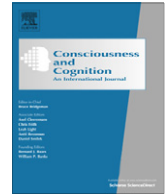




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Review

Solving the “human problem”: The frontal feedback model

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ABSTRACT

This paper argues that humans possess unique cognitive abilities due to the presence of a functional system that exists in the human brain that is absent in the non-human brain. This system, the frontal feedback system, was born in the hominin brain when the great phylogenetic expansion of the prefrontal cortex relative to posterior sensory regions surpassed a critical threshold. Surpassing that threshold effectively reversed the preferred direction of information flow in the highest association regions of the neocortex, producing the frontal feedback system. This reversal was from the caudo-rostral bias characteristic of non-human, or pre-human, brain dynamics to a rostro-caudal bias characteristic of modern human brain dynamics. The frontal feedback system works through frontal motor routines, or action schemes, manipulating the release and reconstruction of stored sensory memories in posterior sensory areas. As an obligatory feature of frontal feedback, a central character, or self, emerges within this cortical network that manifests itself as agent in these reconstructions as well as in the experience of sensory perceptions. Dynamical-systems modeling of cortical interactions is combined in the paper with recent neuroimaging studies of “resting-state” brain activity to bridge the gap between microscopic and macroscopic levels of cortical behavior. This synthesis is used to support the proposal of an information flow reversal occurring in the hominin brain and also to explain how such a reversal generates the wide variety of cognitive and experiential phenomena that many consider to be uniquely human.

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1. Introduction

Man is a singular creature. He has a set of gifts which make him unique among the animals so that, unlike them, he is not a figure in the landscape: He is the shaper of the landscape.

– J. Bronowski (1973)

What is it exactly that makes us human? What is it that allows us to design and build computers and space stations, compose pop songs and symphonies, construct sculptures and skyscrapers, and prepare elegant and extravagant meals? No other animal on the planet can do these things. What is it that makes humans the shaper of their landscape and not merely a figure within it?

It would be easy to say that humans have the cognitive and creative capacities they have because, via the natural processes of evolution, these features developed through their adaptive advantages over a period of time just like the rest of the features of the human body. However, in contrast to the human body, the human mind does not appear to have evolved in this manner. For example, it took on the order of 60 million years and many intermediate stages of primate evolution simply to produce the human hand with its fully opposable thumb (Jones, 2006; Marzke, 1992; Mountcastle, 2005). The development of the varied features and capacities of the human mind, however, appear to have evolved all at once, suddenly and simultaneously with one another, and in the blink of eye, geologically speaking (Calvin, 2004; Gopnik, 2010; McCrone, 1992, 1999; Noack, 2006b).

It will be argued in this paper that the solution to the problem of what it was that happened to the human organism and its brain in order to produce its marvelous mind is a very simple one. It is so simple, in fact, that it has been overlooked by a cognitive neuroscience community bent on finding a complicated answer to how the ostensibly most complicated lump of matter in the universe (Madrigal, 2008), the human brain, works. For the most part, this currently popular complicated approach divides the enigma of the human mind into two parts, a “hard problem” and an “easy problem.” The hard problem relates specifically to how the evolution and organization of the human brain produces the phenomenon of sentience, or consciousness (Chalmers, 1995, 1999, 2004; Harnad, 1998; Smith, 2006, 2009; Thomas, 2001). Recent attempts to solve the hard problem rely largely on quantum-dynamical descriptions of relations between neurons and groups of neurons, and identify the conscious moment as some sort of special superposition or coherence effect that occurs in neural tissue (Globus & O’Carroll, 2010; Hameroff, 2010; McFadden, 2007; McKemmish, Reimers, McKenzie, Mark, & Hush, 2009; Penrose, 1994). Attempts to solve the easy problem(s), on the other hand, tend to “modularize” each problem, such as language, reason, music and mathematical ability, and so on, and then localize its function to discrete regions or systems of regions in the brain, organized mainly in the neocortex (see Bressler & Menon, 2010; Chein, Ravizza, & Fiez, 2003; Cohen Kadosh & Walsh, 2009; Freeman, 2003a; Freeman & Burke, 2003; Fuster, 2006, 2009; Gow, Keller, Eskandar, Meng, & Cash, 2009).

Preuss (2006) has referred to this modularist approach to understanding human brain function as the “model-animal research paradigm.” The model-animal research paradigm views the human brain as simply a larger ape brain whose special abilities are really just “more of the same” of what all other ape, primate, or even mammals in general possess. As with the development of the human hand described above, special features of the human mind such as consciousness and language are thought to be present in all other mammals, only in a less developed, or “proto,” form (e.g., Savage-Rumbaugh, Shanker, & Taylor, 1998; Yamazaki, Yokochi, Tanaka, Okanoya, & Iriki, 2010). As a result, in their attempt to explain how the human mind works, most cognitive-neuroscience researchers have focused on trying to decipher the “neural code” (e.g., McCrone, 1999) explaining how each of these brain-cognitive modules work *generally* in the mammalian brain. From there, they hope that solving the problem of the human mind will be found by simply adding a little bit more functionality to each individual module (Penn, Holyoak, & Povinelli, 2008; Povinelli & Bering, 2002).

While, in general, the modular approach to understanding the birth of the human mind described above has yielded an invaluable wealth of data on brain function, it has done less to solve the problem of the human mind than it has to “solve it away.” That is, by drawing an artificial distinction between a hard and an easy problem, and then by attempting to isolate the

special properties of human brain function such as language and creativity, modularist researchers are sidestepping the real challenge facing cognitive neuroscience. That challenge is to explain how *both* the above hard (consciousness) and easy (modular) problems seem to have been “solved” simultaneously with the evolution of the human brain (Cohen & Dennett, 2011). I call this challenge the “human problem” (Noack, 2008).

The frontal feedback model offers a solution to the human problem by arguing that all of the features of the human mind that many consider to be unique arose essentially at the same time in phylogeny and due to one single evolutionary event. That event was the *reversal* of the preferred direction of information flow in the primate/hominin neocortex due to the continuing disproportionate phylogenetic development of the prefrontal cortex relative to posterior-cortical areas.¹ It was simply this one event that provided the human with the ability for symbolic thought, language, mathematical ability, artistic ability, musical ability, self-awareness, sentient experience, and others (Noack, 1995a, 2004, 2007b). Reversing the preferred direction of information flow in the human neocortex provided for these abilities because that reversal created a unique functional system in the brain referred to here as the *frontal feedback system*. The frontal feedback system works through hierarchically organized motor programs, or action schemes, housed in prefrontal motor cortex, feeding back on and manipulating sensory representations in posterior sensory cortex.

