

## Consciousness and Self-Regulation

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The mystery surrounding consciousness as subjectivity dissipates dramatically when understood in its biological context. The core characteristics of consciousness can be seen to derive from its functionality, and the fundamental function of cognition, given the equivalence of mental activity and brain process, is to advance the survival and thus the self-regulative capacity of the organism of which the brain is a part. These core elements of consciousness are comprised of a self-locational data structure which serves to configure ongoing experience in terms of controllable spatial and temporal parameters, and a processing regime for this orientational schema which has evolved from the feedback architecture necessary for regulating behavior in relation to homeostatic needs. These two self-regulative constituents yield a primitive form of consciousness as subjectivity — simple reflexive awareness — which provides the basis for the subsequent development of metacognitive mechanisms which monitor and control the cognitive processes which regulate behavior in relation to metabolic requirements.

Keywords: consciousness, self-regulation, subjectivity, self schema

Consciousness has proved elusive in the face of concerted empirical research over centuries, to the extent that many today either question its reality (Dennett, 1991; Wilkes, 1995), or insist that while real, it was never meant to be understood by a human mind shaped by evolution for other tasks (Pinker, 2007); or again, that it simply cannot be understood because of the irreducible and unbridgeable divide between subjective and objective domains of knowledge (Chalmers, 1996; Dietrich and Hardcastle, 2004). This lack of purchase on the subject matter extends even to the definition of the term “consciousness” where Natsoulas (1983) methodically analyzed six distinct senses of the word found in the OED, to which Ned Block (1995) has most recently added a further four. For the sake of clarity, and in consonance with the longstanding focus on subjectivity as the primary phenomenal characteristic of consciousness (Dietrich and Hardcastle, 2004; Koch, 2004; Metzinger, 1995; Searle, 1992), as well as its

most primitive evolutionary form (Bermudez, 1998; Farthing, 1992; Flanagan, 1992; Meijnsing, 1997; Reber, 1992; Weiskrantz, 1985), consciousness as subjectivity — simple reflexive awareness — will be the focus of this proposal as distinct from the subsequent evolutionary development of a more elaborate “self-consciousness” involving metacognitive mechanisms for second-order representation of and attentional focus upon the organism’s own mental states (Baars, 1992; Reber, 1992). Subjectivity, in its turn, can be understood as underwriting the capacity to experience “raw feels” or qualia, which can be understood as extending from simple unadorned sensory feels like the colour, texture and taste of foods, distinctive odours in the air, the discomfort of parasites or the pain of bodily injury, to the experience of more elaborate cognitive processes such as inner feelings (love, hope, fear) and thoughts (plans, opinions).

The mystery surrounding consciousness as subjectivity dissipates substantially when this distinct form of psychological processing is understood in its biological context. The core characteristics of consciousness can be seen to derive from its functionality, and the fundamental function of cognition, it can be argued, is to advance the survival and thus the self-regulative capacity of the organism of which it is a part.

### **The Biological Foundations of Cognition and Consciousness**

Cognition, it is often said, cannot be understood properly without reference to its biological foundations (Bickhard, 2009; Churchland, 2002a; Damasio, 2000; Ghin, 2005; Jordan, 2008; Lyon, 2005; Revonsuo, 2005). A significant implication of this relationship is functional — the fact that the functional architecture of the cognitive system serves the self-regulative requirements of the biological organism, and of necessity does so in an energy-efficient manner. The intimate relationship between psychological and biological functionality derives from the fact that the brain is itself a biological organ serving the needs of its biological host organism, and brain activity is regarded as equivalent to mental activity or mind. The equivalence of brain and mind began to find empirical support in the 1880s, when Gustav Fritsch and Eduard Hitzig established that electrical stimulation of specific brain areas induced specific muscles to react. During the course of the twentieth century that kind of brain–behavior correlation was extended to characterize the connection between brain activity and mental phenomena as well. Wilder Penfield’s stimulation of the brain yielding immediate phenomenal experiences, the generation of twin minds consequent upon the splitting of the brain into its constituent hemispheres, hemineglect studies showing a consistent correlation between perceptual awareness and the functional integrity of specific brain areas — all served to demonstrate the tight connection between mental and cerebral activity. Neuroimaging technologies relate a similar story. Applied in real time on conscious awake subjects,

brain imaging studies indicate that when a thought occurs, the brain moves in predictable patterns and specific networks of areas depending on the type of thought (mathematical, visual imaging, event anticipation), or the degree to which such thoughts and experiences will be remembered. In fact, the onset and cessation of particular kinds of mental states (awake, sleep, dream sleep) follow a predictable sequence of brain activation and manifest specific types of brain activity. The consistency of these kinds of brain–mind correlations, while not constituting absolute proof of psychoneural identity (Noe and Thompson, 2004), nevertheless support the working hypothesis of most cognitive science research today that brain and mind are one and the same, that neuroelectrical brain processes *are* mental states. As Joaquim Fuster put it “the spatial and temporal constituents of the cortical order occupy the same relative place with respect to one another as the corresponding constituents of the cognitive order. Thus a change or difference in the cortical order corresponds to a change or difference in the mental order [and] we could legitimately conclude that the two orders are identical” (2003, p. 4; cf Skarda, 1990).

In practical terms, psychoneural or brain–mind identity implies that brain activity (and thus the mind) will be functionally organized to serve the metabolic requirements of the host organism. Cognitive events should not be regarded as biological processes akin to digestion and photosynthesis (*contra* Searle, 1997, p. 163) because mental events are comprised most immediately of the neuroelectric and not the biochemical aspects of neural activity (John, 1976). Nevertheless, brain–mind identity does entail, that like other biological processing networks such as the digestive, respiratory, and pulmonary systems, the functional organization of the cognitive system will have been determined by and will relate directly to the requirements of the biological organism of which it is a part and which it serves. Fundamentally, that requirement is ongoing homeostasis which cognition serves through the provision of self-regulated behavior. Cognitive systems are to be found not in physical stuff (air, water, rocks, gas), but exclusively within biological organisms, and not just any organism, but motile as opposed to sessile organisms. As Llinas (2001) argues, this basic fact is critical for understanding the functional purpose of cognition. The primary challenge for all biological organisms is to survive by sustaining homeostasis — the internal conditions supporting life — in the midst of ongoing interaction with an ever-changing, often-threatening environment (Cannon, 1932). Biological organisms are therefore most basically self-regulative regimes (Ghin, 2005; Lyon, 2005). Cognition provides a means of extending the biological homeostasis-maintaining self-regulative capacity beyond the organism to the organism–environment interaction by developing the capacity to generate self-movement and to control the resulting agent–environment interactivity.

