

Toward a Model of Functional Brain Processes II: Central Nervous System Functional Macro-Architecture

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Abstract

The CNS is endogenously and concurrently active, with primary functional relations being those of oscillatory processes that modulate each other in multifarious ways. One crucial aspect of these processes is that of a kind of set-up of dynamic spaces that regulate other processes within those spaces. Such ‘microgenesis’ of dynamic spaces occurs locally in cortex within differentiations of large and slow processes that set parameters for smaller and faster processes. This is the focus of Part I of this paper. This raises the issue of what modulates such local microgenesis. Modeling such more global processes involves: 1) how they modulate local microgenesis, and 2) how they achieve functional coherence. These are the primary issues addressed in this paper (Part II).

Keywords: CNS oscillatory modulation; neural loops; CNS self-organization; learning; emotion; predictive brain

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Introduction

In part I, a micro-functional model was presented in which large spatial scale and slower temporal scale processes — involving, for example, volume transmitters, astrocytes, silent neurons, and other phenomena — modulate the dynamics of smaller and faster scale processes, such as classic synapses. Such modulation sets the parameters of the faster dynamics, and is the dynamic system equivalent of “programming”.

Further, the large scale processes induce weak coupling among the smaller, faster processes, which, in turn, can induce attractor landscapes in those dynamics (Hoppensteadt & Izhikevich, 1997; Izhikevich, 2007). The form of those landscapes, and of the attractors within them, enable and constrain the fast neural processes.

Such a micro-functional model generates the question of how those dynamic (attractor) landscape modulations are themselves regulated. What controls or modulates the micro-dynamic landscape modulations? The ultimate answer to this question must involve a model of the macro-functioning of the brain: modulations, enablings, and constraints across the entire system must engage each other in accordance with the macro-functional organizations available, and thereby determine the overall flow of CNS processes, including the ongoing modulation of ranges of fast, local processes.

Most broadly, what generates and modulates the flow of macro-processes in the brain? Clearly, the answer cannot be some highest level executive: that answer simply generates a version of the classic homunculus regress. It is this issue that I will pursue in this paper, presenting some themes of macro-evolution, learning and development, and

self-organization within and among various cortical-subcortical loops as perspectives on the macro-functional processes.

1.1

The Dynamics of Learning

The human brain is evolved for learning and development, and for learning to learn. It is not (just) for engaging in interactions with the world. In that sense, homo sapiens is maximally adapted to niches of adaptation (Bickhard, 1973, in preparation; Bickhard & Campbell, 2003).

I will present first a perspective on the dynamics of learning, and then turn to how these kinds of dynamics have been involved in the macro-evolution of the brain. The reason for first addressing learning per se is that learning, like perception, cognition, language, and so on, is not a matter of transduction, induction, symbol manipulation, or information processing. Such passive models of mental phenomena are the descendants of the classic signet ring impressing its form into wax, and they do not explain the phenomena to which they are addressed any better than the signet ring (Bickhard, 2009a).

If, however, representation and cognition and other mental processes are recognized as emergents of interactivity between the organism and its environment, then there is no temptation to think that competent action systems can be impressed by the world into a passive mind. Learning (and development) must be *constructive* processes.

In the absence of prescience, these constructions must be trials that may be in error, variations on what has been constructed before that may be selected out if they fail. An action based model of cognition, in other words, forces a variation and selection

constructivism, an evolutionary epistemology of learning and development (Campbell, 1974).¹

I have argued that normative truth value emerges in processes that anticipate what further processes might be successfully engaged in.² This *might* be conceived of in terms of anticipation of *environmental* consequences of interaction, but such kinds of environmental anticipation already presuppose the emergence of representation of that environment, and, thus, cannot be the most basic form of representational anticipation (Bickhard, 2009a). More locally, these anticipations are constituted as local microgenesis for further processes, and the success or failure can be locally constituted as success in the local process flow remaining within the range of what the microgenesis has prepared for, and failure as the deviation of that process flow from the range that has been prepared for.³

If microgenetic processes tend to stabilize with such local microgenetic anticipatory success, and destabilize with failure, we have a microgenetic variation and selection process that will tend toward stability with local, thus interactive, success. Microgenesis, thus, is the locus of learning (Bickhard & Campbell, 1996).

¹ Generalizing the model of selection beyond biological evolution to epistemological phenomena is the core of evolutionary epistemology (Campbell, 1974). Selection principles can, in fact, be generalized even further to almost any kind of non-accidental and non-designed fit to criteria (Bickhard & Campbell, 2003). In such broad form, models that make selection phenomena central are sometimes known as forms of Universal Darwinism (Dennett, 1995). It should be noted, however, that, just as for any other explanatory principle, variation and selection principles can be used in incorrect models as well as correct models.

² For discussions of emergence, see (Bickhard, 2009a; Bickhard & Campbell, 2003; Clayton & Davies, 2006; Deacon, 2012; Thompson, 2007).

³ And local anticipatory success and failure constitute truth and falsity of the anticipatory set-ups, thus ground representation. See Part I and Bickhard (2009a).

1.1.1

Kinds of Learning

I turn now to some illustrations of how this model of microgenetic evolutionary epistemology can address various kinds of learning — that is, illustrations of how this model of learning can account for all learning.

1.1.1.1

Habituation

Consider first habituation. If there is available a way of interacting with an input stream in a “matching” or “subtractive” manner, then a successful interaction will be one that correctly anticipates that input stream and “subtracts” it to zero. This is effectively what happens with classic habituation (Bickhard, 2000b; Thompson, 2009).⁴

1.1.1.2

Classical Conditioning

Suppose now that no such subtractive process is possible. One example would be if a tone becomes pain, and pain is an input that permits no successful interaction (to a first approximation). How can an input flow of tone-pain (e.g., shock) be successfully interacted with?

By avoiding the pain; jumping off of the shock grid.

⁴ See later discussion for a comparison with ‘predictive encoding’ models.