In the non-human, or “pre-human” (hereafter, non-human), neocortex, posterior cortices, via sensory influences from the environment, trigger associated action schemes in prefrontal cortex in a biased, caudo-rostral fashion. The triggering of an action scheme in these non-human mammalian species serves to establish what neurodynamicists call an *order parameter* (Freeman, 2007a, 2007b, 2009; Freeman & Vitiello, 2009; Haken, 2006; Tognoli & Kelso, 2009). The order parameter, as defined here, refers to the temporary governing state of brain dynamics induced by the triggering of an action scheme representing some biologically significant behavior. Each distinct action scheme induces a unique order parameter in the cortex, which serves to match or marry incoming sensory information with the behavioral output characteristic of that action scheme. The focal region for the establishment of these order parameters is the prefrontal motor cortex, and in the non-human mammal, the prefrontal cortex biases the flow of hemisphere-wide cortical information in a caudo-rostral direction. Globally, this caudo-rostral bias of cortical information flow sets up a mechanism for the governance of behavior known as the perception–action cycle (PAC) (Fuster, 2004, 2009; Noack, 2006c).

In contrast to the situation in non-humans, cortical dynamics in the human brain biases in exactly the opposite direction. In the human brain, the enormous size of the prefrontal cortex tilted the scale, so to speak, so that, instead of sensory representations driving action representations in a caudo-rostral fashion, as in the non-human condition, action representations drive sensory representations in a rostral-caudal fashion. Thus, the order parameters that are established in the human brain work to match the internally generated, or self-organized, release of action schemes in prefrontal cortex to created representations of virtual worlds or virtual environments in posterior sensory cortex. As we will see below, such an arrangement provides a mechanism for the generation of essentially all forms of human cognition, as well as consciousness.

This paper is organized into three general sections. The first section reviews the terms and concepts of the newly developed neurodynamic model of the evolution of mammalian cortical function, an understanding of which is essential to understanding the frontal feedback model. It will be argued in this review that the progressive evolution of the mammalian neocortex eventually distinguished two main anatomical/functional divisions of the cortex, a frontal motor association area, or MAA, and a posterior sensory area, or SA. The second section presents evidence that, in the non-human cortex, it is the SA that drives the MAA in a caudo-rostral fashion, while in the human cortex, it is the MAA that drives the SA in a rostral-caudal fashion. Finally, the third section discusses how the change in the global dynamic regulation of cortical events induced by this reversal gave birth to the human mind.

2. Evolution of the non-human brain and the perception–action cycle

The first important point to consider in the attempt to model brain/cortical function is that interactions within the cortex occur on several levels, or scales, simultaneously (Cohen et al., 2008; Freeman, 2003b, 2007a, 2007b; Kozma & Freeman, 2009; Petrides, 2005). There are interactions between the neurons in individual cortical columns, interactions between the cortical columns within a given cytoarchitecturally defined cortical region, and inter-areal interactions between individual cortical regions. Freeman (2003a, 2007a) has referred to the dynamics of interactions at each of these scales as “microscopic,” “mesoscopic,” and “macroscopic,” respectively (see also Tognoli & Kelso, 2009). Recently, there has emerged evidence of a scale of interaction at an even higher level, between clusters, systems, or networks of individual cortical regions. These structurally and functionally related groups of regions have been called *resting state networks* (RSNs) in that they tend to behave cooperatively during activation *and* at rest (He, Snyder, Zempel, Smyth, & Raichle, 2008; Meindl et al., 2010; Smith et al., 2009; Zou, Wu, Stein, Zang, & Yang, 2009). For this reason, I would like to suggest an extension of Freeman’s

¹ The “preferred direction of information flow” basically denotes which cortical areas exert more controlling influence over the others given a global competition for such influence. While information flow between any two cortical regions or networks of regions is generally bidirectional, one region/network typically has controlling influence over the other given a competition between the two. Thus, the preferred direction of information flow between these two cortical regions/networks runs from the dominant network to the “submissive” network, if you will. In the non-human brain, the dominant network is the posterior-cortical sensory regions. In the human brain, the dominant network is the prefrontal cortex (see Section 2.3 for more information on directional-driving dynamics).

terminology to include a scale of interactions within the brain called “hyper-macroscopic” to refer to the interactions between these RSNs (Freeman generally places these network interactions in the macroscopic dynamics category).

Many neuroimaging studies conducted in recent years have begun to identify a number of RSNs. Some of these RSNs include a visual network, an auditory network, a motor network, a “default-mode” network, a “central-executive” network, and a few others (Corbetta, Patel, & Shulman, 2008; Meindl et al., 2010; Nir, Hasson, Levy, Yeshurun, & Malach, 2006; Toro, Fox, & Paus, 2008; Treserras et al., 2009; Van den Heuvel, Mandl, Kahn, & Hulshoff Pol, 2009). The manner in which cortical RSNs work together in the production of behavior in the animal and in the production of cognition in humans will be discussed later. For now, though, it is necessary to discuss how these critical RSNs developed structurally and functionally in mammalian phylogeny. Doing so will identify the functional infrastructure that the non-human mammalian brain possessed just before frontal feedback began to take place in the human brain.

2.1. Origin of mammalian neocortex

Recent evidence suggests that the neocortex evolved out of the dorsal aspect of an archaic, olfactory-related structure in the pre-mammalian vertebrate brain called the *pallium* (Aboitiz, Morales, & Montiel, 2003; Smith-Fernandez, Pieau, Reperant, Boncinelli, & Wassef, 1998; Striedter, 2005, 2006). Originating in pre-eutherian (pre-placental) mammals roughly 200 million years ago (Kaas, 2005), the cortex developed initially as a sensory-processing structure stacked on top of the pallium’s pial surface exterior to the lateral ventricle (Swanson, 2003). This surface development was to be a key factor in the success of the neocortex as it allowed it to undergo an enormous degree of tangential expansion through gyrification (Aboitiz et al., 2003; Rakic & Kornack, 2001; Toro, Fox et al., 2008).

