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ORIGINAL PAPER

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

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Abstract The first paper in this pair (Bickhard in Axiomathes, 2015) developed a model of the nature of representation and cognition, and argued for a model of the micro-functioning of the brain on the basis of that model. In this sequel paper, starting with part III, this model is extended to address macro-functioning in the CNS. In part IV, I offer a discussion of an approach to brain functioning that has some similarities with, as well as differences from, the model presented here: sometimes called the Predictive Brain approach.

Keywords Interactivism · Representation · Learning · Brain attractor landscapes · Neural loops · Predictive brain

1 Introduction

In the first of this pair of papers (Bickhard 2015), a model of the nature of representation and cognition was outlined, and, on the basis of that model, some properties of the micro-functioning of the brain were derived. It was shown that the brain does in fact function with those properties, and, an outcome in the reverse direction, that what we know about brain functioning yields the essentials of the representation and cognition model as a consequence.

The model of representation is in terms of functional "anticipations" of possibilities of action and interaction—the crucial representational emergence is that such anticipations can have truth value: they can be true or false. This is an interaction based—a roughly pragmatist—model, and, thus, it requires *timing*, not

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just sequence, as in computational or connectionist models. It is argued that the brain realizes such timing in virtue of functioning with ongoingly oscillatory processes that ongoingly modulate each other (not with threshold switches or input processors).

The micro-anticipatory aspect of these processes emerges in larger spatial scale, slower temporal scale, processes—such as volume transmitters and astrocyte processes—that set the parameters for smaller, faster, processes, such as classical synapses. Such parameter setting might or might not turn out to be appropriate for the actual course of the flow of interactive process. If it turns out to be appropriate, then the functional anticipatory setting up of the faster processes—the microgenesis of how the faster processes proceed—was correct; If it turns out to be not appropriate, then the functional anticipation is falsified.

With that framework as background, a next question is how these micro-functional processes are themselves regulated or modulated on more macro scales. That is the main focus of this second paper. I also offer a discussion of a family of approaches that have some convergences with this model, variously known as Predictive or Bayesian Brain models.

2 Part III: Central Nervous System Functional Macro-Architecture

2.1 (Macro-)Introduction

In part II,[1] 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 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 and Izhikevich 1997; Izhikevich 2007). The form (and dynamics) of those dynamic 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

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[1] In the first paper—on micro-level processes—of this pair of papers.

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.

2.2 Foundations of a Macro-functional Model

Functional coherence in brain processes is attained (when it *is* attained) as an emergent of multiple simultaneously inter-modulating processes in all parts of the brain. In this section, the foundations for how such coherence could emerge are limned. These foundations involve properties of the functional architecture of the nervous system—particularly regarding the function of various kinds of learning and emotions, both with respect to ongoing psychological processes and with regard to evolutionary considerations. The central notion is that (macro-)distributed processes tend to recruit connected processes into an overall coherent functional mode—a functional self-organization. How that could happen is the theme of this discussion.

2.2.1 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 adaptability (Bickhard 1973, in preparation; Bickhard and 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.[2] 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 (inter-)action systems can be impressed by the world into a passive mind. Learning (and development) *must* be *constructive* processes.[3]

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

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[2] Further, the dynamics of learning enable the dynamics of functional self-organization.

[3] Constructive processes of various kinds have been postulated in multiple models, but it has not been often recognized that action based models *force* a constructivism.

selection constructivism, an evolutionary epistemology of learning and development (Campbell 1974).[4]

I have argued that normative truth value emerges in processes that anticipate what further processes might be successfully engaged in.[5] 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—on pain of circularity—cannot be the most basic form of representational anticipation (Bickhard 2009a).[6] 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.[7] Anticipations, thus, are constituted in the microgenetic *preparations* for further process flow, and *actual* process flows may support those anticipations or may render them false. The crucial microgenetic anticipations, thus, are of local process flow, not of the environment per se nor of inputs from that environment (though environments and inputs from environments will certainly *influence* that local process flow).

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 anticipatory, thus interactive, success. *Microgenesis, thus, is the locus of learning* (Bickhard and Campbell 1996).

2.2.1.1 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 claim to be able to account for all learning.

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 can be constituted as successful microgenetic anticipation of the

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[4] Generalizing the model of variation and 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 and 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.

[5] For discussions of emergence, see (Bickhard 2009a; Bickhard and Campbell 2003; Clayton and Davies 2006; Deacon 2012; Thompson 2007).

[6] The circularity arises if I claim to model the emergence of representation out of anticipation, but then it turns out that anticipation (or the checking of environmental anticipation) requires representation in turn. So representation would be being defined in terms of representation: a circularity.

[7] And local anticipatory success and failure constitute truth and falsity of the anticipatory set-ups, thus ground representation. See Part II (in the first paper of this pair, on micro-level processes) and Bickhard (2009a).

influences on process flow of registrations of the inputs. This is effectively what happens with classic habituation (Bickhard 2000b; Thompson 2009).[8]

Classical Conditioning Suppose now that no such subtractive process is possible. One example would be if a tone—an input flow of sound—shifts to an input flow of pain, and pain is a kind of 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.

The focus here is on how an evolutionary epistemology model, of which microgenesis provides a functional account, can model classical conditioning. "jumping off of the shock grid" is an example of successful interacting with a tone followed by shock, in spite of the near impossibility of successful interaction with pain per se, and microgenesis is the locus of the variation and selection process that can "find" this solution to the interaction problem.

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 situationally and culturally. Hunger, in whatever environment, will tend to evoke activity that results in eating, and this is a standard example of instrumental conditioning.[9]

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 prima facie established for current purposes that microgenetic variation and selection processes are a candidate for being able to account for all of learning.

2.2.1.2 Development It is possible for the variations in simple learning in simple organisms to be always—every time—generated from the *same* dynamic base, as variations in those basic dynamics. Perhaps, for example, just variations in synaptic strength, if synaptic influences are the only relevant dynamics. More complex learning, however, occurs if *previous* constructions can be used as resources for

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[8] See later discussion for a comparison with 'predictive encoding' models.