1.1.1.3

Instrumental Conditioning

Consider now a case in which the input activity is generated by some part of the CNS itself — perhaps activity in the hypothalamus evoked by low blood sugar. Ultimately, the only way to successfully interact with such a signal is to eat, and thus raise blood sugar. This requires a great deal of learning about how to go about this in various circumstances, such as in a forest or a restaurant or in the vicinity of a refrigerator. As infants, we are aided in this complex learning by simple responses, such as crying, which, in supportive environments, will accomplish the interaction, but adult responses can vary even culturally. Hunger, in whatever environment, will tend to evoke activity that results in eating, and this is a standard example of instrumental conditioning.⁵

1.1.1.4

Other Kinds of Learning

These forms of learning are not exhaustive — incidental learning, for example. Most fundamentally, memory is a multifarious kind of learning (see below for further elaboration). I address these elsewhere (Bickhard, in preparation), and take it as established for current purposes that microgenetic variation and selection processes are a candidate for being able to account for all of learning.

⁵ It should be noted that this quick model is at best a first approximation. There are multiple delays in eating and blood sugar feedback, that have resulted in multiple forms of detection and feedforward and feedback processes to regulate eating (Carlson, 2013). These complexities, however, do not alter the basic point in the text.

1.1.2

Development

It is possible for the variations in simple learning in simple organisms to be always generated from the same dynamic base — perhaps just variations in synaptic strength. More complex learning, however, occurs if previous constructions can be used as resources for later variations, either as units of construction or as organizations within which variations can be induced.

Such recursive constructive processes can yield multiple further properties. For example, it may be that some complex constructions are, as a practical matter, not possible without certain prior preparatory constructions (Bickhard, 2005b). Trajectories of possible construction can split and join, forming complex partially ordered spaces of possibility. Such enablings and constraints of recursive constructive processes is the subject matter of *development* (Bickhard, 2006).

A still more powerful form of learning would be if the variation and selection constructive processes can themselves be learned and developed. This constitutes learning to learn. Heuristic problem solving would be an example, in which the heuristics for trial constructions are themselves learned, as well as, perhaps, the criteria against which the trial constructions are compared. Such an internal process of learned constructive processes and learned selection criteria constitutes an internalized evolutionary epistemology (Bickhard, 2002, in preparation).

All forms of learning, and learning to learn, emerge as forms of variation and selection constructive processes. Examining how such forms are themselves enabled and

constrained within the nervous system yields a perspective on the macro-evolution of the brain.

1.2

Learning: A Macroevolutionary Theme

One powerful perspective on the macro-evolution of the nervous system notes how various physiologically differentiated regions and units have evolved to serve functionally differentiated processes, such as differentiated perceptual systems, basal ganglia specialized for action, and so on. What is less commonly noted is that such functional process differentiation and specialization *ipso facto* constitutes differentiated and specialized resources for learning. I will use this point as a focal theme for integrating a brief overview of the macro-evolution of the brain.

The central recognition is that all learning is constituted as variation and selection processes, and that variations are necessarily variations in some functionally available space of possible processes — variations must be functionally accessible from already available organizations of processes. Variations, in other words, are not free. They are enabled and constrained by the kinds and organizations of the dynamics within which and out of which they occur.

Possible learning variations in the simplest cases might be variations in the concentration of some local hormone that regulates other activity — perhaps precursor to a synaptic neurotransmitter (Nicholson, 2000; Nieuwenhuys, 2000). Such possibilities for variation are inherent in the dynamics involved, and are constrained by those same dynamics. Release of such substances, or generation of a synaptic connection in a more

sophisticated organism, are not fixed. Synapses are not soldered wires. They are relative steady states of ongoing turnover and maintenance relative to such turnover of particular configurations of cellular processes.

Such “steady states” are not absolutely steady, but will inherently involve some variation. If that variation narrows toward a successful value or process when such success is encountered, then we have a primitive version of variation and selection learning.

The crucial point here is to note how the space of possible variations is a property of the dynamics in which those variations can occur. Changing the *organization* of those processes, then, will also change the spaces within which variations and selections, thus learning, can occur. And changing the *architecture* within which those processes occur can change their organization, thus the spaces of possible (or at least easily accessible) variations.⁶

1.2.1

Some Differentiations and Specializations

The evolution of the nervous system has involved multiple such differentiations and specializations for kinds of functions — and that enable further evolution. Early evolution generated architectures that enabled flexibility in processes as well as in further evolutionary differentiation — for example, as neural networks became nervous systems

⁶ That the processes by which variations are generated are themselves aspects of adaptability follows directly from the nature of variation and selection processes (Bickhard & Campbell, 2003). But it is an aspect that has often been overlooked in the focus on selection effects per se (for related discussions, see Brooks & Wiley, 1988; Brooks, Collier, Maurer, Smith & Wiley, 1989; Weber, Depew & Smith, 1988; Kauffman, 1993).

with (head) ganglia and chordate organization (Fritzsche & Gloverb, 2007). This constitutes a partial differentiation between processing and communication, and enables partially independent further evolution for each.

Functional modularization is an important theme in the macro-evolution of the nervous system. Such modularization enables functional specialization, and also variation generating learning specialization, as discussed above. Another important theme is that some architectural developments enable much simpler further evolution. For example, differentiation of relatively specialized nuclei not only enables relatively specialized functioning and concomitant learning, it also permits partially independent further evolution of the nucleus' architectures supporting those processes. I will mention one crucial example of this below: the emergence of the laminar organization of the cortex. Yet another theme in the macro-evolution of the nervous system is a progressively more powerful exploitation of the properties and powers of microgenesis.

Differentiations of processes that regulate conditions and processes internal to the body are an early functional differentiation, (partially) distinct from those that coordinate interactions with the external world. Architectural and functional differentiations can also generate and enable macro-evolutionary emergences, such as the co-evolution of synapses, muscles, and skeleton (Moreno & Lasa, 2003; Nieuwenhuys, 2000).