In other words, cognition provides a basis not simply for self-movement, but for managed self-movement as part of the homeostatic self-regulation regime

(Bickhard, 2009; Cisek, 1999; Panksepp, 1982; Parvizi and Damasio, 2001), because to survive, a cognitive organism must be able to continuously relate its behavior directly to its homeostatic needs (Churchland, 2002a, 2002b). Random, undirected behavior simply burns energy. Thus, cognition is of necessity configured as a control system that relates ongoing action outcomes to current homeostatic requirements. A cognitive organism self-regulates by controlled self-to-environment interaction. In this sense, cognition functions as an adaptive extension of the organism's self-regulative functionality into the realm of behavioral interaction. This vital self-regulative aspect of cognition finds expression in two ways: (a) as the central data structure or reference frame that configures ongoing interaction in a controllable form — as spatiotemporal self-location of the agent in relation to the environment; and (b) as cognitive processing architecture that functions as a control system relating action output to required perceptual inputs (and ultimately thereby to homeostatic needs). These two self-regulative elements, the data structure and the control architecture, constitute central ingredients of the explanation of consciousness-as-subjectivity here proposed.

### Consciousness: The Self-Regulative Data Structure

Conscious cognitive processing displays certain distinctive characteristics. Significant psychological features include the cyclical activation of consciousness over the sleep-wake cycle, distal representational format, egocentric perspective, limited processing capacity, seriality and close association with short term memory, attention, and the detection of novelty. However, debate as to the critical qualities of consciousness which need to be explained has established a consensual recognition that no explanation of consciousness can be considered complete without addressing a specific set of core phenomenal properties (for summaries of such properties see Delacour, 1995; de Sousa, 2002; Metzinger, 1995; Revonsuo, 2005; Searle, 1992; Weisberg, 2005). In addition to the core characteristic of subjectivity, consciousness is everywhere and always characterized in terms of an ongoing experience of self, expressed not merely as an abstract egocentric point of view, but as orientationally situated both spatially and temporally from the first-person perspective — as an “I” (or more primitively “this”) situated “here” and “now” (de Sousa, 2002, p. 150; Metzinger, 1995, p. 16; Nagel, 1986, p. 61; Revonsuo, 2005, p. 133). As Damasio puts it, “The simplest kind [of consciousness], which I call *core consciousness*, provides the organism with a sense of self about one moment — now — and about one place — here (1999, p. 16; cf LeDoux, 1996, p. 278). Consciousness is coherent as an ongoing subjectively self-aware field of spatiotemporal self-location. In the following proposal, the consistent configuring of experience in terms of egocentric self-locatedness will be accounted for in terms of a basic reference frame consisting of a single self-locating event schema; and subjectivity

as the ongoing recursive processing of that self-locational schema. First, this proposal addresses the orientational character of consciousness-as-subjectivity: the derivation of the self-locating reference frame.

### *Cognition Is Based on Representation*

With or without nervous systems, almost all living organisms have found a way of responding adaptively to environmental changes through movement. Photosynthetic organisms such as plants maximize their ability to harvest light by actively orienting stem and leaves toward the sun. Subcellular microtubules, as a consequence of changes in electric polarization which induce movement, are able to position themselves and shift positions so as to move about within the cell. Single-celled eukaryotes such as amoeba and paramecium achieve motility using hairlike flagella activated by a chain of molecular sensors.

Electrotonically-based nervous systems, on the other hand, provide several advantages over molecular chains, including a capacity for spontaneous endogenous activation, faster signal propagation, signal amplification through spike propagation, more selective activation based on sensory pattern recognition, and a capacity to coordinate the action of multiple effectors, underwriting a capacity for more complex movements through multiple dendrites and axon collaterals (Mackie, 1970). But arguably the biggest advantage is that nervous systems can represent, they can generate mediating informational states (Markman and Dietrich, 2000) that carry and display information about something other than themselves — information about the external environment and internal bodily homeostasis. Representation remains a somewhat controversial issue (reviews include Gallistel, 2008; Haselager, de Groot, and van Rappard, 2003; Markman and Dietrich, 2000). However, it is difficult if not impossible to adequately account for a host of cognitive functions without some notion of representation, particularly in the case of hallucination, and dreaming where there is minimal external input (Revonsuo, 2001; Ullman, 1980).

If cognition operates in terms of representations, what, precisely, do representations represent? Is the representational system a kind of Treisman machine, involved primarily in the manipulation of cobbled-together surface features of objects (Treisman, 1996); or by contrast, is cognitive representation designed to operate in terms of a portrayal of dynamic action events (Neisser, 1976; Zacks and Tversky, 2001). If the latter, is representation configured at base in terms of the singular ongoing dynamic self-movement event involving the organism as it interacts continuously with its environment? The evidence indicates that cognition is designed first and foremost to manage the ongoing dynamic agent-to-environment interactional event. Moreover, cognition is designed to manage self-movement in relation to the environment as an actively self-moving platform. This fact is critical, because it determines the

format in which interaction is represented and managed, and the structural parameters of that format will constitute the essential content of consciousness.