[9] 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.

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 or probabilistic matter,[10] not possible without certain prior preparatory constructions (Bickhard 2005b). Such preparatory construction possibilities can form trajectories of possible construction, in which earlier constructions enable later constructions. Such trajectories of possible construction, in turn, 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 1980a, b, 2006; Campbell and Bickhard 1986).[11]

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.

2.2.2 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 modality 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 *already available* space of possible processes—variations must be functionally accessible from already available organizations of processes. Variations, in other words, are not free—e.g., they are not from a uniform probability distribution across a space of

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[10] E.g., too complex for any non-foresighted constructive process to happen to hit upon it directly (Simon 1969; Campbell 1974). See also discussions of functional scaffolding (Bickhard 1992, 2005b).

[11] In this model, learning and development involve the same underlying constructive processes. They focus on differing aspects of that process: learning focuses on short term properties of such constructions, while development focuses on longer term properties. Enabling and constraint relationships among possible constructions were within the core of, for example, Piagetian models, but their study has diminished as non-action based models (e.g., innatist and other maturational models) have proliferated (Allen and Bickhard 2011a, b, 2013). Often, learning and development are considered (at least implicitly, though often explicitly) to involve distinct processes.

all conceptual possibilities. 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 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. Variations are variations from and within a base dynamics—differing dynamics offer differing accessibility trajectories in the overall space of possible variations: that space is not "flat" with a uniform probability distribution for possible variations. 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.[12]

(Macro-)evolutionary central nervous system differentiation and specialization for interactive functioning, thus, *ipso facto* constitutes differentiation and specialization in support of variation and selection learning.

2.2.2.1 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[13]—for example, as neural *networks* became nervous *systems* with (head) ganglia and chordate organization (Fritzsch and Gloverb 2007). This constitutes a partial differentiation between processing and communication, and enables partially decoupled 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

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[12] That the processes by which variations are generated are themselves aspects of adaptability follows directly from the nature of variation and selection processes (Bickhard and 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 and Wiley 1988; Brooks et al. 1989; Weber et al. 1988; Kauffman 1993).

[13] That is, such differentiations and specializations have been retained in macro-evolution because of their adaptability in organism-environment interaction *and* because of the enabling of further specialization in further evolution. Thus, they constitute one among multiple macro-evolutionary trends.

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 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 further macro-evolutionary emergences, such as the co-evolution of synapses, muscles, and skeleton (Moreno and Lasa 2003; Nieuwenhuys 2000).

Within architectures for interacting with an environment, differentiations and specializations emerged for interactions that *detect* properties and conditions in the world as distinct from selecting and guiding *action and interaction* with the world.[14] 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 and 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 et al. 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 et al. 2000)—a system that does not function in terms of (presumed semantic) information flows and information processing.

Emotion A crucial aspect of the overall interactive model is its sub-model of emotion, and of the role that emotion has played 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 with the environment* as well as in learning to the fact that the organism is dynamically 'uncertain' about how to proceed—there isn't available an already learned or otherwise dynamically available process for the current situation. That is, the preparatory conditions for anticipated process flow have to be undone and redone because they do not prepare

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[14] Generally referred to as sensory and motor systems. But "sensory" at least carries strong and unwanted encoding connotations. Gibson's term "perceptual systems" is much more congenial to the interactivist model (Gibson 1966).

correctly for what is actually happening.[15] That is, it would be advantageous if the organism could "*detect*" (or be modulatorily influenced by) its own condition of microgenetic dynamic 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 types of uncertainty-situations.

An ability to respond to *types* 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—e.g., run like hell. This can avoid the risks involved in more primitive trial and error learning in uncertainty situations (Bickhard 2000b). The point is that learning trial and error constructions might be too costly, too subject to potentially fatal error, relative to heuristics for environmental-interacting with situations that give rise to microgenetic uncertainty.[16]

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).[17] Microgenetic uncertainty, in turn, corresponds to dynamic uncertainty[18] about how to interact with the eliciting situation.[19]

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 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 and Heberlein 2002; Harré 1986).

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[15] In abstract machine theoretic terms, this is roughly equivalent to an undefined state transition, but here there is no "halt" condition.

[16] Uncertainty here is an internal functional (microgenetic) condition, not a stimulus.

[17] 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.

[18] Perhaps dynamically constituted in chaotic processes.

[19] Emotion, thus, doesn't necessarily *reduce* uncertainty directly: it yields special kinds of interactions with situations that evoke uncertainty. If *successful*, such interactions will then reduce uncertainty.

Episodic Memory Memory is a prima facie problem for action based models. Here I outline a framework for understanding (episodic) memory within an anticipatory framework.

Anticipations in simpler, or more primitive, organisms are of very general possibilities, such as “a swimming situation” or “a tumbling situation” (e.g., of a bacterium). These become more specific and differentiated with more complex agents, such as “a tongue flicking and eating in such-and-such direction situation” (e.g., a frog).

As species (in macro-evolution) become capable of increasingly specific, differentiated, and complex anticipatory organizations, they also inherently become increasingly context-dependently historistic—dependent on the particular and contingent experience of the organism (e.g., the frog’s recent visual interaction with a worm in a particular direction). Web organizations of an organism’s conditionalized anticipations of what it could do[20] constitute that organism’s knowledge of the interaction potentialities of its current situation—its *situation knowledge*.[21]

Situations do not remain static, nor do organizations of situation knowledge. Such knowledge of extended interactive possibilities must be ongoingly maintained, modified, and updated. This process of updating is *apperception*. Apperceptive processes generate *flows or trajectories* of situation knowledge—of knowledge of what interactions are (conditionally) available in or from the current situation.