Within architectures for interacting, differentiations and specializations emerged for *detection* interactions and for selecting and guiding *action* and interaction with the world. Within forms of detection interactions, specializations evolved for differing modalities within which important kinds of detection occurred, for coordinations among those modalities, and, regarding interactions with the world, for varying sorts of coordinations

of multiple muscle and skeletal groups, and, most importantly, for increasingly complex and sophisticated anticipations of what organizations of (inter-)action are possible and for selections within them (Arnal & Giraud, 2012; Kovach et al, 2012; Zacks et al, 2007). In more complex organisms, these evolved toward perceptual systems, supported by the thalamus, and environmentally interactive systems, supported, for example, by the basal ganglia (Redgrave, Prescott, Gurney, 1999).

I will be mostly focused on a few major differentiations in the human brain, using these to illustrate how a system of oscillatory processes engaged in ongoing mutual modulations can constitute a functional system (Levine, Brown & Shirey, 2000) — a system that does not function in terms of (presumed semantic) information flows and information processing.

1.2.1.1

Emotion

A crucial aspect of the interactive model is its model of emotion, and of the role that emotion has in macro-evolution and learning. The central notion of this model is that it can be advantageous to an organism not only to respond to novel situations with learning trials, in which previous microgenetic learning is not already stabilized around processes that anticipate successful interaction, but to be able to respond *in interaction* as well as in learning to the fact that the organism is dynamically uncertain about how to proceed. That is, it would be advantageous if the organism could “*detect*” its own condition of uncertainty about what to do next, and develop categorizations of *types* of such

uncertainty and concomitant *orientations toward heuristics* of how to successfully interact with such uncertainty-situations.

An ability to respond to *kinds* of uncertainty situations enables the organism to, for example, categorize situations involving an unknown large animal in such a way as to elicit the general heuristic of getting away from that situation — run like hell. This can avoid the risks involved in more primitive trial and error learning in uncertainty situations (Bickhard, 2000b).

Emotion processes, I propose, are future oriented evaluative arousals of kinds of heuristics for dealing with (kinds of) uncertainty within microgenetic processes (Bickhard, 2007a, in preparation; Damasio, 1995, 1999; Panksepp, 1998).⁷ Microgenetic uncertainty, in turn, corresponds to dynamic uncertainty⁸ about how to interact with the eliciting situation.

Support for such interactive responses to uncertainty should evolve within the general *anticipatory framework* of detection and interaction processes, and, therefore within the framework of nervous system supports for detections and interactions. It is with respect to encounters with and anticipations of failure and success that uncertainties (or the lack thereof) are evoked. More powerful abilities to respond to uncertainty, thus, should co-evolve with more powerful abilities to anticipate — to anticipate success, failure, and further uncertainty. The emotion (limbic) system fits both the macro-evolutionary

⁷ The identification of such processes as ‘emotion’ requires further elaboration and argument (Bickhard, 2000b, 2007a, in preparation). The central point for current purposes is that the ability to interact with microgenetic uncertainty constitutes a powerful adaptive possibility, and, therefore, that it is a plausible phase in the macro-evolution of the central nervous system.

⁸ Perhaps dynamically constituted in chaotic processes.

sequence prediction of this model, and also the architectural and functional tight integration with thalamus and striatum.

Within these supports, it is to be expected that there may be partial differentiations and specializations for centrally important kinds of emotional uncertainty detections and resultant future orientations, such as for fear, for example, and these too are found in the overall limbic organization (Panksepp, 1998). Further emotional differentiations and orientations can be learned in socially and culturally specific contexts (Adolphs & Heberlein, 2002; Harré, 1986).

1.2.1.2

Episodic Memory

Primitive anticipations are of very general possibilities, such as “a swimming situation” or “a tumbling situation”. These become more specific and differentiated with more complex agents, such as “a tongue flicking and eating in such-and-such direction situation”.

As they become increasingly specific, differentiated, and complex, they also inherently become increasingly historicistic — dependent on the particular and contingent experience of the organism. Web organizations of an organism’s conditionalized anticipations of what it could do constitute that organism’s knowledge of the interaction potentialities of its current situation — its *situation knowledge*. A major organizational principle of such contingent bases for anticipation is space (O’Keefe & Nadel, 1978), and, of course, anticipation is already inherently temporal: situation knowledge is inherently here and now as well as there and then. A general ability to explore historicistic

experience for possible anticipations constitutes episodic memory; explorations of variations on such contingencies constitutes future and counterfactual thinking (Atance & O’Neill, 2005; Bickhard, in preparation; Botzung, Denkova, Manning, 2008; Hassabis & Maguire, 2007). These are important particular versions of general anticipatory and learning phenomena.

Support for this special form of learning and anticipation should evolve along with emotion — which involves powerful anticipatory functions — and in integrated functional architecture with supports for the learning and construction of situation knowledge organizations, and for the potentialities for success and failure within those organizations (Murray, 2007). In accord with this point, the hippocampus and the amygdala have evolved in concert from early pallium (Broglia et al, 2005), and maintain close functional relationships (Grahna, Parkinson, Owena, 2009; Mizumori, Puryear, Martig, 2009; Pitkänen et al, 2000; Price, 2002).

1.2.1.3

Dynamic Modulation

Microgenesis in simple nervous systems is itself relatively simple, perhaps involving “just” variations in synaptic strength. But one major theme in the macro-evolution of nervous systems is the progressive further exploitation of the powers and enablings of microgenesis. The advantages of partial specialization and modularization — for both interactive functioning, and for the emergence of powerful spaces of potential variations in learning — has been mentioned.

Another major step in the exploitation of microgenesis is the development of the ability for microgenetic uncertainty to evoke not only learning destabilizations, but also to influence directly the resolution of what to do next — an evolutionary development that permits the organism to interact with its own condition of microgenetic uncertainty: emotion.

A further phase in this exploitation of microgenesis is the evolutionary emergence of the ability for some parts of the CNS to interact directly with the microgenetic processes in other parts.

There are several aspects to the emergence of this ability. One is the evolution of partially differentiated microgenesis and interactive processes. One basis for this differentiation is the progressive increase in glia, both absolutely and in percentages, over the course of macro-evolution (Baumann & Pham-Dinh, 2002; Nieuwenhuys, 2000; Verkhratsky & Butt, 2007). This, along with further development of silent neurons, volume transmitters, and other differentiations of scale, permit modulations of large scale microgenetic processes that are partially differentiated from small scale faster processes. This is the central point of Part I of this model.