For about the first 100 million years of its development, prior to the appearance of eutherian (placental) mammals, the neocortex developed almost entirely as a sensory-related structure. In fact, for that initial 100 million years, no dedicated motor cortex, or M1, existed at all (Kaas, 2005, 2008), only a region of cortex where motor and somatosensory processes were combined, the *sensorimotor amalgam* (Striedter, 2005). As a result, the main sensorimotor pathway in these early mammalian brains ran directly from the nascent sensory cortices to subcortical motor structures such as the basal ganglia and related ventral forebrain regions (Aboitiz et al., 2003; Granger, 2006). This arrangement, however, began to change roughly 100 million years ago with the appearance of eutherian mammals (Kaas, 2005). In these animals, a dedicated motor cortex (M1) began to differentiate out of the sensorimotor amalgam with strong relations to the subcortical motor complex/basal ganglia on its ventral-rostral end and to the sensory neocortices on its dorsal-caudal end (Kaas, 2005, 2008; Striedter, 2005). Now existing at the top of the motor control chain, the intrinsic activity within the nascent motor cortex served to organize and coordinate a complex hierarchy of movement control centers running down the ventral forebrain and into the spinal cord (Swanson, 2003, 2005). Therefore, while still being coupled to the sensory systems at its caudal end, the main intrinsic activity within the now-distinct motor cortex was hierarchically and sequentially structured (Badre & D’Esposito, 2009; Fuster, 2007; Petrides, 2005; Swanson, 2003).

At the same time the motor cortex was differentiating out of the sensorimotor amalgam, the caudal sensory neocortices began to redirect their main output from the basal ganglia toward the nascent motor cortex (Aboitiz et al., 2003; Granger, 2006). As these transformational processes continued to mature throughout mammalian phylogeny, three functionally distinct divisions of the cortex began to appear: (1) a dedicated rostral motor cortex, or motor area (MA), (2) a dedicated caudal sensory cortex, or sensory area (SA), and (3) a cortical “association area” (AA), where both motor and sensory influences merged. In present-day mammals, the MA is associated mostly with primary motor cortex (M1) along with some contribution from premotor and supplementary motor cortices, while the SA combines the contributions of dedicated visual, somatosensory, and auditory networks as a whole. The AA is most specifically associated with the prefrontal cortex, but also includes premotor, supplementary motor, and sensory-association cortices in higher anthropoid primates.

It is important to note here that this tripartite division of the functional anatomy of the cortex, MA-AA-SA, belies a true bipartite operation that combines the MA and the AA into a larger MAA. The reason that it is better to view MA and AA as a single MAA in its role in global cortical operation will be discussed in Section 2.5. For now, though, it is best to view the operation of the cortex using the tripartite division for illustrative purposes.

2.2. Evolution of mammalian cortico-cortical interactions

The key to understanding mammalian cortical dynamics and, ultimately, the evolution of the human frontal feedback system lies in understanding the difference between the type of activity that is generated in the cortical sensory systems versus that generated in the cortical motor systems. Each system generates a distinct type of activity that, governed by the association areas, produces goal-directed, or *intentional*, behavior in the animal (Freeman, 1995; Fuster, 1989, 2002; Kozma, Aghazarian, Huntsherger, Tunstel, & Freeman, 2007).

The sensory systems represent information on a *frame-by-frame* basis much like a film reel represents a sensory episode, or scenario, through the temporal sequencing of static photographs (Freeman, 2005, 2006, 2007c; Panagiotides, Freeman, Holmes, & Pantazis, 2011; Tsuda, 2001). In vision, for example, as sensory information hits the retina, a collective signal representing the visual scene is sent to primary visual cortex (V1). Here, the collective dynamics between the cortical columns in V1 begin to produce a collective pattern of neuroactivity, a *gestalt*, which not only represents the particular features of the stimulus, but more importantly, reflects the meaning, or significance, of that stimulus to that particular individual (Freeman,

1995; Harter & Kozma, 2005; Kozma, Aghazarian et al., 2007; Kozma, Puljic, Balister, Bollobás, & Freeman, 2005; McFadden, 2007; Piaget, 1952). The collective pattern of neuroactivity that results from the presentation of a significant stimulus to the animal is known as a *chaotic attractor* or, more specific to neurodynamic terminology, a *wave packet* of information in the cortex (Bressler, 2004; Freeman, 2003b; Kozma et al., 2005). The concept of the wave packet is important because the wave packet is the fundamental *currency* that governs cortical dynamics at each level of the information-processing hierarchy discussed in Section 2. Freeman and Vitiello (2006) define the wave packet as follows:

What appears to emerge from our experiments is a *wave packet* acting as a bridge from quantum dynamics at the atomic level through the microscopic pulse trains of neurons to the macroscopic properties of large populations of neurons. The wave packet we refer to is a macroscopic collective field of action that has measurable field properties: the phase, the amplitude, and their spatial and temporal rates of change (gradients and frequencies) at each point in time and space in the sustaining neuropil. (p. 5)

2.2.1. Simple-level interactions

The wave packet can be considered information currency because it serves to enact a change in cortical dynamics upon its generation. That is, in the same way that retinal stimulation acts to produce an associated wave packet in V1, the production of a wave packet in V1 acts to produce an associated wave packet in the cortical regions it is connected with. This collection of regions that V1 is directly connected with is known as its *connection set* (Bressler, 2004; Bressler & Menon, 2010; Passingham, Stephan, & Kotter, 2002), and a wave packet generated in V1 will act to directly influence the subsequent production of wave packets in each of those regions simultaneously.

As a simple illustration of these wave-packet dynamics, imagine a model cortex consisting of two cortical regions, V1 and M1 (Fig. 1). In this example, we present a banana to the animal's retina, which triggers a wave packet in V1 related to bananas. Because, in previous experience, our model animal has received reinforcement when attempting to peel and consume a banana, an association is made between the wave packet representing the visual image of a banana in V1 and that representing the action of peeling and consuming a banana in M1. This association is made through strengthened "Hebbian" (1949; Skarda & Freeman, 1987; Tognoli & Kelso, 2009; Varela, Lachaux, Rodriguez, & Martinerie, 2001) synaptic connections between the two regions. As a result, the triggering of a *banana* wave packet in V1 will have the effect of triggering what can be referred to as a *peeling-and-consuming-an-object* wave-packet sequence, or action scheme, in M1. This wave-packet sequence triggered in M1 then acts to express a hierarchically sequenced motor behavior in the musculature, resulting in the animal proceeding to peel and consume the banana (Noack, 2006c, 2007b).