*Cognition Represents Ongoing Mobile Interaction of the Self-Moving Agent with the Environment*

Evidence suggests that cognition provides biological organisms with the means to extend homeostatic self-regulation through the provision of a self-movement capacity. This means that cognitive systems are self-movement systems, designed to operate while moving, to represent in terms of interaction while “on the hoof” as it were (Clark, 1997), as a moving platform (Merker, 2005). Within the embodied cognition and dynamical systems literature, the understanding that cognition manages interaction and does so while mobile is referred to as situated activity (Wilson, 2002, p. 626). This designed-for-motility or situated character of cognition underwrites the design of cognitive processing in several critical dimensions. From the perspective of evolutionary psychology, perceptual systems first emerge to detect the self-movement of the agent through the environment (Milner and Goodale, 1998), and virtually all perceptual channels anticipatively adjust their output for this ongoing self-movement through the environment in order to maintain the stability of the egocentric perceptual display (Merker, 2005). Moreover, object recognition requires interactive self-movement both to develop properly (Held and Hein, 1963), and to function optimally when developed (Churchland, Ramachandran, and Sejnowski, 1994).

Indeed the entire perceptual process is configured in terms of motile agent-to-environment interaction. Studies show that entities are first perceptually “individuated” as locus-of-movement (Spelke, 1990), and then initially identified through categorization in terms of kinds of movement (Csibra, Gergely, Bíró, Koós, and Brockbank, 1999). Ensuing interpretation, in turn, focuses significantly on action potential — how the subject can or should interact with the object, what the object offers or affords in terms of the potential-for-action (Gibson, 1979). As a result, the knowledge base drawn upon in this affordance-identification process is configured in terms of a privileged interactive “basic level” of categorization (Rosch, 1973) reflecting the distinctive actions we perform on particular classes of objects. Indeed, the entire spatiotemporal manifold in which behavioral output takes place is inherently meaningful to the cognitive system only by virtue of bodily interaction, the history of self-motion in terms of spatiotemporal parameters. Primitive meaning schemas relating to space (up–down, in–out, front–back, left–right, near–far), motility (momentum, source–path–goal, towards–away from), force (compulsion, blockage, counterforce, resistance, enablement, attraction), and particularly temporal (then–now) and spatiotemporal schemas (fast–slow, change) are all action-oriented and derived from self-movement through the environment (Grush, 2000; Mandik, 2005).

Most significantly, the distal “out there” representational format itself serves the agent-to-environment interactional purpose. Perceptual representations reflect neither sensory stimulation nor the excitation patterns in the brain. Rather, events as a whole (including objects and agent) are represented as positioned beyond the sense organs (Prinz, 1992), in a way that satisfies the needs of action control (Rosenberg and Anderson, 2008). And this distal format is itself further configured in terms of an interaction-oriented first-person perspective that involves the perspective of an agent in relation to the environment in which he is situated. In this sense, cognitive processes configured to facilitate and manage agent-to-environment interaction, can be said to be “embodied.” They arise from bodily interactions with the world (Johnson, 1987) and act as “controller of embodied action” (Clark, 1997) or agent-to-environment interaction.

The fact that sensory individuation, perceptual identification, the memory knowledge base and representational format are all configured in interactional terms, indicates not simply that cognition is designed to guide action (Barsalou, 2002; Borghi, 2005; Glenberg, 1997), but that the cognitive system is designed to operate under action-oriented circumstances (ongoing agent-to-environment interaction). The organization of motor output is similarly structured to operate in the midst of ongoing mobility. Action output is more or less continuous, commencing immediately upon perceptual input, and continuing in successive waves of adjustment and realignment as action proceeds (Eriksen, Coles, Morris, and O'Hara, 1985). Consequent upon this commitment to ongoing motility, interactional cognition bears the marks of being time-pressured, of having to function under the pressures of real-time interaction (“runtime”) with the environment (Wilson, 2002).

#### *Ongoing Mobile Interactivity is Represented Cognitively as One Ongoing Interaction*

The fact that cognition is designed to operate as a moving platform, in terms of *ongoing* interaction, suggests that interactional cognition is configured cognitively as one singular temporally extended action event. That is to say, ongoing interaction is represented not simply as an event, but as the same event with the same representational structure at every successive moment. For purposes of management, that structure is configured in terms of the moment-to-moment spatiotemporal location of the agent in relation to the environment. Interaction is managed by the interactor in terms of moment-to-moment self-location. Gallistel (2008) points out that direct electrophysiological observation of neural activity has shown that the nervous system represents where the animal is and has been within the environment, how it is oriented in terms of both its spatial and temporal relationship to the environment. That is to say, the cognitive system manages the ongoing interactional event in terms of a continuously

updated computation of spatiotemporal self-location. In order to represent self-to-environment interaction, cognition constructs an egocentric reference frame (Carlson, 1999) which is continuously and automatically updated (Riecke, Cunningham, and Bühlhoff, 2007) in relation to ongoing self-movement through the landscape. The reference frame is self-locating because it is constituted by continuous updating through a combination of external sensory, as well as internal proprioceptive and vestibular feedback from self-movement to yield an ongoing sense where and when the organism is in relation to the environment (Riecke, Beykirch, and Bühlhoff, 2003; Ventre-Dominey and Vallee, 2007; Wirth et al., 2007). The spatial aspect of self-locational functionality, which is computed on the basis of self-motion cues rather than with reference to external visual or acoustic landmarks, is referred to as *path integration* (Etienne and Jeffery, 2004; Glasauer, Amorim, Vitte, and Berthoz, 1994). The temporal aspect of self-location is referred to as *scalar timing* (or interval timing), which involves the computing of rate of motion and time spent travelling in a certain direction (Eagleman et al., 2005). Phylogenetically, this spatiotemporal self-locating navigational functionality has been identified in virtually all species of animal from humans to crustaceans.

Because the cognitive system is designed for constant interactivity, it is designed, *ipso facto*, to constantly track this ongoing interaction. Consequently, egocentric self-locational updating in terms of the self-locating schema can be considered as constituting the primary ongoing reference frame (Avraamides and Sofroniou, 2006; Briscoe, in press; Hartley and Burgess, 2002; Wirth et al., 2007), and as such, can be accounted, in some sense, an important component of the functional heart of the cognitive system.