A major organizational principle of such contingent bases for interactive anticipation is space (O’Keefe and 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 organismic historistic experience for possible anticipations constitutes *episodic memory*; explorations of *variations* on such contingencies constitutes *future and counterfactual thinking* (Atance and O’Neill 2005; Bickhard in preparation; Botzung et al. 2008; Hassabis and Maguire 2007).[22] These are important particular versions of general anticipatory and learning phenomena.[23]

Support for this special form of learning and anticipation should evolve along with emotion—which involves powerful anticipatory functions—and in integrated

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[20] E.g., it could do X if it first did (conditional on first doing) Y and then Z.

[21] Indications of the possibilities of interacting with a toy block in front of a toddler would be an example of part of the situation knowledge for that toddler.

[22] Indications of potentiality are modal and can functionally connect in counterfactual ways. So, memory can be what could be anticipated ***if*** the organism were to return to the situation (or ***if*** some counterfactual conditions obtained). Note that one of the adaptive advantages of episodic memory is that it does permit recreating past trajectories of experience for, e.g., the purpose of figuring out anticipations that were not made explicit originally. E.g., the group was headed for water, but, now that we’ve been able to drink, it would be advantageous to mentally re-trace our route to see if there were any indications of available food along the way.

[23] Episodic memory, construed as transduced images or videos, constitutes the ground of standard encoding models. It poses a challenge to action based models: how can episodic memory be modeled within an action based, anticipatory, model—a non-image, non-video, non-encodingist model? The model outlined above of exploring trajectories of situation knowledge apperceptive processes provides a frame of an answer.

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 (Broglio et al. 2005), and maintain close functional relationships (Grahna et al. 2009; Mizumori et al. 2009; Pitkänen et al. 2000; Price 2002).

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 (micro-)learning destabilizations, but also to influence directly the (macro-)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, to be outlined now, 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 and Pham-Dinh 2002; Nieuwenhuys 2000; Verkhratsky and 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 II of this discussion (in the first of these papers, in micro-level processes).

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 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 usefully modify and expand. A laminar architecture (to a first approximation) can, in contrast, "simply" be expanded into more *area* of laminar organization (Aboitiz 1992).

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 *prefrontal cortex*. Prefrontal 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. Such internal interactions, then, constitute a kind of second level interactive system, one that interacts with activities—especially microgenesis processes—elsewhere in the nervous system.

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 prefrontal 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.

2.2.3 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.

2.2.3.1 Thalamus-Cortex Among the most important of these macro-scale architectures are the reciprocal projections between thalamus and cortex (Churchland 1995; Hoppensteadt and Izhikevich 1998; Izhikevich 2001, 2002; Izhikevich et al. 2003; Purpura and Schiff 1997; Steriade 1996; Steriade et al. 1997a, b). Such reciprocal connections are ideal organizations for oscillatory processes within the reciprocal organizations.[24]

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

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[24] "Re-entrant" is a common term for this kind of architecture, but it carries the connotation that what is being "re-entered" is semantic information, and that is false.

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 and Izhikevich 1998; Izhikevich 2001, 2002; Izhikevich et al. 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 and Todd 2007; Steriade 1996), these modulations and reconfigurations will be with respect to the microgenesis processes taking place in those cortical areas.

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?

2.2.3.2 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 prefrontal cortex to striatum to thalamus and back to prefrontal (Crosson and Haaland 2003; Edelman and Tononi 2000; Fuster 2004, 2008; Koziol and Budding 2009; Marzinzik et al. 2008; Middleton and Strick 2000; Smith et al. 2004).[25] 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 et al. 2007; Koziol and 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 unacceptable interpretation.

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 prefrontal to striatum to thalamus to prefrontal. We know, however, that virtually all projections in the CNS are

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[25] 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 and Budding 2009).

reciprocal (Adolphs and Heberlein 2002; Deacon 1989, 1997; Ohye 2002), and that this holds at least for some parts of this particular larger scale loop as well (Fuster 2008; Middleton and 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 fundamentally 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: if semantic information models were correct, then much simpler models would suffice.

2.2.3.3 Other Prefrontal Loops Other major loops involving the prefrontal cortex are with the cerebellum and thalamus, and the limbic system and thalamus (Koziol and Budding 2009; Price 2002). There is convergence of these loops in the general area (and subdivisions) of the prefrontal 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 and 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 is part of central connectivity networks in the brain (Sporns 2011). 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 prefrontal cortex, thus, constitutes learning of dynamic modulational "programming" for *other* areas of the CNS.

2.2.4 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 that is in some situation with which it can interact (Bickhard 2008a). 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 and 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 and 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, b, in preparation).[26]

2.3 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

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[26] For a model of language within this framework, see Bickhard (2007b, 2009a, in preparation). For perception, see Bickhard and Richie (1983) and Bickhard (2009a, b, 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 seductive power fades, however, if it is recognized that perception, cognition, action, and language (not to mention emotion, etc.) are *all* interactive processes, not semantic-information flows.

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, b; Freeman and Barrie 1994; Bickhard 2008b). 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 microgenetic 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 the results of 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. Prefrontal 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 command-issuing executive.

2.3.1 Self-Organization: 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 steady 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 al process. 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.[27]

2.3.1.1 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).

2.4 (Macro-)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* (i.e., covariation, in this model, via modulatory influence) is necessarily involved, but this does *not* constitute semantic or representational phenomena (Bickhard 2000a).[28]

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

[28] Shannon information is often taken to be inherently “semantic” because it is framed in terms of meaningful messages (meaningful to senders and receivers), but all that the mathematics does is to quantify amount of modulation of one process on another. If that second process is being modulated with respect to “problem or conceptual spaces”, then this will involve meaning *for the people who interpret things into such spaces*. But the mathematics applies equally as well to, for example, the control of a factory of refinery process, in which there is much less, or no, temptation to conclude that the control is “semantic”. “Information” is a measure of control theoretic correlation, and such correlation is, more broadly, what constitutes technical information.

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.

3 Part IV: Prediction, Anticipation, and the Brain

3.1 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–both interactivist and predictive brain 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 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 major 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 here primarily on a few differences with regard to functional characteristics of the brain.[29]

3.1.1 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 or influence perceptual inputs grew out of the cybernetics movement (Powers 1973)[30] and (partially) resonates with Gibson's notions of sensory interactions (Gibson 1966, 1979).[31]

An important elaboration of these ideas was to postulate Bayesian decision procedures (or approximations thereof) as the form of the predictive processes.