2.2.2. Intermediate-level interactions

In looking at the simple-level interaction discussed above, we can see that the two main divisions of the cerebral cortex, sensory and motor, indeed, represent information in two distinct fashions (Fuster, 2001, 2009). In the sensory systems, wave-packet dynamics represent temporally extended sensory scenarios, with the wave packets representing individual, serially related frames of the scene much like the frames of a film reel (Freeman, 2006, 2007c; Tsuda, 2001). In the motor systems, on the other hand, wave-packet dynamics represent the hierarchical sequencing of individual movements in the musculature (Badre & D'Esposito, 2009; Fuster, 2001, 2002, 2007; Greenfield, 1991; Swanson, 2003). Thus, more than representing the faithful reproduction of a natural scene, as in the sensory systems, wave-packet dynamics in cortical-motor regions represent more a sequenced *strategy* for effectively negotiating a motor behavior (Greenfield, 1991; Reilly, 2002). For example, if asked to perform the same cup-stacking task, two different human children might employ different hierarchical strategies in order to stack the cups. One child might use the "sub-assembly" strategy whereby individual cups are first assembled into small groups and then combined into a larger whole. The other child, however, might use the "pot" strategy whereby one cup is simply added to another in succession in order to create the larger whole (Fragaszy, Galloway, Johnson-Pynn, Hirsh, & Brakke, 2002; Greenfield, 1991; Reilly, 2002). Thus, while the sensory wave-packet dynamics in the brain can be considered to be similar between the two children upon the presentation of the cups, the motor wave-packet dynamics may be very different

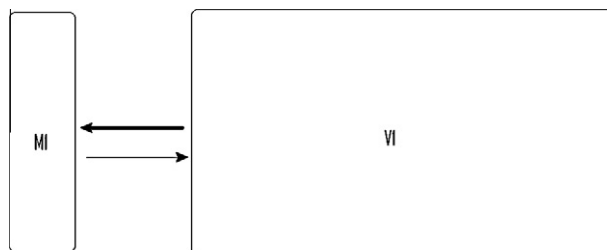


Fig. 1. Simple-level cortical interactions. Above is a schematic illustration of a hypothetical cortex with one visual region and one motor region. The bold, arrowed line running from V1 to M1 denotes that this is the preferred direction of information flow in this model cortex (see footnote 1). In this and subsequent figures, the relative thickness or boldness of the arrowed lines between cortical regions and networks of regions will denote the proposed relative strength or bias of influence that region or network has over the indicated target region(s).

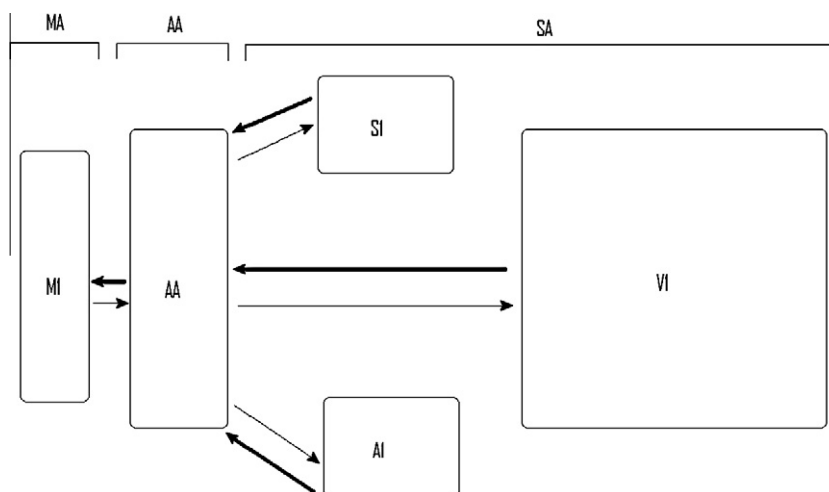


Fig. 2. Intermediate-level cortical interactions. Note that none of the primary sensory regions interact with one another but that each feeds robustly into AA, which, in turn, strongly drives the motor region (MA).

depending on which strategy each child implements. This fundamental difference in the manner in which information is represented in the sensory and motor areas will become of critical significance later on when discussing the frontal feedback system.

For now, though, it is important to discuss how these two fundamentally different manners of representing information interact within the cortex to produce intentional behavior in the animal. In order to most effectively describe how the cortex accomplishes this task, it will be helpful to add some additional cortical areas to our simple-level model discussed in the previous section. The added cortical regions are a primary somatosensory area (S1), a primary auditory area (A1), and an association area (AA). As we can see from Fig. 2, none of the primary cortical regions are connected with one another. However, each primary area feeds directly into AA, which, in turn, is reciprocally connected with M1. What this means is that, while the wave packets produced in the primary sensory areas faithfully represent the current environmental scene, the wave packets that are formed in AA represent a more ambiguous gestalt reflective of the relative contributions of each sensory modality.

The importance of this AA gestalt is that it can more effectively *instruct*, or trigger, a biologically successful behavior, or action scheme, in M1 than can be triggered from a wave packet coming from a single-sense modality such as V1 (Kozma, Harter, & Achunala, 2007). For example, while a banana may appear to be ripe and thus edible from its visual appearance, the simultaneous tactile sensation of firmness and the crisp sound of the banana being peeled help an animal to make the decision to actually consume the fruit. This sensory gestalt, or consensus on the significance of the current sensory scene, is housed largely within the AA regions of the cortex (Ashby & Spiering, 2004; Freedman & Miller, 2008; Freedman, Riesenhuber, Poggio, & Miller, 2002; Sigala & Logothetis, 2002). In these AA regions, sensory wave-packet dynamics merge with motor wave-packet dynamics to implement and guide a successful sensorimotor behavior.

One useful way to model the cortical interactions described above is through identifying two main functional processes that interact within the AA regions of the cortex. The first process is that of coming to a consensus on the biologically significant aspects of the sensory environment. This consensus is housed in the wave-packet dynamics in AA, which represent the combined input from the sensory streams. Again, the wave packets produced in AA represent the polymodal gestalt of the current sensory scene and form what I have referred to as *category attractors* (Noack, 2006c, 2007b). A category attractor is a wave packet that is associated with, and thus serves to instruct or trigger, an associated motor wave-packet sequence, or action scheme, in motor cortex. As its central role, the category attractor serves to categorize and associate a wide variety of individual, but related, sensory impressions with a single action scheme (Noack, 2006c, 2007b). For example, the general category attractor *objects to consume* can serve to represent many thousands of individual sensory wave packets produced in SA related to edible objects. The functional utility of the category attractor is its role in associating this wide variety of complex sensory impressions with a single effective behavior to negotiate them. In the example above, the category attractor *objects to consume* and all of the items it represents is coupled to and associated with the single action scheme *consuming an object*. In our example with the banana, the category attractor formed in AA while the animal is exploring the banana is a bit more specific and can be labeled *objects to peel and consume*. This category attractor includes only those edible objects that must be peeled before consuming. The triggering of this *objects-to-peel-and-consume* category attractor then instructs the *peeling-and-consuming-an-object* action scheme. From the above two examples, it is not difficult to see how the hierarchical organization of category attractors and the action schemes that they are coupled to can serve to quickly classify a large variety of sensory data as well as to provide associated behaviors that can be readily expressed in the presence of those stimuli (Freedman & Assad, 2006; Noack, 2006c).