*The Primitive Self Schemata Which Captures the Ongoing Self-Locational Event is Configured in Terms of a Single Set of Egocentric Orientational Parameters — This-Here-Now*

Spatiotemporal updating of ongoing interaction is consistently structured in terms of a basic self-locating action-event schema configured in the form of spatiotemporal self-location of the causal agent, the self-mover in relation to the environment. The three primary parameters of interactional event representation — spatial, temporal, and causal — are configured in agent-centric terms, because computations designed to generate and control self-movement in relation to the environment must necessarily be framed in terms of the perspective of said self-movement — the first-person or egocentric perspective of the agent. The structural parameters of the interactive event are, then, causal, spatial, and temporal. Casting these in the perspective of the self-moving agent: the egocentric depiction of the self-moving causal agent (the self-mover) at every moment is “this” (or, at the biographically-elaborated human level, “I”); the egocentric



representation of real space, actual spatial location of the agent-in-relation-to-the-environment is always “here”; and the egocentric representation of real time, the actual temporal location of the agent-in-relation-to-the-environment at every interactional moment is “now.” Collectively, these three egocentric parameters structure the self-locational reference frame (and consequently the content of subjective space) as *this–here–now*. The extraction of the three critical parameters from the continuous processing of the ongoing interactional event to form a single, self-locational schema involves a process of schema-abstraction operated by the cognitive system as part of the normal process of memory consolidation, whereby the structure of interactive events is abstracted and retained as a skeletal event-schema (Alba and Hasher, 1983). Experienced events are constantly configured (and consistently coherent) in terms of the egocentric self-location of the agent (Wallentin, 2008) within a spatiotemporal manifold of subjective presence (Metzinger, 1995; Revonsuo, 2005) because the configuration of events is consistently engineered (and constantly updated) in terms of this basic schematic spatiotemporal reference frame.

Because the three structural parameters of the self-locational schema constitute the basic content of consciousness-as-subjectivity, it is important to clarify precisely what they represent. As the *this–here–now* reference frame models an ongoing dynamic relational process between agent and environment, a relationship rather than *things* or *objects* themselves, it cannot properly be considered a model of the self *and* the environment (Churchland and Churchland, 2002; Damasio, 2000; Edelman, 2003) or a representation of the self model *nested in* a map of the environment, as has also been proposed (Metzinger, 2000). The self-locational schema is a tripartite data structure which functions to consistently configure the internal representational product of self-locational event processing, and as such, it captures the controllable parameters of an interactional event from the perspective of the agent. In so doing, it does conjure up a kind of self and thus can be said to constitute a self schema. What sort of self, then, is this intrinsically orientational, self-located self?

As described thus far, the primitive or core self structure does not reference the self in isolation (as either a self-contained psychic or bodily monad), but a self in temporal and spatial relation to the environment with which it is in constant interaction. That spatiotemporal relation is constantly updated as part of the ongoing self-locational process. This self thus constitutes an intrinsically situated self. It has been suggested that the self-schema is tripartite (*this–here–now*) because it comprises the abstracted structural parameters of the ongoing interactional event, the reference frame necessary to structure ongoing organism-to-environment interaction in a continuously coherent fashion. But there is a more substantial cause: the self arises as part of a tripartite self-locational schema fundamentally because the cognitive system must be able to manage the interaction in order that behavior can fulfill its fundamental purpose of

servicing homeostatic needs. In other words, a cognitive organism that simply distinguishes itself from the environment without the capacity to configure and thereby manage its interaction with that environment is likewise, a dead organism. Differentiating self from environment does not suffice for survival. Management of the interaction is essential. According to this understanding, the differentiation of self from nonself is achieved as part of the self-location of the self in relation to the environment.

It is this management principle which fundamentally informs the character of the “core” self structure. Control of the ongoing self-to-environment interaction requires representation in terms of controllable parameters, organizing perception of ongoing interactivity in terms of controllable spatiotemporal terms — in terms of the self-location of the organism vis à vis the environment as such. The self-locating event schema embodies the fact that self-regulating organisms have developed cognition in a form which extends that capacity for self-regulation through controlled self-movement, or controlled self-to-environment interaction (and this self-regulative character of cognition extends also to the configuration of its architecture as a feedback system relating action to metabolic needs).

Thus, while the cognitive system is designed to operate as an ongoing interactive platform, suggesting a purely agential core self (see Gecas, 1982, for a review), this is not the complete story. Ultimately, as part of a tripartite self-locating event schema, the minimal self operates to configure interactive experience in a way that permits self-regulation, thus enabling the self-sustaining metabolic system to self-regulate (Ghin, 2005), and on this basis, like its architectural counterpart (the feedback system), the minimal self structure must be accounted essentially a self-regulatory device permitting managed interaction. As the abstracted foundational structure of interactional event cognition, this paradigmatic self-locating event schema has become part of the innate heritage of the vertebrate cognitive system in much the same way as the innate domain-specific learning device (Carey and Spelke, 1994) and the language-acquisition device (Chomsky, 1975). Beyond this, its significance to cognition lies in the fact that if activated on its own within a tightly recursive processing architecture, this self-locational schema has the potential to manifest cognitively as a primitive form of subjective self-awareness (consciousness-as-subjectivity). The evolutionary development of just such a recursive processing circuit forms the focus of the following section.

### **Consciousness: The Self-Regulative Processing Architecture**

As canvassed in the introduction, subjectivity as simple reflexive awareness can be considered the primary phenomenal characteristic of consciousness as well as its most primitive evolutionary form. What sort of referring-back-upon-itself processing regime could account for this recursive style of cognition manifest phenomenally as conscious self-awareness? It will be argued here that cognition is

designed not merely to regulate agent-to-environment interaction in relation to homeostatic needs, but is obliged as a result of evolutionary pressures to do so in an energy efficient manner. And this evolutionary pressure has driven the feedback architecture toward feedforward processing, and in the particular instance of the orientational schema, to the emergence of recursive feedforward circuitry capable of supporting reflexive self-awareness (subjectivity).