Another aspect is the evolution of the laminar architecture of the cortex — in which the differentiation of microgenesis is at a maximum. This laminar architecture is a very general dynamic support with high flexibility in the potential microgenetic modulations that it permits. It is an approximation of a(n endogenously and concurrently active) dynamic systems version of a “programmable” central processing unit (though there are also partial specializations within that basic architecture).

A concomitant enabling of a laminar architecture is that it makes the evolutionary generation of more processing support relatively “easy”. The internal micro-architecture of nuclei can be detailed and complex, and, therefore, relatively difficult to modify and expand. A laminar architecture (to a first approximation) can, in contrast, “simply” be expanded into more *area* of laminar organization (Aboitiz, 1992).

1.2.1.4

Internal Interaction: Reflection

Powerful exploitation of these potentials, however, also requires some degree of modularization and specialization of supports for (internal) interactions with microgenesis. In the mammalian line, this has emerged as an extension of interactive — motor — cortex with an ability to internally interact with multiple domains of the CNS, and with microgenesis processes, especially elsewhere in the cortex. This is the pre-frontal cortex. Pre-frontal cortex co-evolved with possibilities of internal dynamic modulation of microgenesis: dynamic modulation possibilities enabled internal interaction with microgenesis processes.

This constitutes a kind of internal interaction with internal microgenesis and situation knowledge processes: these *internal* processes constitute the “environment” for such internal interactions in a manner similar to that of the external environment for external interactions. In the sense in which external interactions represent and know that environment, the internal interactions represent and know those internal cognitive and emotional processes — they constitute internal ‘knowing’ processes, internal reflection.

The cortex, thus, is, to a first approximation, a general “programmable” dynamic processing architecture. There are, however, several disanalogies with a programming model. One is that the cortex, along with the rest of the nervous system, is *endogenously* active, rather than constituted out of passive elements, as in a computer. Another is that it is *concurrently* active across its entirety. A third is that modulations among endogenously active processes are not definitive “instructions” in the manner of a computer. And a fourth is that the pre-frontal cortex does not *command* such instructions to the rest of the CNS — just how the global CNS arrives at resolution of what to do next is further addressed below.

1.3

Forms of Metamodulation

Microgenesis in various parts of the CNS, especially the cortex, is modulated via a macro-interconnected system of several major divisions. It is important to note that these macro-scale architectures support macro-level oscillatory processes: they are not (semantic) information processing circuits, though they are most commonly interpreted in that guise.

1.3.1

Thalamus-Cortex

Among the most important of these macro-scale architectures are the reciprocal projections between thalamus and cortex (Churchland, 1995; Hoppensteadt & Izhikevich, 1998; Izhikevich, 2001, 2002; Izhikevich, Desai, Walcott & Hoppensteadt, 2003; Purpura & Schiff, 1997; Steriade, 1996; Steriade, Jones, & McCormick, 1997a, 1997b). Such

reciprocal connections are ideal organizations for oscillatory processes within the reciprocal organizations.⁹

Together with the multiple intra-cortical connections, these loops introduce a fascinating possibility. Some neurons have natural resonance frequencies, and neural circuits, especially loops, can also have natural resonance frequencies. If one area of cortex generates signals with a particular carrier frequency, broadcast broadly to many other cortical areas, only those other areas that have that same (or close enough) resonance frequency will pick up those signals. This could constitute a general broadcast of signals, that are nevertheless targeted for those other areas with the same resonance frequency. This is formally akin to FM radio (Hoppensteadt & Izhikevich, 1998; Izhikevich, 2001, 2002; Izhikevich, Desai, Walcott & Hoppensteadt, 2003).

Furthermore, the thalamic loops with cortical areas are ideally placed to influence those resonance frequencies, and could tune them variously in an ongoing fashion. As various areas of the cortex are induced to have similar resonance frequencies, they become functionally connected and integrated via being able to “pick up” each others’ signals. The thalamus, thus, could, in effect, reconfigure the functional architecture of the cortex in an ongoing fashion — the thalamus could “tune” the functional architecture.

Further, insofar as the thalamic loops connect with the larger scale, slower processes in cortex (ascending reticular, etc.: Lewis & Todd, 2007; Steriade, 1996), these modulations and reconfigurations will be with respect to the microgenesis processes taking place in those cortical areas.

⁹ “Re-entrant” is a common term for this architecture, but it carries the connotation that what is being “re-entered” is semantic information, and that is false.

These points, of course, raise the question of what modulates the influences of the thalamus? What regulates the thalamic regulations of cortical processes and functional configurations?

1.3.2

Prefrontal-Striatum-Thalamus-Prefrontal

The ultimate answer to this question, of course, is the overall global activity of the CNS, but one particular architecture is worth examining in a little more detail in order to illustrate how this might work.

The architecture that I will expand is the loop from pre-frontal cortex to striatum to thalamus and back to pre-frontal (Crosson & Haaland, 2003; Edelman & Tononi, 2000; Fuster, 2004, 2008; Koziol & Budding, 2009; Marzinzik, Wahl, Schneider, Kupsch, Curio, & Klosterman, 2008; Middleton & Strick, 2000; Smith, Raju, Pare, Sidibe, 2004).¹⁰ This loop is now recognized as participating in cognitive processes, contrary to the classical view of the basal ganglia as being dedicated exclusively to motor processes (e.g., Balleine, Delgado, Hikosaka, 2007; Koziol & Budding, 2009). But the loop is, as is by now familiar, interpreted as supporting information flow and information processing, where the information is assumed to be semantic (representational) information. The general critique of encoding models, which include information semantic models (Bickhard, 2009a), renders this an impossible interpretation.