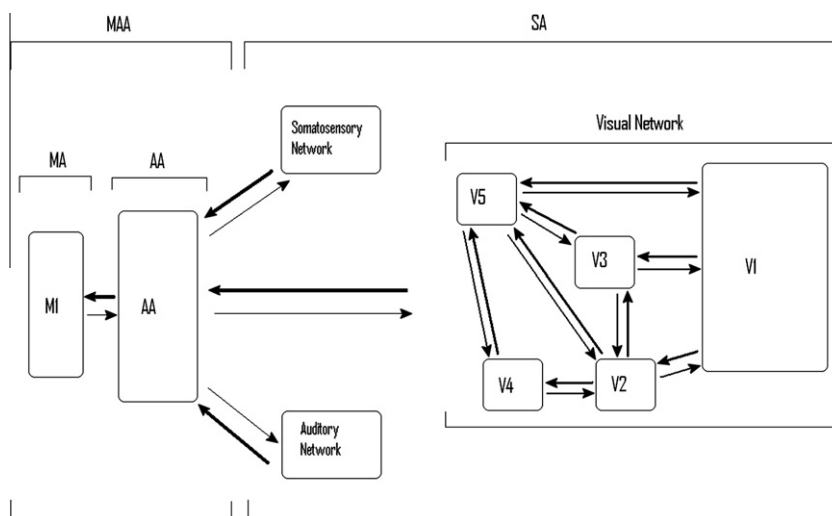


Fig. 3. Complex-level cortical interactions. Note that the preferred directions of information flow are more balanced between cortical regions *within* the visual network (and also presumably within auditory and somatosensory networks) than between the SA and MAA networks as a whole. Visual network topology adapted from Damasio (1994).

To summarize, a useful way to view cortical dynamics in this discussion of the frontal feedback model is through a process whereby the continual formation of category-attractor gestalts in AA instruct associated action schemes in related motor cortex (Freedman & Assad, 2006; Lamme, Supèr, & Spekreijse, 1998; Noack, 2006c, 2007b; Piaget, 1952). As a given animal goes about its business during the day, it is presented with a continuous myriad of complex sensory impressions from the various sense modalities (Seeley et al., 2007). The animal's neocortex acts to manage this onslaught of diverse environmental energies by channeling them into specific category attractors and related behaviors in the association areas (Freedman & Miller, 2008; Lamme et al., 1998; Noack, 2006c, 2007b). Importantly, this channeling process yields an information-representation *gradient* in the cortex where more specific features of sensory stimuli are represented in the caudal regions and more general polymodal gestalts are represented in the rostral regions (Cowell, Bussey, & Saksida, 2010; Ishai, Ungerleider, Martin, Schouten, & Haxby, 1999; Reid, Krumnack, Wanke, & Kötter, 2009; Vinckier et al., 2007). Understanding how this gradient is organized in the non-human mammalian brain is critical in understanding how frontal feedback generates the human mind in the human brain. Accordingly, the next section will discuss this gradient in more detail in order to set the stage for the discussion of the human frontal feedback system.

2.2.3. Complex-level interactions

One of the principal pillars that modern cognitive neuroscience has been built on is the idea that sensory signals are processed in the brain via a hierarchical “neocortical March” of information through the cortex. As the model goes, raw sensory signals from the environment are “processed” first in primary sensory cortex, which reveals the finest details of a stimulus's identity or character. Next, secondary and tertiary regions “extract” more general or specialized information about the stimulus or sensory scene.² Finally, even more general polymodal information is extracted from the unimodal sensory modalities/networks in the polymodal association areas.

This hierarchical model is essentially accurate and has been verified by countless observations that receptive field properties of sensory input become wider as one moves out from the primary receiving cortex (e.g., Felleman & Van Essen, 1991). However, I believe that the popular idea that information is being extracted for some modular function or purpose is misplaced. Instead, I see the functional utility of the proliferation of secondary sensory and association regions in later developing mammals as serving primarily to bias the general influence of some cortical RSNs over others. As we will see in the next section, larger cortical regions or networks of regions tend to have more control over global cortical dynamics than do smaller regions/networks. A given mammalian species likely proliferates a large number of secondary sensory regions within a given sense modality simply because that modality has special significance in its ecological niche. For example, mice have a relatively large somatosensory cortex in order to process important information coming from their whiskers, bats have a relatively large auditory cortex in order to process echolocation signals, and monkeys have a relatively large visual cortex to aid life in an arboreal habitat (Krubitzer & Kahn, 2003; O'Leary and Sahara, 2008; Van Essen, 2004).

The reason each progressively distal secondary region possesses wider and wider receptive fields most likely has to do with the fact that each receives input from a progressively greater number of regions further removed from the primary source (Fig. 3) (Rosa, 2002; Rosa & Tweedale, 2005). Thus, each progressively removed secondary region—which, by the

² In order to simplify the discussion, the phrase “secondary sensory region” will be used to denote any region of a given sensory network outside of the primary region. Thus, in vision, V2, V3, V4, V5, and so on, will all be referred to as “secondary” regions.

way, is also progressively more phylogenetically recent (Fuster, 2002; Gogtay et al., 2004; Rosa & Tweedale, 2005)—is, in effect, a mini-AA of the collective of regions that came before it. The end result is that a gradient of information specificity becomes established as the brain develops, with information being more specifically represented in the caudal regions and more generally represented in the rostral regions.