As an adaptive extension of the organism's self-regulative functionality beyond biology and into behavioral interaction, the cognitive system is of necessity configured most basically as a control system relating ongoing action outcomes to current homeostatic requirements. This self-regulative character finds expression both in the central data structure or reference frame — the self-locating event schema — as well as in a processing architecture configured essentially as a feedback control system. But survival and reproductive success depend not only on a self-regulatory operating regime, but on the regime's ability to operate in an energy efficient manner, because motor output in particular is energy expensive. With this in mind, biological organisms can be viewed most basically as energy regimes (over half the body's weight is devoted to cellular elements that manufacture energy), so that "any organism that can capture prey, escape predators and achieve goals with a minimum demand on metabolic energy, has an evolutionary advantage" (Neilson and Neilson, 2005). Thus, whatever the somatic and neurological changes engineered by the need to meet specific environmental challenges, the challenge is always to operate with maximum energy efficiency. In terms of the critical relation between action and homeostasis, cognitive systems can thus be viewed as managers, not simply of ongoing homeostatic balance, but of the energy budget available to maintain that balance through action.

The evolutionary pressure for ever-greater energy-efficiency has driven elaboration at several functional levels of the neurocognitive system. At the molecular level, for example, the energy cost of information transfer has been found to constitute a significant constraint on the number of signaling molecules and synapses used by neurons (Schreiber, 2002). In terms of neuronal interconnectivity, the evidence indicates that energetic costs could limit absolute numbers of neurons and synaptic connections (information channels) in the brain (Laughlin, van Stevenick, and Anderson, 1998). At the systemic level, evolutionary pressures for increased energy efficiencies have encouraged not only the emergence of successive levels of control, as outlined by Hughlings-Jackson and his contemporaries (Prescott, Redgrave, and Gurney, 1998), but also the elaborative changes in the control mechanism itself, which, studies indicate, has evolved from feedback, to feedforward (see Figure 1), and finally, within the spatiotemporal self-location (path integration) module, to a simplified, recursively-feedforward circuitry (see Figure 2 panels b and c). In so doing, the hierarchical perceptuo-motor control system is provided with an energy-saving default state of cognitive activation

in its top tier which does not require physical motor output for its completion. As discussed below, it is this recursive processing circuit in the top tier that underwrites the state of consciousness.

*Due to Energy-Efficiency Pressures, Self-Regulative Processing Evolves from Feedback to Feedforward*

The earliest self-regulatory processing mechanism that serves to maintain a tight relationship between behavioral motor output and internal homeostatic needs, comprises a simple negative feedback control mechanism. Within such a system, behavior is no longer simply a kneejerk reaction to external stimuli, but a reaction geared to the maintenance of critical internal conditions. The fundamental self-regulatory operating principle linking motor output to homeostatic needs is initially embodied within cognitive functionality in the form of feedback control, which acts to restore deviations from regulated internal set points through corrective external actions. In this way, the brain exercises control over homeostasis by using motor output to produce desired homeostasis-regulating inputs (Cisek, 1999).

However, the fact that the cognitive system has been constituted to function as a continuously moving platform presents two significant problems for the maintenance of homeostasis via self-movement: feedback processing is too slow for accurate control of a constantly mobile cognitive organism (Churchland, 2002a), and in addition, too costly in terms of the energy-expenditure on corrective actions. To overcome multiple delays in sensorimotor feedback loops (Miall and Wolpert, 1996), and eliminate the need for further corrective movements as far as possible, fast motor control must necessarily be anticipative as far as possible, involving a combination of predictive feedforward models of both muscle kinematics and the perceptual outcome of movement (Desmurget and Grafton, 2000).

Feedforward processing provides increased energy efficiency in several significant ways: most basically, predictive adjustment to ongoing motor output saves energy through improved accuracy and minimization of the motor trajectory (Wolpert and Flanagan, 2001). Anticipation of (rather than feedback from) environmental change reduces the ultimate effect and thereby, the amount of compensatory adjustment required (Brosilow and Joseph, 2002). In the case of anticipated danger, for example, predictive feedforward circuitry underwrites the capacity for complete avoidance (Prescott, Redgrave, and Gurney, 1998, p. 18). The capacity, in feedforward architecture, to represent the expected results of upcoming actions provides the basis for replacing aimless wandering with proactive, goal-focused foraging (Glasauer, 1992), as well as the anticipatory orientation of attention toward stimuli which are relevant for action in general (Mehta and Schaal, 2002). In addition, feedforward representation provides

the capacity to completely replace energy-expensive external trial-and-error activity with internal mental planning (Mandler, 2002). Finally, feedforward goal representation supports not just trajectory minimization, but action minimization, the replacement of attack with threat (of attack), of extended bodily movement with gesture as the initial basis of communication.

The net result of these avenues to improved energy efficiency is a cognitive system capable of self-regulating for homeostasis in a predictive fashion by means of feedforward processing mechanisms. Most significantly, as regards the central claim of the theory outlined here, the dedication of cognitive architecture to an anticipative feedforward processing format (for speed and energy efficiency) implies that the recursive circuitry required to underwrite conscious subjectivity is most likely to have evolved out of such predictive cognitive architecture. Specifically, this theory proposes that evolutionary pressures for ever-more energy-efficient sensory-motor processing has encouraged the progressive attenuation of feedforward processing circuitry into a simplified recursive feedforward circuit capable of underwriting autoreferential conscious self-awareness.

The architecture customarily used to model predictive feedforward processing casts the perceptuo-motor control system as a Markov processor whereby the current states of a process lead to its own future states when current motor commands exert their effect. These future states, in turn, update the current state (Grush, 2004, sec 2.1). Markov process models explain the mechanical operations involved in guiding the transition of present state into the next present state. These anticipatory processing mechanisms use predictive or “forward” perceptual models of what the future state will be (if we go ahead and execute this action) as a way of guiding the transition from present moment to next present moment. Specifically, anticipatory self-regulatory-processing architecture (as illustrated in Figure 1) utilizes four internal models to represent the various elements of the predictive Markov control system: models for the desired state, the actual current state, the predicted future state (the “forward model”), and a structuring schema which acts to configure both current state model and forward model into a consistent interactional event representation — the self-locating event schema which has been abstracted from the ongoing agent-to-environment interaction.