¹⁰ This is much more complex than I will expressly take into account: the striatum is itself differentiated into rough architectural components, the loop in some respects is a four (or more) node loop, not just three, and there are within-nuclei differentiations as well as between-nuclei differentiations. One example of the latter point is that the head of the caudate is more specialized for cognitive processes, while the tail of the caudate is involved in more traditional motor processes (Koziol & Budding, 2009).

To understand this architecture within the general oscillatory-modulatory functional framework, consider first that a multi-node loop is just as capable of oscillation as is a two-node loop. So the loop itself could support oscillatory processes. Furthermore, the loop is most commonly presented as if the projective segments of it are unidirectional, from pre-frontal to striatum to thalamus to pre-frontal. We know, however, that virtually all projections in the CNS are reciprocal (Adolphs & Heberlein, 2002; Deacon, 1989, 1997; Ohye, 2002), and that this holds at least for some parts of this larger scale loop as well (Fuster, 2008; Middleton & Strick, 2000).

If so, then not only is the large loop potentially oscillatory, so also is each segment. Instead of linearly carrying semantic information, then, this loop, and others like it, can participate in various forms of intra-loop modulations of activity that can, in turn modulate other processes. One set of other processes that can be modulated by processes in this loop are the thalamic modulations of cortical activities and cortical functional configurations.

This is a drastically different framework for understanding CNS functional processes. Note that, on standard information processing views, it is superfluous for such loops to exist, and for such reciprocal projections to exist. This is similar to the sense in which, on standard views, it is superfluous for volume transmitters, silent neurons, astrocyte processes, and so on to exist.

1.3.3

Other Prefrontal Loops

Other major loops involving the pre-frontal cortex are with the cerebellum and thalamus, and the limbic system and thalamus (Koziol & Budding, 2009; Price, 2002). There is convergence of these loops in the general area (and subdivisions) of the pre-frontal cortex, and in various subdivisions of the thalamus, thus permitting joint influence on each other as well as other processes in the cortex and other subcortical structures. Limbic loops are involved in emotional processes and memory, while cerebellar loops exert fine feedback system control over motor, cognitive, emotional, motivational, and sensory processes (Koziol & Budding, 2009; MacLeod, 2012; Molinari, 2002).

There is also high interconnectivity of prefrontal cortex with other areas of the cortex, primarily *not* those relatively dedicated to sensory or motor functions (Fuster, 2008), so there are oscillatory and modulatory loops within loops that connect prefrontal cortex with sub-cortical areas, back to prefrontal, as well as to other portions of the cortex, and again to prefrontal. Prefrontal cortex, thus, is in ideal architectural position to engage in mutual and integrating influences with subcortical areas, and *with other areas of the cortex itself*.

We now have a rough outline of a model of CNS functioning organized around:

- well-habituated feedback control, with little anticipation of the possibility of error, via the cerebellum;
- ongoing planning and feedback control, not necessarily well habituated, via the striatum;

- more complex anticipations, including of possibilities of error, via the limbic architectures;
- finer and more elaborate differentiations of situation knowledge, increasingly specific to here and now (and there and then) for corresponding power in planning and in anticipating possible successes and errors, via limbic and hippocampal structures (with partial sub-differentiations for types of emotional responses);
- and elaborations of frontal (motor) cortex that interact with microgenesis in other parts of the brain, especially other parts of the cortex.

Learning within the microgenesis processes in pre-frontal cortex, thus, constitutes learning of dynamic modulational “programming” for other areas of the CNS.

1.4

Thought as Internal Interaction

The model as outlined so far has a number of interesting properties. The basic framework of anticipation and interaction yields consequences that the processes are inherently situated and embodied because the interactions require a body in some situation (Bickhard, 2008b). The flow of interaction as influenced by the anticipatory organizations of situation knowledge is inherently contentful, and, in sufficiently complex organisms, is saturated with emotional tone and memory.

The internal interactions of the prefrontal area with other processes in the CNS capture a second level of knowledge: knowledge of the organizations and flows — and attractor landscapes — of first level interactive processes (Campbell & Bickhard, 1986).

This fits Piaget’s notion of thought as internal interaction. I have argued elsewhere that “experiencing of experiencing” emerges in these internal interactions, yielding what are mis-labeled “qualia” (Bickhard, 2005a).

Second level, internal, interactions are suited for examining situation knowledge in order to more powerfully anticipate possibilities and impossibilities in further interaction with the environment — for planning, future exploration, counterfactual exploration, holding goals and values in relative stability, exploring new possibilities of variational construction and selection criteria, various kinds of self-regulation, and so on (Lewis & Todd, 2007). They are suited for powerful forms of learning to learn.

In multiple respects, then, the model offers an emergence interface between the functional/biological level of process and the cognitive/phenomenological realm. These are explored more fully elsewhere (Bickhard, 2009a, 2009b, in preparation).¹¹

1.5

The Predictive Brain: A Comparison

There are some interesting convergences between the interactivist model and a family of related models called variously the predictive brain, the Bayesian brain, or action oriented predictive processing (Clark, 2013). In particular, both approaches emphasize future oriented prediction or anticipation. This is especially evident regarding Sokolov habituation, which both approaches characterize in terms of anticipations which are, in

¹¹ For a model of language within this framework, see Bickhard (2007b, 2009a, in preparation). For perception, see Bickhard & Richie (1983) and Bickhard (2009a, 2009b, in preparation). In the standard information processing framework, perception is construed as an input flow into cognition, and cognition, in turn, generates an output flow into action or language. These presumed input and output flows are among the most seductive pulls into an information processing view. This seduction fades, however, if it is recognized that perception, cognition, action, and language (not to mention emotion, etc.) are *all* interactive processes, not information flows.

effect, ‘subtracted’ in comparison with input flow, thus yielding a zero result if the anticipations are accurate, and a residual signal inducing arousal or further processing if they are not accurate.

Nevertheless, there are significant differences between the approaches, and I would like to outline some of them here. The predictive brain family of models is large and complex, and has developed multiple variants over the last decades; I will address some of the most basic framework differences but focus primarily on a few differences with regard to functional characteristics of the brain.