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[29] For a more detailed critique of predictive-Bayesian-free energy models, see Bickhard (in press).

[30] Sometimes called feed-forward models.

[31] Though they are strictly inconsistent with Gibson's claim that perceiving is not based on intermediate representational sensing (Gibson 1979; Bickhard and Richie 1983).

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 and 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 $\tilde{y}$ ["$\tilde{y}$ 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"] Put simply, adaptive systems or agents should minimise unlikely or surprising exchanges with the environment. (Friston and 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, at the highest level, innate (because there is no higher level to provide the priors). 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 evolutionary setting of the higher level expectations. Thus, minimizing free energy—surprise—drives both evolution and action.

3.1.2 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 briefly outlined in part I of this paper (in the first paper of this pair; 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 encodings, 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.[32]

The predictive brain approaches also argue that a system that minimizes free energy will have internal states that factually track external states and conditions, such as the presence of an object—that is, will as a *matter of fact covary* with them. Such tracking is assumed to constitute representation. Tracking, however, is “just” a version of an encoding model, and it has no solution to problems of, for example, the emergence of truth valued processes, or organism detectable error (Bickhard 2009a, 2014).

As usual, the problem is getting from such factual relations to a normatively representational relation: from fact to norm, is to ought: An internal state either tracks (encodes) or it doesn’t. If it doesn’t, then there is no tracking (encoding) taking place, and, thus, there is no “tracking representation” to be false. In general, an encoding relationship either exists or not. If not, then no encoding exists, and therefore an encoding model cannot account for a representation existing but being false.

The predictive brain approaches and the interactive model have an interesting 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, however, 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 extensionally with *prediction of inputs* to that processing. The interactive model, however, is ***not*** focused on predicting inputs: the central functional normativity is that of internal, local anticipations of internal local flows of activity, of internal local flows of process (Bickhard 2001, in press; Bickhard and Terveen 1995).

The apparently subtle difference between predicting inputs and anticipating local processes, however, generates major divergences in other cases. With regard to

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[32] Note that the spaces over which these parameters ‘parameterize’—spaces of functional forms for prediction—must themselves be already available (Friston et al. 2009 on switching between functional forms)—presumably innate. The highest level innate prior probability distributions, over whatever spaces they are distributed, are the highest level instance of this point.

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. This, clearly, is contrary to fact, but successful prediction is the *only* criterion in this model, so predicting shock should be just as successful as avoiding shock. 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 and evolutionarily absurd "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 2013a). 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 et al. 2012)—all such considerations have to be already built-into the system, by the designer in the case of artificial systems and presumably by evolution in the case of living systems (Friston et al. 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, not just a result of evolution (Maturana and Varela 1980; Varela 1997; Weber and 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—a necessary and essential inherence—not just a contingent point about their evolutionary history (Bickhard 2009a).[33]

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.[34] Many details of this perspective are unclear, including whether or not the reciprocal projections carry the kinds of “prediction” and “error” signals postulated,[35] but when consideration turns to more general considerations, the model does not fit at all.

Among other problems, such a layered 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 and 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 organism-level inputs and derivatives from them, including various tracking states, that are supposedly representational. For the interactivist model, it is the *anticipating process itself* that is representational, *not the inputs nor tracking states*. These differences and their consequences are crucial.

Ergodicity and Markov Blankets? Friston (2013b) argues that any system that is ergodic and has a Markov blanket will “manifest” minimization of free energy, and, thus, realize (something like) free energy predictive brain dynamics. He claims that this is an improvement over his earlier “somewhat tautological” argument that

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[33] Another framework that emphasizes prediction and anticipation is that of Rosen (1985, 1991). Rosen, however, focuses on prediction based on representational models and does not address the (emergent) nature of representation.

[34] Note that this makes the Bayesian layers, insofar as they exist at all, *innate* in the architecture of the brain, i.e., not learned.

[35] Note that such reciprocal projections would be ideal for engaging in oscillatory processes that could modulate connected such oscillatory processes.

living systems would manifest predictive brain dynamics because, if their ancestors did not do so, then the current living systems would not exist (the ancestors would have died). This is a (partially) different perspective on life and whether or not the essential characteristics of life support the free energy model, so I would like to address it briefly.

First, what is ergodicity and what is a Markov blanket? Ergodicity is a property of an ensemble of stochastic elements. In particular, it is the property of any time average of any element being equal to the average over the ensemble at any one time: time average of an element equals ensemble average at a time—there is a kind of stochastic equilibrium within the ensemble over time.[36]

A Markov blanket, in turn, is a partitioning of the states of a system that distinguishes between inside, outside, and boundary (with a subordinate distinction between input and output boundary states). This is purely definitional, but the definition does not guarantee that any given system will yield non-empty partitions in the partition scheme: for example, a candle flame does not have any stable set of boundary states, and, thus does not have a Markov blanket (Friston 2013b).

The basic idea is that, any system with such a boundary that manages to maintain the stochastic stability of ergodicity must in some way counter any perturbations that might otherwise knock it out of being ergodic. A rock, for example, will tend to radiate heat that impinges on it.

Such countering of perturbations means that the system will manifest something like free energy predictive processes.

This is an interesting analysis, but I would suggest that it doesn't accomplish what Friston wants it to. First, there is no explanation of why we would or should expect ergodic systems (with Markov blankets) to come into existence at all. In this respect, this model seems to require the same argument that it is intended to replace: systems that did not achieve ergodicity in the past would not leave descendants today. Friston does not explain how or why any ergodic systems would emerge or evolve in the first place.[37]

Furthermore, ergodicity is not manifest in living systems that grow or develop or learn: neither the state space nor the stochastic properties over any such space have the homogeneity of ergodicity. If they did, the system would be dead. This is the wrong kind of model for living systems.