Within the feedforward control circuit (as with negative feedback loop), the desired homeostatic state is constantly compared with the actual current state, and actions are generated on the basis of the difference between the two. But action generation necessary to close the gap between desired and current states is not random trial and error. The system makes use of an inverse controller (or inverse model) to provide motor commands specifically tailored to achieve a desired sensory outcome state. This inverse controller is capable of retrieving motor output likely to produce required sensory inputs (Held, 1968), so that current state becomes more closely aligned with desired state. The inverse con-

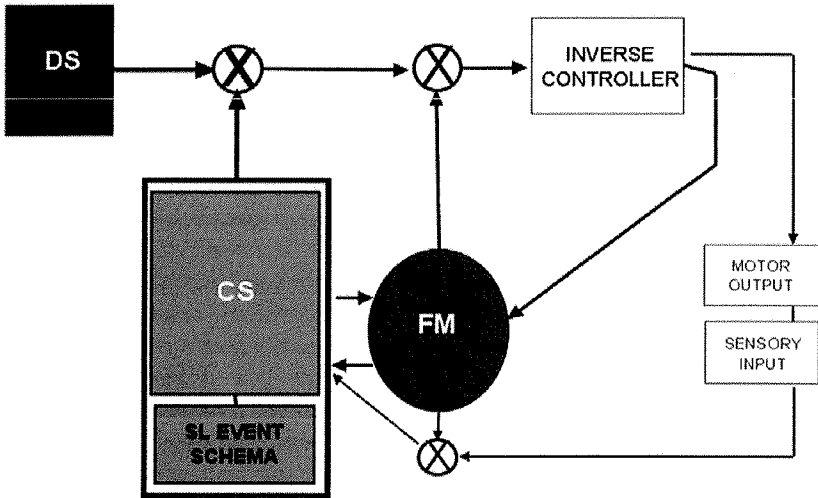


Figure 1: Predictive feedforward processing architecture.

troller also produces a copy of its motor command (corollary discharge, efference copy) which provides the basis for a predictive or forward model of the expected perceptual result of that action (Miall and Wolpert, 1996). The forward model is able to feed into a comparator and anticipatively adjust ongoing action; and at the same time, the forward model predictively updates current state in advance of feedback from actual motor output.

The current state model is the central representation in this control system because it is the end result that is being controlled for. Current state is constituted by three inputs: (1) continuous feedforward updating from the forward model; (2) periodic feedback from the sensory systems; and finally (3), the ongoing structuring input from a memory buffer (Bridgeman et al., 1994; Merfeld, 2001; Neilson and Neilson, 2005) consisting of the self-locating event schema, which acts as a constant reference frame to configure input as an interactional event. Based on brain imaging studies consistently identifying the posteromedial cortex as the neural source for conscious cognition (Laureys et al., 2004), and the direct innervation of this area by the wake-sleep arousal system sourced from the postero-lateral hypothalamus via the basal forebrain (Saper, Scammell, and Lu, 2005), it is postulated that this structure-providing memory buffer is independently activated by the sleep-wake innervation system, thus providing a self-activating base to the interactional configuration of waking experience.

The functional independence, as it were, of the self-locating event schema memory buffer feed is of particular importance, given that current state is a

computation of spatiotemporal self-location updated moment to moment from self-movement feedback. Without the initial structural input from the self-locating event schema feed, current state would be utterly dependent on continuous movement for its activation. With the self-locational update functioning as the primary reference frame of the cognitive system, this would, in effect, hold the entire cognitive economy hostage to ongoing movement, both large limb ambulatory movement and tonic postural adjustment. The self-locating event schema memory buffer is relatively independent of sensory feedback for its activation, and as a result of continuous evolutionary pressure to reduce energy-expensive physical activity to a minimum, it is encouraged to become more so, to sustain its activity through self cueing. Self-activation of the self-locating event schema accounts for the twin facts that (a) orientative self-locating spatial updating is automatic and continuous (Rieke et al., 2007), and (b) that self-location is still operative in deafferented individuals where there is no active sensory feedback from self movement (Meijsing, 2000).

In sum, evolutionary energy-efficiency pressures on a cognitive system built initially for the generation of self-movement for active regulation of homeostasis, have encouraged the development of feedforward (top-down) processing architecture that can maintain orientative cognition even when the organism is more or less stationary (such as during periods of rest, vigilance as well as immobile ambush hunting or predator avoidance immobility) such as to constitute a base state of alert action readiness for the timely resumption of appropriate action (predation, avoidance of predation, etc). The significance of the connectivity involved in this feedforward processing architecture is that under evolutionary pressure to achieve further energy efficiencies, the processing circuit can be minimized and the connectivity simplified to the point that feedforward processing functions as a single *recursively* feedforward circuit capable of underwriting subjectivity.

#### *Self-Regulative Processing Evolves from Feedforward to Recursively Feedforward*

Reflexivity, the self-referring or recursive quality of subjective self-awareness constitutes the primary characteristic of consciousness in need of explanation. Several existing explanations of phenomenal subjectivity refer to psychological processing mechanisms which are not, in themselves, recursive in nature, such as Dennett's multiple drafts (a series of static updates), or secondary processing theories such as higher-order thought (Dretske, 1993), attentional highlighting of representational content (Crick, 1984), linguistic coding (Edelman, 1989) or global accessibility (Baars, 1988; Dennett, 2001), where the additional processing of a perceptual representation somehow confers qualia-like status upon that representation. But in each case, the process doing the consciousness-conferring does not employ autoreferential processing circuitry and is not itself

self-consciously aware. A more credible candidate for the generation of auto-referential self-awareness (consciousness) would be a self-referring cognitive mechanism, a processing circuit which is itself recursive, continuously feeding back upon or "referring to" or "recognizing" itself. This is the solution here proposed. In a nutshell, everything currently known about the evolution of cognition points to a consistent increase in attenuated processing of existing circuitry as a more energy-efficient way of maintaining homeostatic self-regulation through self-movement. Attenuation of feedforward circuitry (Figure 2 panels a and b) leads to fully *recursive* feedforward circuitry (Figure 2 panel c).