1.5.1

Predictive Brain Models

The predictive brain program developed out of a Helmholtzian framework for perception, in which input sensations are presumed to form the basis for inference to representations of the world. Two major advances within this framework were the analysis by synthesis movement of the 1960s and the related recognition that actions might be performed for the sake of the inputs which they induce from the environment. In the analysis by synthesis movement, synthesizing, or predicting, input sensations — a form of abduction — was substituted for more classical induction and deduction forms of inference from sensations to the world (MacKay, 1956, 1969; Neisser, 1967). Recognition that interaction could induce perceptual inputs grew out of the cybernetics

movement (Powers, 1973) and resonates with Gibson's notions of sensory interactions (Gibson, 1966, 1979).¹²

An important elaboration of these ideas was to postulate Bayesian decision procedures (or approximations thereof) as the form of the predictive processes. Bayes procedures involve prior probability distributions that are modified into posterior probability distributions on the basis of current data. Those posterior probability distributions constitute the (probabilistic) predictions concerning the input. What is being predicted, thus, is the probability distribution of the input pattern or flow.

Bayes requires a source of *prior*, initial, probability distributions, and this lends itself to postulation of a hierarchy of levels of Bayesian procedures, each predicting the inputs from the level below, and sending those predictions to the level below. The lowest level predicts sensory inputs and sends the errors of those predictions upward to the next level, which, in turn attempts to predict those discrepancies from the lower level. Collectively, then, such a hierarchy can account for the "errors" of prediction resulting from lower levels until, optimally, all of the distributional patterns of the inputs are accounted for. It has been proposed that such a hierarchy constitutes the basic functional architecture of the brain (Friston & Stephan, 2007).

Friston has also proposed an integrating framework for such models centered on a statistical notion called "free-energy":

"The basic premise we start with is that biological systems must keep γ [" γ can be regarded as sensory input"] within bounds (i.e. phase-boundaries) through adaptive changes in α .["effect[s] of the system on the environment"]

¹² Though they are strictly inconsistent with Gibson's claim that perceiving is not based on intermediate representational sensing (Gibson, 1979; Bickhard & Richie, 1983).

Put simply, adaptive systems or agents should minimise unlikely or surprising exchanges with the environment.” (Friston & Stephan, 2007, p 425)

That is, they should minimize free energy. The reason that agents will tend to minimize free energy (surprise, or unpredicted input) is that ancestral organisms that did not so minimize would fail to keep inputs “within bounds” and thus cross phase boundaries and cease to exist. Such evolutionary dissolution would tend to eliminate those agents who did not minimize free energy, and, thus, select for such a tendency to minimize in future populations.

Friston argues that, within this framework, there is no need to postulate normative phenomena such as goals or preferences or values — higher level “expectations” will yield actions that produce “expected” consequences. These higher level expectations are constituted by higher or highest level Bayesian priors, that are ultimately innate. Such expectations yield actions that produce outcomes that are generally thought of as desirable, but without any explicit consideration of utility or value — value considerations are built into the functioning of the higher level expectations. Thus, minimizing free energy — surprise — drives both evolution and action.

1.5.2

Some Problems

A most basic problem with these models is that they assume classic sensory encoding empiricism. Inputs, in such models, must be somehow transduced into representational sensations in order to support the inferences that are supposedly based on them. No one has been able to provide a model of such transduction of factual input into representation in several millennia of trying, and there are in principle grounds for concluding that this

is impossible. Those are outlined in part I of this paper (see also Bickhard, 2009a and multiple other references).

Furthermore, even if sensory transduction of inputs into sensations is accepted, no one has been able to account for how higher level representations, such as of chair or triangle or the number ‘3’ or the concept of justice, etc., could possibly be constructed out of such input sensations. The predictive brain approach, in fact, seems weaker in this regard than classical sensory empiricism: classical models could postulate various kinds of aggregations and organizations of sensory inputs, while the Bayesian brain approaches are limited to parameters of probability distributions over lower level spaces of parameters of probability distributions over ... over patterns and flows of sensory inputs.¹³

The predictive brain approaches and the interactive model have a strong convergence with regard to the general emphasis on anticipation or prediction, and especially for the particular case of Sokolov habituation. For the predictive brain models, the brain attempts to predict inputs, and matches the predictions against the inputs via something like a subtraction process, so that any discrepancies yield a non-zero “error” signal. For the interactive model, local brain processes “attempt” to anticipate their own near future processing (via microgenetic set-up for such processing). If the only relevant activity — process — of a local domain is that of *registering inputs*, then anticipation of local processing converges with *prediction of inputs* to that processing.

¹³ Note that the spaces over which these parameters ‘parameterize’ — spaces of functional forms for prediction — must themselves be already available (Friston, Daunizeau, Kiebel, 2009 on switching between functional forms)— presumably innate. The highest level innate priors are the highest level instance of this point.

The apparently subtle difference between predicting inputs and anticipating local processes, however, generates major divergences in other cases. With regard to classical conditioning with respect to a shock grid, for example, the interactive model proposes that there are no subtractive processes possible for pain inputs (habituation, to a first approximation, is not possible), thus generating destabilization of the microgenesis processes that failed to anticipate, and, thus, that the only way to successfully anticipate such internal processes is to avoid the shock. Within the predictive brain framework, in contrast, the rat on the shock grid should, upon hearing the tone that signals shock, simply predict pain inputs — successfully — and stay on the grid. Friston could postulate some sort of highest level expectation for avoiding pain, an innate “hyperprior” perhaps, but this encounters problematic exceptions, such as for *seeking* pain inputs, e.g., from hot peppers. Accounting for such exceptions and exceptions to exceptions, etc., yields an epicyclic elaboration of ad hoc “expectations”.

Similarly, if successful prediction is the only criterion, why wouldn't a person simply head for a dark room and stay there? Prediction of input is easy if there are no inputs (Clark, 2013). Again, Friston can claim that there is a high level expectation to avoid darkness, and that thus produces action such as turning on a light (Friston, 2013). But again there are exceptions: sometimes a person *wants* darkness, perhaps to sleep, or hide, or hunt.

