinatorial explosion of parameters, an insoluble problem given current computing power.

Any proposed model of large-scale phenomena must facilitate the quantification of neuroscience, avoiding or minimizing the combinatorial explosion problem. It must also be able to provide a theoretical framework within which the functions of currently challenging large-scale phenomena can be explained and these phenomena too eventually quantified. The model proposed here is at a very early stage. However, the general approach can be demonstrated, and its usefulness seen, by applying it to examples of large-scale phenomena.

THE ENERGY (E) MODEL:

Traditionally neurons have been viewed as discrete entities performing computational functions. The continuous alternative proposed here, the 'energy' or E model, views neural activity in terms of

energy flows between neurons, where energy is an abstract variable which models neuronal activity. Consider the cortical surface. This can be simplistically modelled as a two-dimensional spatial domain in which the energy of a given point changes with time - that is as a scalar energy field. Of course, the cortical system is not closed: energy flows into it from inputs (both from the environment, via the senses, and from the body) and flows out via outputs (terminating in behaviour, which dissipates energy in interactions with the environment).

Quantification of the E model

To indicate that the E model is in principle quantifiable, consider one possible model of flow within the energy field, derived by approximating the cortical surface by a solid medium. The differential equation relating change of energy with time to spatial energy gradient is then of the general form:

$$\frac{\partial E(x, y, t)}{\partial t} = I(x, y, t) - O(x, y, t) - \nabla \cdot (W \nabla E(x, y, t)) \quad (1)$$

$I(x, y, t)$ and $O(x, y, t)$ describe how the system's inputs and outputs, respectively, vary across space and time. In the heat transfer equation from which the above derivation is taken ⁶, the parameter W is typically held constant for energy flow between two points, and depends on the density and mass heat capacity of the medium through which the energy is flowing. However, for the cortical surface, W , the parameter governing how readily the energy flows between points, clearly depends primarily on the synaptic weights between neurons. W is therefore not constant: it takes the form $W(x, y, t)$. We can assume that a Hebbian learning mechanism governs weight changes in cortex; there is ample evidence for some form of Hebbian learning (7-9). The weight change

between two points in the energy field then depends on the product of the energy at each points. In other words, the weights can be treated as a ‘connectivity function’ defined over the domain $(x1, y1, x2, y2, t)$, with learning rate parameter k (which may vary with W).

$$\frac{\partial W(x1, y1, x2, y2, t)}{\partial t} = k E(x1, y1, t) E(x2, y2, t) \quad (2)$$

These two non-linear differential equations describe the behaviour of the energy field with time. In principle, they should facilitate the quantitative investigation of large-scale phenomena. In practice, work is at present only just beginning on their precise formal structure. However, the overall approach can be illustrated qualitatively by applying it to the domain of cognitive disorders.

The paths through which energy flows between points on the cortical surface are dependent on learning (i.e. on the history of prior energy flows through those points, from Equation 1). As paths strengthen, the time taken for the energy to flow through them to the system’s outputs will decrease. The length of time for which any given two points in the path have high energy will therefore also decrease, so the capacity for weight change will be less (from Equation 2). Weights will therefore tend to ‘settle’ to fixed values over time, and these patterns will reflect the statistical structure of the system’s inputs.

APPLYING THE E MODEL TO COGNITIVE DISORDERS

Altering energy levels in the cortical system will have interesting consequences. If the overall energy is decreased, energy will tend to flow along fewer paths - those which are already strongest -

resulting in poverty and stereotypy of thought and behaviour. Such symptoms are characteristic of cognitive disorders such as schizophrenia (negative symptoms) and bipolar disorder (depressive phase). If energy is increased, more paths will become channels for flow. This increased activity corresponds to higher creativity (flow between normally unconnected points in the field), and to some extent thought disorder (the progression of flow along its usual input-output paths is disturbed). Such symptoms are characteristic of cognitive disorders such as schizophrenia (positive symptoms), attention-deficit disorder and bipolar disorder (manic phase). The E model therefore predicts a continuum of 'disorders of energy level', with extreme depression and the withdrawn phase of schizophrenia toward the 'low energy' end of the continuum, and mania and the florid symptoms of schizophrenia toward the 'high energy' end.

Altering the balance of internal and external inputs

There are two main ways in which energy levels can be altered. Firstly, the usual balance between internal and external inputs can be altered, as in the wake-sleep transition. If the alteration is due to decreased internal activation, the resulting deficit in overall energy levels may trigger compensatory behaviour: seeking out sensory or biochemical stimulation. This, I speculate, could provide an outline for considering the addictive effects of drugs which affect internal inputs, such as amphetamines. If the internal/external balance is changed by increased internal stimulation, the paths normally channelling sensory inputs may receive energy from internal rather than their usual external inputs. The resulting energy flows will thus be misattributed to external causes, when in fact they are due to internal input activity. The result will be hallucinations and delusions (the exact content of

which will depend on the sufferer's experiential history). Incidentally, the E model suggests that similar misattributions may occur if there is little sensory input (in which case the energy flows will be driven by internal inputs more than by inputs from the sensory boundaries). This suggests a mechanism for the hallucinations induced by sensory deprivation (10, 11).

Altering the rate at which connections change

Secondly, the rate at which weight change occurs (the learning rate parameter k in Equation 2 above) can be altered. If k is increased, for example, weight changes and therefore energy flows will both become larger and more disordered (weights will take longer to settle; changes in input will have a much more disturbing impact on the patterns of cortical activity; unusual flow patterns will be dominant). Cognitively, these phenomena correspond to increased thought disorder, mental instability, and hyperactivity, all of which are characteristic of schizophrenia. This is intriguing because the parameter k governs the rate at which synaptic connections form, which may be abnormal in schizophrenics. David Horrobin has suggested that schizophrenics may have abnormal pruning of brain connectivity because of a genetic deficit (at two or more genomic sites) in processing the phospholipids which make up cell membranes (12-14). The E model may thus provide a framework for exploring further the cognitive consequences of Horrobin's biochemical hypothesis (15), in which case the continuum of disorders of energy level, described above, should be explicable in terms of that hypothesis. Research linking attention deficit disorder to Horrobin's hypothesis supports this claim (16, 17).

Some predictions of the E model

Among other things, the E model predicts that sensory overload coupled with behavioural restraint should induce psychosis more readily than sensory overload alone. This is because, according to the E model, behavioural restraint prevents energy from leaving the cortical system and dissipating in interactions with the environment. The model further predicts that sensory stimulation may be of use in reversing symptoms of depression; that patients with 'high energy' disorders such as manic disorder, attention deficit hyperactivity disorder and schizophrenia (positive symptoms) should all have a greater gestural repertoire than either normals or depressed patients; and that subjects with mild forms of these disorders may be helped by increasing their behavioural expression (18). These predictions, which are all empirically testable, give an indication of the theoretical richness of the E model.

CONCLUSION

The model described here is at an extremely preliminary stage. Much remains to be done in developing and formalizing the central idea. However, I hope to have shown that the idea itself can mesh with and contribute to currently available theories of cognitive disorders, such as the phospholipid hypothesis of schizophrenia, and is furthermore a prime candidate in its own right for further theoretical and empirical research.

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