Further, no living system has a Markov blanket. Friston acknowledges that the model applies to, for example, rocks, and, thus, that more is needed in order to differentiate living systems from rocks. But that the model applies to rocks and not to candle flames, I would suggest, is already a deep refutation of the model as a model of living systems: living systems are intrinsically and necessarily open systems, like a candle flame, and unlike a rock. The changing of elements, the absence of any classical boundary, of a candle flame is precisely what the candle

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[36] This might be considered, in an *extended analogical* sense, as a kind of homeostasis. But it is a homeostasis in a probabilistic sense (ergodicity) rather than a maintenance of set-point sense. Also, it doesn't necessarily involve feedback.

[37] Note that the assumption of ergodicity is not new in this paper, but has been central to the general model's conceptual and mathematical framework, e.g., Friston (2012), Friston et al. (2012a, b).

flame has in common with living systems, and what rocks do not have in common (e.g., Bickhard 1993, 2009a, 2011; Froese et al. 2011). Friston's model here can appear to apply to living systems only if the slower time scales of turnover of, e.g., cell walls, is ignored in favor of taking them to be akin to the fixed phase change boundary of a rock. But the slower time scales of turnover of cell walls does not make a cell any the less an ontologically necessarily open system. A cell *is* the process of turnover and the maintenance of the (far from equilibrium) conditions under which such process stability (not state or element or component stability) can be maintained.

Friston's model, in fact, cannot apply to any self-organizing or self-maintaining or recursively self-maintaining process, and, thus, certainly not to any living system. In view of these considerations, it seems that Friston's earlier "somewhat tautological" argument is not tautological, just weak, but the assumption that it, or the newer argument, either one, captures a fundamental property of life is simply false.

In sum, any model that applies to the dynamics of rocks but not candle flames is thereby refuted as a model of living systems, including living systems with brains, including human beings.

3.1.3 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 et al. 2008). For the interactivist model, time scale differences are inherent in the nature of the neural-glial 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.

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

3.2 Information? Of Course!

I have argued against semantic information models throughout this paper,[38] 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 (or correlations among processes) to be representational.[39]

In this sense, information is a *control theoretic* notion, and a fundamentally important one, not a *semantic* notion (Bickhard and Richie 1983). Information in the technical correlational sense 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 2000a).

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. The issue is whether any of that information is "*semantic*". 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 (successful) anticipation, but it is only the anticipation that can be representational.

One consequence of this point for brain functionality is that information is a property of ongoing modulatory influence on further processing. Information is not

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[38] And in the first of this pair of papers.

[39] Regarding the possibility of correlational information constituting representation in itself, consider: information is a *factual* relationship, not a semantic relationship. It either exists or it does not; there is no way for it to exist but be false. This is a basic Brentano point, one that has been and still is pervasively ignored. For discussion of some recent ingenious but ultimately failed attempts to address it, see Bickhard (1993, 2009a).

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 et al. 2008, 2012).

4 Conclusion

The encoding framework for "predictive brain" models ensures that they cannot successfully model (cognitive or) brain activity. Multiple derivative and subsidiary problems have been presented, and it is argued that the interactive model resolves or simply avoids these issues. Predictive brain models constitute one of the most sophisticated contemporary encoding approaches to cognition and brain models; their failure constitutes yet one more demonstration that such frameworks should be abandoned.

According to the interactivist model, representation and cognition emerge in *anticipations* of further interactive activity. Timing is crucial to such activity, thus oscillation is the central form of process; functional influences occur as various forms of modulation, both within the nervous system and between the nervous system and its body and external 'environments'. The brain does not function in terms of the processing of information-semantic inputs; it is everywhere always endogenously active. Its basic functional activity consists in multifarious forms of interaction and modulation among oscillatory processes and microgenesis processes.

The fundamental form of brain dynamics, thus, is that of endogenously active oscillatory processes that have modulatory influences on each other. One crucial form of modulation is that of slower, larger scale, processes on smaller, faster processes, inducing a microgenesis of dynamic spaces, such as attractor landscapes. These processes occur at multiple spatial and temporal scales, such as those of gap junctions, synapses, volume transmitters, multiple kinds of astrocyte influences, and so on. Large scale, thus slower, processes parameterize smaller scale, faster, processes: they microgenetically set-up dynamic spaces—e.g., attractor landscapes—for those faster processes. Learning is involved in the evolutionary-epistemological construction of abilities to microgenetically induce new dynamic spaces.

These processes, in turn, are modulated by oscillatory interactions among widespread macro-organizations in the brain. Importantly, some of these macro-oscillatory-processes modulate microgenetic processes in other CNS areas, thus *interacting with* the (setting up of the) dynamic spaces of other processes. Also, some microgenetic processes can more directly influence *other* microgenetic processes, e.g., in terms of the dynamic stability or instability of one process influencing other microgenesis processes. In various ways, such interactions among macro-oscillatory-processes and microgenetic processes are involved in learning, emotions, and conscious thought.

Processes occurring throughout the brain tend to recruit among themselves into locally and globally interactively successful forms of interactive process, where ‘success’ is constituted by successful microgenetic anticipation of interactive process. If such recruitment is globally successful, the brain attains functional coherence of its internal interactions. These processes are all modulated by interactions with the environment, so functional coherence entails successful environmental interactions: the body and external environment are, in various modes, interactive environment for the CNS similar to the sense in which some parts of the brain are ‘environment’ for other parts of the brain.

Mind emerges in such overall dynamic processes. Some aspects of mental processes—e.g., emotions and reflective consciousness—have emerged in macro-evolution in differing architectural organizations that elaborate and add to earlier evolutionary developments. A central theme in this macro-evolution is the exploitation of increasingly powerful modes of making use of, and interactively modulating, the processes of microgenesis. Functionally, this constitutes a macro-evolution of increasingly powerful modes of learning and learning to learn. In turn, human capacities in these respects have made possible the further evolutionary and historistic emergence of full person-based linguistic sociality (Bickhard 2007b, 2009a, 2013, in preparation).