The information gradient described above is manifested in cortical dynamics as the progressive coarseness of topographic maps representing the sense environment as one moves rostrally through the hierarchy. Each cytoarchitecturally defined secondary, tertiary, and association region in effect possesses its own complete topographic map of the environment, which becomes coarser or more distorted the further it is removed from the primary area (Rosa, 2002; Rosa & Tweedale, 2005). Likewise, each of these regions possesses its own unique wave packet that has its own unique properties (Bressler, 2004; Freeman, Gaál, & Jornten, 2003). While these unique properties are often attributed to a specific processing role for that region (e.g., color processing), the apparent specialization of that region for that role is likely an artifact of a more general effort by the brain simply to increase the size of the modality/network in general (see Tanigawa, Lu, & Roe, 2010).

One other important feature of cortical dynamics must also be discussed. This feature is the tendency, as described in Section 2, of cortical interactions to occur at several levels simultaneously. Thus, while separate wave packets form in each separate primary and secondary sensory region upon the presentation of a sensory stimulus, a more global wave-packet/category-attractor forms over the entire collection of individual regions (Bressler, 2004; Freeman & Burke, 2003). This global wave packet/category attractor represents the collective behavior of the entire individual sensory network/RSN. Each of these macroscopic global attractors then combines to form an even more global hyper-macroscopic wave packet/category attractor representing the collective activity of the entire SA (Freeman & Burke, 2003).

2.3. The dynamics of information flow in the cortex

As a general rule in cortical dynamics, it can be said that, all other variables being equal (e.g., connection density, myelination, neurochemistry, receptor density, etc.), larger cortical regions and networks of regions tend to control the dynamics of, or wave packet formation in, smaller regions rather than the reverse (Noack, 1995a, 2007b). There are two reasons for this rule, one relating to the dynamics that occur between individual cortical regions and the other relating to the dynamics that occur between networks of regions.

In relation to individual regions, the rule follows from the intrinsic architecture of those regions. That is, a larger cortical region tends to possess more neurons/columns and more interconnections between those neurons/columns, or *neuropil* (Kozma et al., 2005), than a smaller region possesses (Hilgetag, 2006; Kaas, 2008). Considering that dendritic currents summate in neuropil tissue (Bressler & Kelso, 2001), a physically larger cortical region produces a more robust wave packet in that region that (1) tends to produce a greater action-potential pulse-density distribution targeted at the smaller region and (2) tends to render the larger region less sensitive to the weaker wave packet targeted on it from the smaller region (Freeman & Barrie, 1994).

In relation to networks of individual regions, the rule follows from the way individual regions are connected inter-areally. That is, the inter-areal projections from any one cytoarchitecturally defined cortical region (e.g., V1, V2, V5, S2, M1, etc.) to another tends to account for less than 5% of the excitatory synapses in the recipient region regardless of the disparity in the physical sizes of those regions (Bressler, 2004; Young, 2000). However, the combination of influences from several independent, but functionally related, cortical regions (a network) upon a given recipient region or network of regions can account for up to 40% of the excitatory synapses in each of the regions of the recipient network as a whole (Bressler, 2004; Young, 2000). This powerful combinatorial influence of a large network of functionally related regions, such as the visual system/RSN in primates, provides insight as to how that large network is the principal driver of primate cortical dynamics (Bressler & Menon, 2010).

Considering that larger networks of cortical regions tend to control smaller networks, simply looking at the comparative anatomy of mammalian brains can yield telling insights as to what the preferred paths of information flow may be in each species' brain. The important point to make for the present discussion is that, as described earlier, the neocortex developed initially as a primarily sensory-related structure. As such, it had a 100-million-year head start in developing those cortical sensory systems before the appearance of even a small strip of dedicated motor cortex, or M1, appeared (Kaas, 2005, 2008). Once M1 did appear, its development and dynamics were subsequently dominated and controlled by the sensory systems. This trend in cortical development continues up to the present day where we see that the ratio of the size of SA-related cortical regions to MA-related regions is, in almost every extant mammalian species, in excess of 5:1 (Changeux, 2004; Fuster, 2002; Goldberg, 2001). This huge discrepancy in the amount of cortical territory devoted to SA regions versus MA regions suggests that, at least from a hemisphere-wide global perspective, information in the form of macroscopic wave packets flows almost exclusively in a caudo-rostral direction. That discrepancy implies that the wave-packet dynamics that exist in the MA are continuously controlled and directed by the SA.

2.4. The perception–action cycle

At this point in the discussion, we can use the concepts presented above to model the ongoing, intentional behavior in any given mammal. This process can be divided roughly into four main stages, which produce a closed-loop cycle. In the first stage, sensory information arrives at primary sensory cortices and, from there, rapidly spreads, or “sweeps” (Gaillard

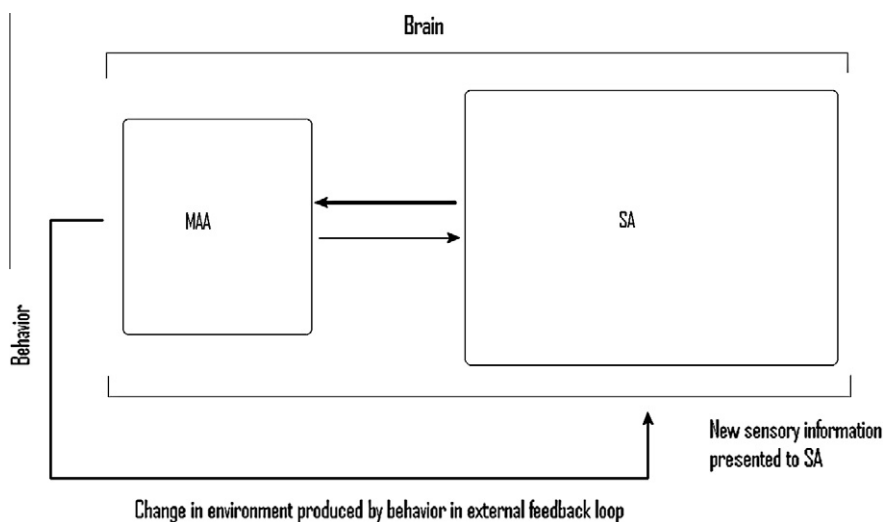


Fig. 4. The perception–action cycle. Note the strong feedforward “looping” effect of information flow through the brain, into the external environment, and back into the brain.

et al., 2009; Lamme, 2006), throughout the unimodal networks. In the second stage, these unimodal, macroscopic wave packets then combine to produce a more global, hyper-macroscopic wave packet/category attractor representing the collective activity of the entire SA. In the third stage, the global category attractor that reflects the SA wave packet merges with its associated action-scheme wave packet in the AA–MA regions of the frontal cortex. In the fourth and final stage, the overt motor behavior triggered by the action-scheme wave packet changes the animal's proximate sensory environment, which, in turn, presents new sensory stimuli to the animal. This new sensory stimulation then starts the next cycle in the loop, and so on, through to the completion of the selected action scheme (Fig. 4).