Such examples demonstrate that the free energy principle cannot account for utility, or normative phenomena (Roesch, Nasuto & Bishop, 2012) — all such considerations have to be already built-in to the system, by the designer in the case of artificial systems

and presumably by evolution in the case of living systems (Friston, Daunizeau, Kiebel, 2009).

The basic problem is already manifest in the “basic premise” quoted above. First, phase boundaries are not necessarily “bad” for an organism; they are intrinsic in internal structure, both of cells and of organisms, and “crossing” or changing such boundaries is intrinsic to learning and development. So “phase-boundaries” does not work as an explication or definition of keeping inputs “within bounds”. Further, “within bounds” does not specify what constitutes relevant bounds. Assuming that staying “within bounds” is equivalent to minimizing surprise, prediction failure, is not supported — once again, there seem to be important exceptions and counterexamples. For example, seeking surprise would seem to be central to novelty seeking, play, exploration, esthetic motivation, and so on — all central to human adaptive behavior. Normativity, whether of representations or actions (or emotions, etc.), is fundamentally missing from these models.

The evolutionary-selection account of why organisms would tend to minimize surprise renders “minimizing surprise” a consequence of evolutionary history, not an intrinsic property of living beings. This is different from, for example, enactivist models in which autopoietic construction of the system’s own components is claimed to be inherent to life (Maturana & Varela, 1980; Varela, 1997; Weber & Varela, 2002). And it is in *strong* contrast to the interactivist model which focuses on the point that maintaining essential thermodynamic relationships with the environment (self maintenance) is *in fact* ontologically inherent to living beings, not just a contingent point about their evolutionary history (Bickhard, 2009a).

The proposal that the hierarchical form of processing — in which each layer attempts to predict the “errors” generated by the predictions of the lower layer, and sends its own “errors” to the layer above — constitutes the basic functional architecture of the brain seems to have a partial fit to the visual system (and perhaps to other sensory parts of the brain) in that it can be modeled as ‘layers’ of cortex that reciprocally project between adjacent layers. Many details of this perspective are unclear, including whether or not the reciprocal projections carry the kinds of “prediction” and “error” signals postulated, but when consideration turns to more general considerations, the model does not fit at all.

Among other problems, such a hierarchical model does not account for:

- Multiple node (non-hierarchical) loops, such as from prefrontal to basal ganglia to thalamus to prefrontal;
- General widespread neuromodulator projections, such as of dopamine (Marder & Thirumalai , 2002; Marder, 2012);
- The functionality of silent neurons;
- The functionality of astrocytes;
- And has no non-ad hoc account for such phenomena as the ubiquitous oscillatory-modulatory activity of the brain, the vast ranges of physical and temporal scale involved in various of these processes, and so on.

In addition to the basic conceptual framework problems, thus, the model has serious flaws as a general model of brain functional architecture.

The predictive brain approaches propose that the brain is engaged in *global* prediction of sensory inputs, including the inducing of such inputs via action. The interactivist

model proposes that each *local* region of the brain is engaged in its own anticipative microgenetic adjustments which tend to stabilize if microgenesis successfully anticipates *local* flow of processing. For the predictive brain, it is the inputs and derivatives from them that are supposedly representational. For the interactivist model, it is the *anticipating process itself* that is representational, *not the inputs*. These differences and their consequences appear to be crucial.

1.5.3

Hierarchical Time Scales

In addition to the emphasis on prediction or anticipation, there is another terminological convergence between the Bayesian brain model and the interactivist model that is worth commenting on: time scale differentials. In the Bayesian brain models, higher levels track changes in the environment that are supposed to change more slowly than lower levels. Lower levels, for example, might anticipate sensory inputs while higher levels anticipatively track objects that “cause” those sensory inputs — the objects change more slowly than the sensory flows that they “cause”.

In the interactivist model, spatially larger processes, such as astrocyte processes and volume transmitter diffusions, are dynamically slower than smaller, faster processes, such as classical synapses or gap junctions.

Thus the neural-glial level dynamics in the interactivist model are slower at larger spatial scales, while the neural-glial dynamics in the Bayesian brain model might well be at the same time scales at all ‘predictive’ levels, but what they track, and, therefore, some “tracking” aspect or property of that dynamics will be slower than at lower levels. The

time scale differences for the Bayesian brain models are a reflection of presumed time scale hierarchical differences in the environment: sequences of sequences change more slowly than sequences per se (Kiebel, Daunizeau, Friston, 2008). For the interactivist model, time scale differences are inherent in the nature of the neural-glia dynamics, regardless of what they might or might not be tracking or at what ‘environmental level’ they might be tracking. In general, the interactivist model is not built on information semantic notions such as tracking, though non-semantic information relationships may certainly exist and be useful in some cases (see discussion below).

So, as with “anticipation”, the two models make use of similar notions, but to refer to fundamentally different kinds of dynamics.

1.6

Information? Of Course!

I have argued against semantic information models throughout this paper, including those of the predictive brain approaches. Lest this be understood as arguing against the functional importance of information per se, I would like to mention some considerations supporting that importance.

The crucial point is that information is a technical term meaning, roughly, being correlated with, and information in this sense is essential for an organism to be appropriately sensitive to conditions in the environment in its interactions with that environment. If there were no processes in the brain that were correlated with properties of the environment, the organism’s interactions would have no ability to take the

environment into account. But there is no necessity for such correlated processes to be representational.

In this sense, information is a control theoretic notion, and a fundamentally important one, not a semantic notion (Bickhard & Richie, 1983). And it is involved in all of the modulatory influences in the CNS: each local process sends signals to related domains that are correlated with — that are in a control theoretic informational relationship with — the local processes that generate those signals. The entire CNS, then, can be viewed from a correlational information ‘processing’ perspective, but the only such informational relationships that are representational are those that modulate (‘control’) microgenetic anticipatory set-up processes. That is, it is ‘information’ that control theoretically anticipates the future of endogenous processes that is representational (Bickhard, 2000c).