References

Aboitiz F (1992) The evolutionary origin of the mammalian cerebral cortex. Biol Res 25:41–49

Adolphs R, Heberlein AS (2002) Emotion. In: Ramachandran VS (ed) Encyclopedia of the human brain. Elsevier, Amsterdam, pp 181–191

Allen JWP, Bickhard MH (2011a) Emergent constructivism. Child Dev Perspect 5(3):164–165. doi:10.1111/j.1750-8606.2011.00178.x

Allen JWP, Bickhard MH (2011b) Normativity: a crucial kind of emergence. Hum Dev 54:106–112. doi:10.1159/000327096

Allen JWP, Bickhard MH (2013) Stepping off the pendulum: why only an action-based approach can transcend the nativist-empiricist debate. Cogn Dev 28:96–133

Arbib MA (1972) The metaphorical brain. Wiley, New York

Arnal LH, Giraud A-L (2012) Cortical oscillations and sensory predictions. Trends Cogn Sci 16(7):390–398

Atance CM, O’Neill DK (2005) The emergence of episodic future thinking in humans. Learn Motiv 36:126–144

Balleine BW, Delgado MR, Hikosaka O (2007) The role of the dorsal striatum in reward and decision-making. J Neurosci 27(31):8161–8165

Baumann N, Pham-Dinh D (2002) Astrocytes. In: Ramachandran VS (ed) Encyclopedia of the human brain. Elsevier, Amsterdam, pp 251–268

Bickhard MH (1973) A model of developmental and psychological processes. Ph.D. Dissertation, University of Chicago

Bickhard MH (1980a) A model of developmental and psychological processes. Genetic Psychol Monogr 102:61–116

Bickhard MH (1980b) Cognition, convention, and communication. Praeger Publishers, New York

Bickhard MH (1992) Scaffolding and self scaffolding: central aspects of development. In: Winegar LT, Valsiner J (eds) Children’s development within social contexts: research and methodology. Lawrence Erlbaum Associates, Hillsdale, pp 33–52

Bickhard MH (1993) Representational content in humans and machines. J Exp Theor Artif Intell 5:285–333

Bickhard MH (2000a) Information and representation in autonomous agents. J Cogn Syst Res 1:65–75

Bickhard MH (2000b) Motivation and emotion: an interactive process model. In: Ellis RD, Newton N (eds) The caldron of consciousness, pp 161–178. J. Benjamins

Bickhard MH (2001) Function, anticipation, representation. In: Dubois DM (ed) Computing anticipatory systems. CASYS 2000—fourth international conference. American Institute of Physics, Melville, pp 459–469

Bickhard MH (2002) Critical principles: on the negative side of rationality. New Ideas Psychol 20:1–34

Bickhard MH (2005a) Consciousness and reflective consciousness. Philos Psychol 18(2):205–218

Bickhard MH (2005b) Functional scaffolding and self-scaffolding. New Ideas Psychol 23(3):166–173

Bickhard MH (2006) Developmental normativity and normative development. In: Smith L, Voneche J (eds) Norms in human development. Cambridge University Press, Cambridge, pp 57–76

Bickhard MH (2007a) The evolutionary exploitation of microgenesis. Interactivist Summer Institute, May 28, 2007, The American University in Paris

Bickhard MH (2007b) Language as an interaction system. New Ideas Psychol 25(2):171–187

Bickhard MH (2008a) Is embodiment necessary? In: Calvo P, Gomila T (eds) Handbook of cognitive science: an embodied approach. Elsevier, Amsterdam, pp 29–40

Bickhard MH (2008b) The microgenetic dynamics of cortical attractor landscapes. May 22–23, 2008. Workshop on "Dynamics in and of attractor landscapes", Parmenides Foundation, Isola d'Elba, Italy

Bickhard MH (2009a) The interactivist model. Synthese 166(3):547–591

Bickhard MH (2009b) Interactivism. In: Symons J, Calvo P (eds) The Routledge companion to philosophy of psychology. Routledge, London, pp 346–359

Bickhard MH (2011) Some consequences (and enablings) of process metaphysics. Axiomathes 21:3–32

Bickhard MH (2013) The emergent ontology of persons. In: Martin J, Bickhard MH (eds) The psychology of personhood: philosophical, historical, social-developmental, and narrative perspectives. Cambridge University Press, Cambridge, pp 165–180

Bickhard MH (2014) What could cognition be, if not computation … or connectionism, or dynamic systems? J Theor Philos Psychol 35(1):53–66

Bickhard MH (2015) Toward a model of functional brain processes I: central nervous system functional micro-architecture. Axiomathes. doi:10.1007/s10516-015-9275-x

Bickhard MH (in preparation) The whole person: toward a naturalism of persons—contributions to an ontological psychology

Bickhard MH (in press) The anticipatory brain: two approaches. In: Müller VC (ed) Fundamental issues of artificial intelligence. Springer (Synthese Library), Berlin

Bickhard MH, Campbell RL (1996) Topologies of learning and development. New Ideas Psychol 14(2):111–156

Bickhard MH, Campbell DT (2003) Variations in variation and selection: the ubiquity of the variation-and-selective retention ratchet in emergent organizational complexity. Found Sci 8(3):215–282

Bickhard MH, Richie DM (1983) On the nature of representation: a case study of James Gibson's theory of perception. Praeger Publishers, New York

Bickhard MH, Terveen L (1995) Foundational issues in artificial intelligence and cognitive science: impasse and solution. Elsevier Scientific, Amsterdam

Botzung A, Denkova E, Manning L (2008) Experiencing past and future personal events: functional neuroimaging evidence on the neural bases of mental time travel. Brain Cogn 66:202–212

Broglio C, Gomez A, Duran E, Ocana FM, Jimenez-Moya F, Rodriguez F, Salas C (2005) Hallmarks of a common forebrain vertebrate plan: specialized pallial areas for spatial, temporal and emotional memory in actinopterygian fish. Brain Res Bull 66:277–281