Attenuation plays a major role in the metamorphosis of the self-locational updating module from a merely anticipatory feedforward mechanism to a recursively feedforward processor. For cognitive organisms, where cognition is essentially designed to maintain homeostasis through self-movement, the drive toward improved energy efficiency necessarily involves both brain and body operating efficiencies. In both instances, *attenuation* constitutes a common theme. When somatically active, all movements are constructed on a minimum-trajectory basis which is managed by last-minute, only-as-much-as needed adjustments (Todorov, 2004). Periods of behavioral torpor (sleep, hibernation) can be seen as a way of limiting active self-to-environment interaction to only the most energy-rewarding periods. Proactive foraging that deploys top-down feedforward circuitry to focus activity on specific targets is, again, a form of attenuated activity. And the development of communication from bodily gesture can also be seen as embodying this tendency toward attenuated somatic activation. Undoubtedly, the most extreme form of behavioral attenuation is exhibited in surviving species of primitive tunicates which abandon both somatic (tail, tail musculature) and cognitive (brain, nervous system) capacity for motility altogether. Surviving forms develop a gut, gills, and brachial structures which are present but no longer operative (Llinas, 2001), indicating that these creatures have regressed from what was once a more actively motile life, to a highly-attenuated one-day excursion to find a suitable substrate to attach itself before resuming a permanently sessile existence.

Attenuation is particularly critical for cognitive processing, because the brain, unlike the body, expends most of its energy on active information processing, not metabolism. Where the soma devotes 70% of its energy budget to ongoing metabolism and the balance to behavioral activity (posture, locomotion, mating), cognitive costs are the reverse. The brain expends 80% of its energy on information processing as opposed to purely metabolic activity (Attwell and Laughlin, 2001; Raichle and Gusnard, 2002). Thus, the achievement of energy economies in the way information is processed have a significant impact on the overall energy expenditure (Attwell and Laughlin, 2001) and the cognitive economy, as a result, is replete with cost effective information-processing mechanisms such as sparse coding (Churchland, Ramachandran, and Sejnowski,



1994) and minimal updating of scene (Rensink, 2000), schema abstraction for memory storage (Hess and Flanagan, 1992), and attentional limitation (Mack and Rock, 1998). Attenuation of the feedforward processing architecture leads to the development of recursive processing circuitry.

Understood in terms of the ongoing interactive event, which consists of an initial self-locational calibration (this-here-now) followed by action output, attenuation proceeds on two fronts: (a) an extension of the initial orientative phase of interactional processing while minimizing the subsequent physical action component; and (b) the development an extremely truncated feedforward processing circuit within the orientational phase itself, facilitated by decreasing dependence on feedback from self-movement as major driver of the circuitry, and an increased capacity to complete its feedforward processing loop internally. This attenuated circuitry consists, eventually, of the orientational schema feeding forward immediately into itself, independent of additional representational feedback from self-movement. This recursive self-conversation, as it were, constitutes the rudiments of subjectivity, so that the recursive processing underwriting conscious subjectivity emerges, in effect, from the increased evolutionary fitness derived from the capacity to remain cognitively alert while physically inert, exchanging energy expensive physical activity for low-cost pre-physical orien-

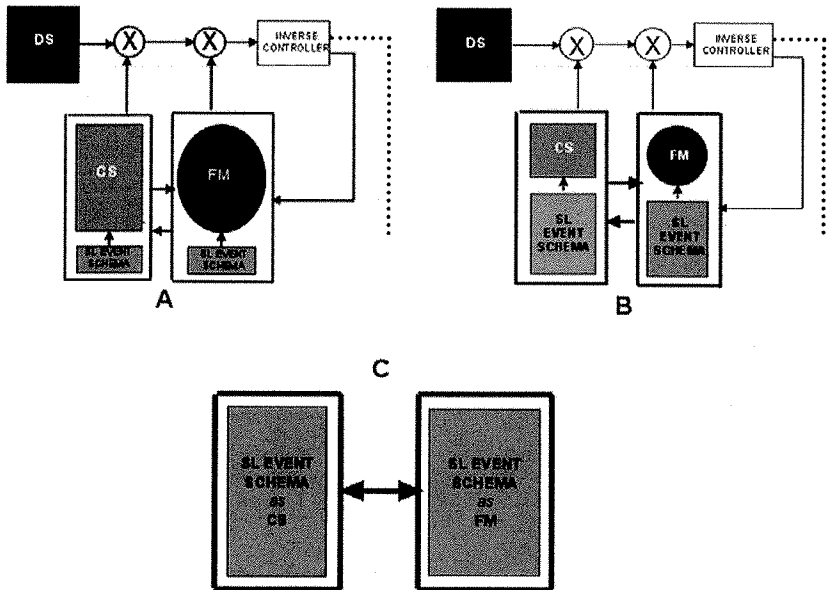


Figure 2: Feedforward processing evolves to recursive feedforward architecture.

tative processing. Thus, the primary (but certainly not the sole) adaptive value of recursive conscious processing is energy efficiency.

Figure 2 illustrates the specifics of this evolutionary development from feedforward to recursively feedforward processing circuitry. As in Figure 1, current state constitutes the final representative product of the self-locational feedforward processing architecture. It is normally understood that continuous spatiotemporal updating involved in this process is driven largely by external sensory and internal proprioceptive feedback from self-movement. But while spatiotemporal self-location constitutes the primary orientational reference frame on the basis of which motor output can be calculated (distance from "here" to there), it is also the case that the perceptuomotor-control system consists of a hierarchy of these kinds of feedforward calculations (Prescott, Redgrave, and Gurney, 1998). Thus it is possible for the top tier of the processing circuitry to evolve away from absolute dependence on feedback from physical self-movement without the entire motor control hierarchy grinding to a halt. Evolution encourages development in this direction because it produces cognitive circuitry that can remain activated without reliance on actual energy-expensive physical movement. Organisms that can remain cognitively alert while minimally active at the physical level have increased fitness.