Furthermore, *extraction* of higher order (partial) correlations can be important because those can be the correlations that an organism should be responsive to. In that sense, information *processing* is crucial. But it is the *generation* of future oriented anticipatory information — which does not necessarily occur via extraction — that generates and evokes truth valued process, and, thus, representation.

So, the issue is not whether information and information processing exist — of course they do. The issue is not whether information and information processing are important — of course they are. The issue is what kind, if any, of information generates or constitutes representation. And the answer is that it is future oriented anticipatory information that influences further processes — information that can modulate, regulate, or control further processes — that has truth value and thus constitutes representation.

Information, thus, is crucial to anticipation, but it is only the anticipation that can be representational.

One consequence of this point for brain functionality is that information serves an ongoing modulatory influence on further processing. Information is not a representational state that needs to be created or retrieved — it is a property of real time ongoing influence of some processes on other processes. The brain, thus, does not function in terms of creating stable representational conditions and then (inferentially) responding to them. CNS processes are always in transit, always influencing other processes, always being influenced by other processes. In this sense, it is the dynamic transients that are of importance, not any stable attractors (Rabinovich, Huerta & Laurent, 2008; Rabinovich, Afraimovich, Bick & Varona, 2012).

2

Macro-CNS Processes

A basic issue that remains to be addressed is that of how the global processes in the CNS achieve a functional and pragmatic coherence. As mentioned, the “obvious” answer that the prefrontal area enforces such a coherence suffers from a serious homunculus regress — how does the prefrontal area “decide” what it, and therefore, everything else, is supposed to do?

The general form of the answer has already been introduced: self-organization. Multiple processes that are endogenously and concurrently active may form multifarious resultant kinds of processes. They may be chaotic, and chaos is in fact a highly functional form of process for some conditions, such as when awaiting some further

determination of activity (Freeman, 1995, 2000a, 2000b; Freeman & Barrie, 1994; Bickhard, 2008a). They may exhibit instability that is a form of incoherence — of *conflicting* orientations and kinds of preparedness — rather than of chaos, but note that such global instability also forces local anticipations to fail, and, thus, to evoke learning processes. So a lack of global coherence contains its own instabilities.

Or they may exhibit self-organization into some coherent trajectory of further processing. Self-organization occurs when multiple micro-level processes compete to recruit other local processes to themselves — as when “random” molecular motions in a pan of heated water recruit neighboring motions into macro-level boils of water. Self-organization is a macro-perspective on micro-level recruitment competition. In the brain, there are many ongoing processes that participate in such self-organization. These processes, as mentioned above, involve interactive anticipations; situation knowledge anticipations of success and failure and uncertainty; emotional orientations to attempt to deal with various forms of uncertainty; use of memory, future, and counterfactual organizations of contingent possibilities, enablings, and failures to enhance anticipation and planning; and so on. These processes modulate and compete with each other, yielding the potential for the self-organization of globally coherent activity. Pre-frontal cortex is in a position to maximally support such process and functional coherence — multiple kinds of process can integrate there — but it is not a supreme executive.

2.1

Multiple Considerations

The differentiated processes that participate in the global self-organizing flow of CNS activity are specialized for differentiated kinds of sensitivities and modulations. All local activities in the CNS tend to evoke other processes that generate successful interactions with the given local activities, but there is constant ongoing competition among them. Thus, the overall self-organizing process (a flow, with no final self-organized state) tends to maintain self-anticipatory success among interactions with the external world, with respect to situation knowledge, with the body (e.g., hunger), with relatively stable set points or goals, with more stable guidances at higher knowing levels (meta-goals, meta-attitudes, values), with emotional heuristic anticipations, and with internal thought processes.

Self-organization of the CNS, thus, is with respect to competitive modulations from all areas. Local processes will have functional effects in terms of what they tend to elicit or modulate in other processes, and these effects compete in the overall self organization. The functional efficacy of such local processes is massively constrained by architecture, but also massively constrained by learning — learning what sorts of local modulations and processes will succeed with respect to neighboring modulations.¹⁴

¹⁴ Variants on models of CNS self-organization can be found in, for example, Arbib (1972) and Juarrero (1999).

2.1.1

Synergetics

As the adversions to self-organization make clear, both micro- and macro- brain dynamics are instances of synergetic processes: resultants of ‘cooperative’ activity within complex systems (Haken, 1980, 1983, 2010). In one sense, this is necessarily the case, and can be seen to be necessarily the case once it is recognized that all parts of the brain are dynamically coupled, and ongoingly, endogenously, and concurrently active — there are no passive pure recipients of inputs. Consequently, any activity will be the result of synergetic mutual influences among the multifarious components. The notion of *control* parameters captures part of such mutual influence, though it is not as clear that the notion of *order* parameters is directly applicable: all processes are engaged in transient dynamics, and it is only with respect to much higher order functional properties that are both relational and time varying that full self-organization occurs, so there would not seem to be any fixed order parameters. Perhaps this could be approximated with a complex foliation of center manifolds within which the control parameters induce trajectories (Izhikevich, 2007).

3

Conclusion

There is a strong consilience of theory and evidence that the CNS functions in terms of oscillatory processes that modulate each other at multiple scales and within multiple architectures. There is an inherent anticipatory aspect to these processes, which gives rise to representation and cognition. The multiple modulations give rise to an overall

ongoing self-organization of activity that resolves the flow of process in ways that are sensitive to multifarious considerations, such as interaction, thought, planning, emotion, and memory. This flow is inherently contentful, situated, embodied, saturated with meaning, anticipatory, and, via internal reflective interaction, capable of experiencing the flow of experiencing (Bickhard, 2005a).

Such a theoretical framework is in strong contrast to standard assumptions that the nervous system processes semantic information. There are a large family of arguments that this cannot be the case (Bickhard, 2009a). Information in the technical sense is necessarily involved, but this does *not* constitute semantic or representational phenomena (Bickhard, 2000a).

This model is an interpretive framework that fits with extant knowledge of brain architectures and processes, as well as with multiple theoretical and philosophical considerations. It is hoped that it provides a fruitful framework within which to explore, develop, and correct more detailed models.

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