The closed-loop cycle described above has been referred to as the *perception–action cycle* by Fuster (2004), who states:

The perception–action cycle is the circular flow of information from the environment to sensory structures, to motor structures, back again to the environment, to sensory structures, and so on, during the processing of goal-directed behavior. (p. 143)

This concept of intentional behavior in non-human mammals existing as a closed-loop cycle is echoed in models developed by Freeman (2007a; Freeman & Holmes, 2005; Kozma, Aghazarian et al., 2007) and Swanson (2007). However, Fuster's (1989, 2004, 2009) emphasis on the sensory-perceptual systems driving this cycle is most specifically in line with the current discussion. Therefore, the term PAC will be adopted here when referring to this non-human mode of global cortical function.

2.5. Putting it all together: The perception–action cycle and Ledberg et al.'s large-scale visuomotor integration study

At this point in the discussion, it is relevant to ask whether or not there have been any targeted empirical studies that the PAC formulation offered here can be tested against. Although there have been many studies demonstrating the scaled formation of the wave-packet dynamics discussed above (Freeman, 2005; Kozma et al., 2005; Panagiotides et al., 2011), until recently, there have been no studies related directly to the more global question of how visuomotor integration is timed and organized. Fortunately, Ledberg, Bressler, Ding, Coppola, and Nakamura (2007) have conducted such a study and that study appears to support the idea of a PAC-type organization in the non-human cortex.

In their study, Ledberg et al. (2007) fitted three macaque monkeys with electrodes distributed about the cortex. These monkeys were trained to associate a particular behavior (lever release) with a particular stimulus (a certain light pattern). During the experimental trials, the activation latencies of the electrodes were recorded as the monkey made the stimulus discrimination and executed the appropriate, or rewarded, behavior. An analysis of these latencies revealed *which* cortical areas were activated *when* during the trials. The results of the study, as interpreted here, suggest that visuomotor integration in the cortex can be divided into four stages, which closely relate to those discussed in the previous section. In the first stage, a visual stimulus arrives initially at V1 and from there sweeps rapidly through the visual network/RSN. Ledberg et al. refer to this process as *stimulus-evoked activation onset*. In the second stage, widespread regions of the SA become activated in what Ledberg et al. refer to as *stimulus-specific processing*. In the third stage, hyper-macroscopic dynamics appear to make a decision in the MA–AA as to the correct behavior to execute in response to the stimulus in what Ledberg et al. refer to as *response-specific processing*. Finally, in the fourth and last stage, new stimulus-related activity appears in the visual network, which suggests that a new stimulus (or at least an updated interpretation of the old stimulus) is being processed there in preparation for the next round in the cycle.

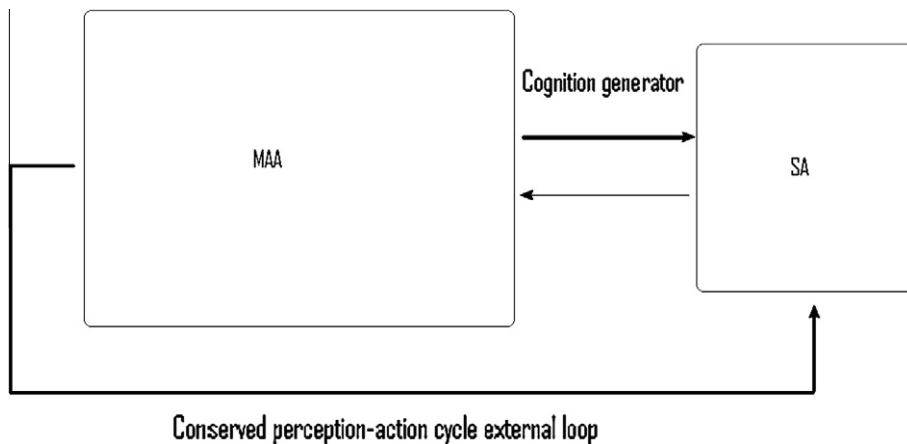


Fig. 5. The frontal feedback system. Note the reversal of the preferred direction of information flow from the MAA to the SA at the highest level of cortical operation while conserving the primal PAC looping effect at lower levels of cortical operation (see Section 3.1 for more explanation).

One important feature of the experiment that also appeared in the third stage was what Ledberg et al. (2007) refer to as *category-specific processing* in the prefrontal cortex. In conjunction with late response-specific processing, there were units in the prefrontal cortex that responded specifically to the categorical nature of the presented stimuli. Considering that this action overlapped with the appearance of the next round of information processing in sensory cortices, it is possible that this prefrontal activity identifies the establishment of a “category attractor-action scheme complex,” which manifests as an order parameter (see Freeman, 2007a, 2007b, 2009; Freeman & Vitiello, 2009; Haken, 2006; Tognoli & Kelso, 2009) guiding the monkey’s lever-release behavior through to completion. The order parameter is defined here as the temporary constraint over global cortical dynamics during a goal-directed behavior that the establishment of a specific category attractor-action scheme complex induces.

Referring back to Section 2.1, one important insight derived from the above study is that it appears as if response-specific processing, category-specific processing, and frontal (MA) motor activity occur in conjunction with one another relative to the stimulus-specific (SA-related) processing component of the PAC. Such a result may be expected in relation to the present formulation of the PAC in that it is argued here that the AA regions are really a motor-derived component of the cortex. The AA’s primary function is to fix a specific category attractor-action scheme complex to the current, combined output of the SA. Thus, the AA really lies at the top of the motor-processing hierarchy and serves as the central hub of brain dynamics governing sensorimotor conversions (Fuster, 1989; Modha & Singh, 2010; Noack, 2006c). For this reason, the AA and the MA will be combined and referred to collectively as the MAA from here on (see Fig. 3). Since the MAA becomes increasingly large in anthropoid primates and especially humans (Fuster, 2002; Toro et al., 2008; Vallender, Mekel-Bobrov, & Lahn, 2008), the following discussion will divide the MAA into two separate, but related, divisions. One division, the anterior aspect of the MAA, will refer more to the prefrontal region and the action scheme component of the category attractor-action scheme complex described above. The other division, the posterior aspect of the MAA, will refer more to posterior parieto-temporal association cortex and the category-attractor component of the complex. Parcellating the MAA in this way will become especially helpful when it comes time to model the actions of the extremely large MAA in humans.