Increased reliance of the self-locational processor on internal drivers for continuous activation begins, as we have noted above, with the self-cueing of the event schema memory buffer that provides the basic structure of both current state and forward model representations. Continued evolutionary pressure for increased energy efficiency then, encourages further development in the familiar form of attenuated processing. In the particular case of self-locational updating, this consists of decreased reliance on feedback from external physical self-movement (shown in Figure 2 as a change from heavy to light connectivity in the external loop) along with increased emphasis on the internal processing circuit comprised of the reciprocal current state-forward model circuit. Decreased external feedback means that both current state and forward model can be envisaged as consisting, to an ever-greater extent, of the structural input from the self-locating event schema memory buffer. As it does so, the current state-forward model circuit is able to become ever more tightly interlocked because more completely based on its own arousal feed for self-activation, and less dependent upon the desired state comparators as drivers. Essentially, this enables the self-locational calculation to complete its cycle within the current state-forward model circuit alone, and for each of the twin data structures within that circuit to consist, increasingly, of the self-locating event schema alone.

This highly attenuated positive feedback loop is now completely recursive, and driven by a self-activating memory buffer which is directly linked to the wake-sleep cycle of its principal arousal feed sourced in the lateral hypothalamus.

The recursively-processed content consists essentially of the same self-locating event schema represented as current this–here–now state and the expected next current this–here–now state. The current state-forward model circuit has emerged as a stand-alone recursive working memory loop or reverberatory circuit consisting of the this–here–now event schema referring continuously back upon itself. Because it is self-activating and thus tonically sustainable as well as supremely energy efficient, this new form of self-locational alertness becomes the default processing state of active cognition; a default state of recursive this–here–now schema processing which manifests at the phenomenal level as subjectivity, conscious self-awareness.

In terms of Nagel's sense of subjectivity wherein there is always "something it is like to be that organism, something *for* that organism" (1974, p. 436); that "something it is like to be" is everywhere and always primarily what it is like for that organism to be a this–here–now. At the phenomenal level, conscious self-awareness arises as a singular unified field of self-awareness because underwritten by a single schema, processed continuously in an autoreferential or recursive style where "self" is always experienced, subjectively, as a "this" (or an "I") explicitly located "here" and "now." This recursive this–here–now processing provides the basis of subjective self-awareness, of what it feels like to be oneself here and now. This is consciousness.

### Conclusion

The picture painted thus far depicts consciousness as an outgrowth of the need for energy-efficient self-regulation. Consciousness is understood to bear the self-locational content that it does because orientation grounds the behavioral output of any self-moving cognitive platform and of biological necessity, does so in a way that represents the crucial parameters by which behavior can be controlled. The recursive circuitry processing the self-locational event schema derives from the evolutionary requirement for energy-efficient forms of self-regulation, driving the self-regulatory motor hierarchy to function at its seniormost level in a way that does not require external behavior.

But once established, consciousness also contributes directly to the self-regulative capacity of the cognitive system in another way: it supports the extension of metacognitive self-regulation, and in so doing, gives rise to the development of voluntary behavior (free will). Metacognition is a broad term, encompassing both knowledge of cognitive abilities ["I have a bad memory"] and regulation of cognitive activity ["I'll make a decision on that in the next hour"] (Flavell, 1979; Moses and Baird, 1999). Preconscious metacognitive regulation includes automatic error detection, source monitoring, and memory retrieval. However, recursive consciousness-as-subjectivity provides an additional offline metacognitive controlspace for self-regulative cognitive processes that require self-

awareness in order to take the agent's own thinking, remembering, and feelings as objects of awareness and reflection. This capacity for introspective self-awareness manifests as the monitoring and non-automatic modification of cognitive processes such as conflict resolution, error correction, inhibitory control (of feelings and actions), intention formulation and action planning, self-activated memory search, voluntary attentional focus, and decision-making (Nelson and Narens, 1990; Reder and Schunn, 1996). In providing these sorts of capacities for the considered, non-automatic direction of the cognitive processes controlling behavior, consciousness introduces a capacity for voluntary, proactive behavior or free will.

Of particular interest to the self-regulative theme is that consciously metacognitive capacities such as voluntary attentional focus, planning, and decision-making are fundamentally self-regulative in nature. They all concern the voluntary, self-initiated relating of action output to inputs needed for homeostatic (including emotional) stability. Conscious metacognition, in other words, is simply a further extension of self-regulation from unconscious reactive self-regulation to a less environmentally-dictated, more self-determined or proactive form of self-regulation based on intentions and plans.

Consciousness is most appropriately characterized as a self-regulative phenomenon then, for several reasons. Firstly, it is itself constituted, in terms of a self-locating data structure and recursive processing circuitry, from the self-regulating character of cognition. Secondly, as the evolutionary elaboration of feedforward to recursive feedforward circuitry, consciousness-as-subjectivity is the product of an evolutionary drive for energy-efficient self-regulation. And finally, because as a fully developed subjective processing regime, it constitutes a metacognitive control space with a capacity for the voluntary control of cognitive processes (attention, memory, intentions, and decisions) which in turn regulate behavioral output in relation to metabolic needs. As the most highly-developed element of the self-regulative cognitive functionality, consciousness provides the functional capacity not merely for self-initiated (voluntary) proaction, but of equal significance, it provides the capacity for *masterful inaction*, or vigilance, the capacity to maintain action-ready alertness while restricting physical activity to only the right action at the right time and the right place. As support for masterful inactivity as well as anticipative, self-initiated activity, consciousness provides unsurpassed advantages for a self-regulating biological system.

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