Brooks DR, Wiley EO (1988) Evolution as entropy, 2nd edn. University of Chicago Press, Chicago

Brooks DR, Collier JD, Maurer BA, Smith JDH, Wiley EO (1989) Entropy and information in biological systems. Biol Philos 4:407–432

Campbell DT (1974) Evolutionary epistemology. In: Schilpp PA (ed) The philosophy of Karl Popper. Open Court, LaSalle, pp 413–463

Campbell RL, Bickhard MH (1986) Knowing levels and developmental stages. Contributions to human development. Karger, Basel

Carlson NR (2013) Physiology of behavior, 11th edn. Pearson, Upper Saddle River

Churchland PM (1995) The engine of reason, the seat of the soul. MIT, Cambridge

Clark A (2013) Whatever next? Predictive brains, situated agents, and the future of cognitive science. Behav Brain Sci 36:181–253

Clayton P, Davies P (2006) The re-emergence of emergence. Oxford University Press, Oxford

Crosson B, Haaland KY (2003) Subcortical functions in cognition: toward a consensus. J Int Neuropsychol Soc 9:1027–1030

Damasio AR (1995) Descartes' error: emotion, reason, and the human brain. Avon, New York

Damasio AR (1999) The feeling of what happens. Harcourt, New York

Deacon TW (1989) Holism and associationism in neuropsychology: an anatomical synthesis. In: Perecman E (ed) Integrating theory and practice in clinical neuropsychology. Erlbaum, Hillsdale, pp 1–47

Deacon TW (1997) The symbolic species. Norton, New York

Deacon TW (2012) Incomplete nature. Norton, New York

Dennett DC (1995) Darwin's dangerous idea. Simon & Schuster, New York

Edelman GM, Tononi G (2000) A universe of consciousness. Basic, New York

Freeman WJ (1995) Societies of brains. Erlbaum, Mahwah

Freeman WJ (2000a) How brains make up their minds. Columbia, New York

Freeman WJ (2000b) Mesoscopic brain dynamics. Springer, London

Freeman WJ, Barrie JM (1994) Chaotic oscillations and the genesis of meaning in cerebral cortex. In: Buzsaki G, Llinas R, Singer W, Berthoz A, Christen Y (eds) Temporal coding in the brain. Springer, Berlin, pp 13–37

Friston KJ (2012) A free energy principle for biological systems. Entropy 14:2100–2121

Friston KJ (2013a) Active inference and free energy. Behav Brain Sci 36:212–213

Friston KJ (2013b) Life as we know it. Interface J R Soc 1–27

Friston KJ, Stephan KE (2007) Free-energy and the brain. Synthese 159:417–458

Friston KJ, Daunizeau J, Kiebel SJ (2009) Reinforcement learning or active inference? PLoS ONE 4(7):e6421. doi:10.1371/journal.pone.0006421

Friston KJ, Adams RA, Perrinet L, Breakspear M (2012a) Perceptions as hypotheses: saccades as experiments. Front Psychol 3:1–20

Friston KJ, Samothrakis S, Montague R (2012b) Active inference and agency: optimal control without cost functions. Biol Cybern. doi:10.1007/s00422-012-0512-8

Fritzsch B, Gloverb JC (2007) Evolution of the deuterostome central nervous system: an intercalation of developmental patterning processes with cellular specification processes. In: Kaas JH (ed) Evolution of nervous systems, vol 2. Elsevier, Amsterdam, pp 1–24

Froese T, Virgo N, Ikegami T (2011) Life as a process of open-ended becoming: analysis of a minimal model. In: Lenaerts T, Giacobini M, Bersini H, Bourgine P, Dorigo M, Doursat R (eds) Advances in artificial life, ECAL 2011: proceedings of the eleventh European conference on the synthesis and simulation of living systems. MIT Press, Cambridge, pp 250–257

Fuster JM (2004) Upper processing stages of the perception-action cycle. Trends Cogn Sci 8(4):143–145

Fuster JM (2008) The prefrontal cortex, 4th edn. Elsevier, Amsterdam

Gibson JJ (1966) The senses considered as perceptual systems. Houghton Mifflin, Boston

Gibson JJ (1979) The ecological approach to visual perception. Houghton Mifflin, Boston

Grahna JA, Parkinson JA, Owena AM (2009) The role of the basal ganglia in learning and memory: neuropsychological studies. Behav Brain Res 199:53–60

Haken H (1980) Synergetics. Naturwissenschaften 67(3):121–128

Haken H (1983) Synergetics, 3rd edn. Springer, Berlin

Haken H (2010) Information and self-organization, 3rd edn. Springer, Berlin

Harré R (1986) The social construction of emotions. Basil Blackwell, Oxford

Hassabis D, Maguire EA (2007) Deconstructing episodic memory with construction. Trends Cogn Sci 11(7):299–306

Hoppensteadt FC, Izhikevich EM (1997) Weakly connected neural networks. Springer, New York

Hoppensteadt FC, Izhikevich EM (1998) Thalamo-cortical interactions modeled by weakly connected oscillators: could the brain use FM radio principles? Biosystems 48:85–94

Izhikevich EM (2001) Resonate and fire neurons. Neural Netw 14:883–894

Izhikevich EM (2002) Resonance and selective communication via bursts in neurons. Biosystems 67:95–102

Izhikevich EM (2007) Dynamical systems in neuroscience. MIT, Cambridge

Izhikevich EM, Desai NS, Walcott EC, Hoppensteadt FC (2003) Bursts as a unit of neural information: selective communication via resonance. Trends Neurosci 26(3):161–167

Juarrero A (1999) Dynamics in action: intentional behavior as a complex system. MIT Press, Cambridge

Kauffman SA (1993) The origins of order. Oxford University Press, Oxford

Kiebel SJ, Danunizeau J, Friston KJ (2008) A hierarchy of time-scales and the brain. PLoS Comput Biol 4(11):e1000209. doi:10.1371/journal.pcbi.1000209

Kovach CK, Daw ND, Rudrauf D, Tranel D, O'Doherty JP, Adolphs R (2012) Anterior prefrontal cortex contributes to action selection through tracking of recent reward trends. J Neurosci 32(25):8434–8442

Koziol LF, Budding DE (2009) Subcortical structures and cognition. Springer, New York

Levine DS, Brown VR, Shirey VT (2000) Oscillations in neural systems. Erlbaum, Mahwah

Lewis MD, Todd RM (2007) The self-regulating brain: cortical-subcortical feedback and the development of intelligent action. Cogn Dev 22:406–430

MacKay DM (1956) The epistemological problem for automata. In: Shannon CE, McCarthy J (eds) Automata studies. Princeton University Press, Princeton, pp 235–251

MacKay DM (1969) Information, mechanism and meaning. MIT Press, Cambridge

MacLeod C (2012) The missing link: evolution of the primate cerebellum. In: Hofman MA, Falk D (eds) Progress in brain research, vol 195. Elsevier, Amstredam, pp 165–187

Marder E (2012) Neuromodulation of neuronal circuits: back to the future. Neuron 76:1–11

Marder E, Thirumalai V (2002) Cellular, synaptic and network effects of neuromodulation. Neural Netw 15:479–493

Marzinzik F, Wahl M, Schneider G-H, Kupsch A, Curio G, Klosterman F (2008) the human thalamus is crucially involved in executive control operations. J Cogn Neurosci 20(10):1903–1914

Maturana HR, Varela FJ (1980) Autopoiesis and cognition. Reidel, Dordrecht

Middleton FA, Strick PL (2000) Basal ganglia and cerebellar loops: motor and cognitive circuits. Brain Res Rev 31:236–250

Mizumori SJY, Puryear CB, Martig AK (2009) Basal ganglia contributions to adaptive navigation. Behav Brain Res 199:32–42

Molinari M (2002) Cerebellum. In: Ramachandran VS (ed) Encyclopedia of the human brain. Elsevier, Amsterdam, pp 611–627

Moreno A, Lasa A (2003) From basic adaptivity to early mind. Evol Cogn 9(1):12–30

Murray EA (2007) The Amygdala, reward and emotion. Trends Cogn Sci 11(11):489–497

Neisser U (1967) Cognitive psychology. Appleton-Century-Crofts, New York

Nicholson C (2000) Volume transmission in the year 2000. In: Agnati LF, Fuxe K, Nicholson C, Syková E (eds) Volume transmission revisited. Progress in brain research, vol 125. Elsevier, Amsterdam, pp 437–446

Nieuwenhuys R (2000) Comparative aspects of volume transmission, with sidelight on other forms of intercellular communication. In: Agnati LF, Fuxe K, Nicholson C, Syková E (eds) Volume transmission revisited. Progress in brain research, vol 125. Elsevier, Amsterdam, pp 49–126

O'Keefe J, Nadel L (1978) The hippocampus as a cognitive map. Clarendon Press, Oxford

Ohye C (2002) Thalamus and thalamic damage. In: Ramachandran VS (ed) Encyclopedia of the human brain. Elsevier, Amsterdam, pp 575–597

Panksepp J (1998) Affective neuroscience. Oxford University Press, Oxford

Pitkänen A, Pikkarainen M, Nurminen N, Ylinen A (2000) Reciprocal connections between the amygdala and the hippocampal formation, perirhinal cortex, and postrhinal cortex in rat. A review. Ann N Y Acad Sci 911:369–391

Powers WT (1973) Behavior: the control of perception. Aldine, Chicago

Price JL (2002) Limbic system. In: Ramachandran VS (ed) Encyclopedia of the human brain. Elsevier, Amsterdam, pp 695–702

Purpura KP, Schiff ND (1997) The thalamic intralaminar nuclei. Neuroscientist 3:8–15

Rabinovich M, Huerta R, Laurent G (2008) Transient dynamics for neural processing. Science 321(48):48–50

Rabinovich MI, Afraimovich VS, Bick C, Varona P (2012) Information flow dynamics in the brain. Phys Life Rev 9:51–73

Redgrave P, Prescott T, Gurney KN (1999) The basal ganglia: a vertebrate solution to the selection problem? Neuroscience 89:1009–1023

Roesch EB, Nasuto SJ, Bishop JM (2012) Emotion and anticipation in an enactive framework for cognition (response to Andy Clark). Front Psychol 3:1–2

Rosen R (1985) Anticipatory systems. Pergamon Press, Oxford

Rosen R (1991) Life itself. Columbia University Press, New York

Simon HA (1969) The sciences of the artificial. MIT Press, Cambridge

Smith Y, Raju DV, Pare J-F, Sidibe M (2004) The thalamostriatal system: a highly specific network of the basal ganglia circuitry. Trends Neurosci 279(9):520–527

Sporns O (2011) Networks of the brain. MIT, Cambridge

Steriade M (1996) Arousal: revisiting the reticular activating system. Science 272:225–226

Steriade M, Jones EG, McCormick DA (1997a) Thalamus, vol I. Organisation and Function. Elsevier, Amsterdam

Steriade M, Jones EG, McCormick DA (1997b) Thalamus, vol II. Experimental and clinical aspects, vol II. Elsevier, Amsterdam

Thompson E (2007) Mind in life. Harvard, Cambridge

Thompson RF (2009) Habituation: a history. Neurobiol Learn Mem 92(2):127–134

Varela FJ (1997) Patterns of life: intertwining identity and cognition. Brain Cogn 34:72–87

Verkhratsky A, Butt A (2007) Glial neurobiology. Wiley, Chichester

Weber A, Varela FJ (2002) Life after Kant: natural purposes and the autopoietic foundations of biological individuality. Phenomenol Cogn Sci 1:97–125

Weber BH, Depew DJ, Smith JD (1988) Entropy, information, and evolution. MIT Press, Cambridge

Zacks JM, Speer NK, Swallow KM, Braver TS, Reynolds JR (2007) Event perception: a mind-brain perspective. Psychol Bull 133(2):273–293