3. Evolution of the hominin brain and the appearance of the human frontal feedback system

The PAC form of the global-dynamic regulation of brain activity in the non-human mammalian brain was and is so biologically successful that it continues to be the primary functional mechanism utilized in essentially every mammalian species alive today—that is, every species but one, *Homo sapiens*. In *Homo sapiens*, or present-day humans, the trend in the expansion of frontal motor-association cortices (MAA) relative to posterior sensory cortices (SA), which began with early anthropoid primates, reached a threshold whereby the preferred caudo-rostral driving of activity that defines the PAC was reversed to a preferred rostro-caudal driving of activity (Noack, 1995a, 1995b, 2004, 2006a, 2006b, 2007a). Reversing the preferred direction of driving influence in the human brain succeeded in creating a relatively autonomous functional system within that brain, biased largely to the dominant (usually left) hemisphere, and referred to here as the frontal feedback system (Fig. 5). The frontal feedback system works to achieve its biologically advantageous effects by reversing the dynamics of the PAC and, hence, reversing the preferred direction of information flow through the cortical representation gradient outlined above. Specifically, the frontal feedback system utilizes the human’s stored action schemes in prefrontal motor cortices to literally reach into posterior sensory cortices and internally reconstruct or recreate sensory scenarios/memories there. It is simply this ability of the human frontal cortices to drive the posterior cortices that accounts for the entirety of mental attributes that many consider to be uniquely human, such as symbolic thought, language, creativity, self-awareness, and even consciousness.

3.1. Evolution of the hominin brain

Thus far in the discussion, data has suggested that information processing in the brains of virtually all non-human mammals was largely constrained within a PAC-type framework. In order to ensure the effective operation of the PAC, selection pressures on brain evolution had to ensure that, in general, the development of the sensory processing structures outstripped that of the motor structures (see Section 2.3). In looking at the comparative anatomy of mammalian brains, it is, indeed, the case that the sensory systems dominate the territory of the neocortex in essentially all orders (Kaas, 2005, 2008), that is, all orders but one, primates (Bush & Allman, 2004). While in the majority of primate species the sensory systems continue to greatly outstrip that of the motor systems, the primates are distinct from all other mammals in that they possess a trend in cortical development that favors the elaboration of the motor systems relative to the sensory systems (Bush & Allman, 2004; Fuster, 1989). For example, the percentage ratio of prefrontal motor cortex to total cortex is 3.5% and 7% in the common cat and dog, respectively (Changeux, 2004; Fuster, 1989; Goldberg, 2001), the rest of the cortex being primarily sensory related. The vast majority of mammals in general tend to have similar ratios of prefrontal cortex or even less. In the primates, however, we see that this ratio begins to increase throughout their phylogeny. In the lemur, a primitive prosimian primate, the ratio of prefrontal cortex to total cortex is still only 8.5%. In the macaque monkey, however, this ratio rises to 11.5%, and in the chimpanzee, it rises to 17% (Changeux, 2004; Fuster, 2002; Goldberg, 2001).

There can be little doubt that the trend toward the biased development of the motor systems in primates was due to the selection pressures placed on these species in living in an arboreal habitat. In fact, such a habitat had a dual effect upon the evolution of primates that was to be a key factor in the organization of the frontal feedback system. That dual effect was the co-development of visual and motor systems in order to (1) visually distinguish biologically significant stimuli from the rich detail of leaves and branches in forests and jungles and (2) negotiate those trees and jungles with highly specialized prehensile limbs (Kaas, 2008; Padberg et al., 2007). In lower prosimian (new world monkeys) and catarrhine (old world monkeys) primates, the bias in cortical development was caudal since the development of the visual systems led the development of the motor systems. As we get to pongid (great ape) species, however, this bias begins to shift rostrally toward the development of the motor systems and, by the time we get to hominins, it shifts *decidedly* rostrally toward the motor systems (Noack, 2007b).

The end result is that, in humans, we see a ratio of prefrontal cortex to total cortex that is upwards of 30%, almost a full third of the total amount of neocortex (Changeux, 2004; Fuster, 2002; Goldberg, 2001). The next logical question to ask is why this biased prefrontal development in hominins continued to occur even after those hominins went bipedal and came down from the trees roughly 4.5 million years ago (White et al., 2009). The answer is most likely that the combination of having a highly specialized hand along with the freeing of that hand through bipedality led to other uses for it on the savanna such as tool use and development. Accordingly, we see that the hand continued to develop in hominins, as is witnessed in the appearance of a fully opposable thumb, along with prefrontal motor regions to control the fine motor coordination of that hand (Calvin, 2004; Pinker, 1997).

It is argued here that, with the appearance of *Homo erectus* (~2 million years ago), the expansion of the prefrontal cortex relative to posterior cortices surpassed a *threshold* whereby that frontal cortex took principal control over cortical dynamics. There are two lines of evidence supporting this argument. The first is that *Homo erectus* was the first species of mammal ever known to *not* flee from fire when it encountered it, suggesting that the tyranny of the PAC had been broken in this species (Noack, 2006c). The second is that it was just about the time of the appearance of *Homo erectus* that the brain in general and frontal cortex in particular began to undergo an unprecedented burst in development (Gilbert, Dobyns, & Lahn, 2005; Kaas, 2008; Krienen & Buckner, 2009; Leonard, Snodgrass, & Robertson, 2007; McHenry, 1994). This sudden burst in the development of the brain/frontal cortex suggests that selective pressures placed on hominins at this time began to bias toward the development of brain systems supporting the frontal feedback system over those supporting the PAC (see Gilbert et al., 2005; Toro, Perron et al., 2008).

In relating the above argument to current neuroimaging models, it appears as if the main brain system/RSN supporting the mammalian PAC is a network known as the default-mode network (DMN). Several recent studies suggest that, as the rostral aspect of the DMN grew disproportionately in size throughout hominin phylogeny, a point occurred whereby a bifurcation in brain dynamics split the DMN into two separate, but functionally coupled, networks (e.g., Draganski et al., 2008; Krienen & Buckner, 2009; Middleton & Strick, 2000a, 2000b). One network, retaining the title of DMN, was the phylogenetically older portion of the coupled network and continued to support caudo-rostral sensorimotor conversions in a PAC-type fashion. The other network, referred to as the central executive network (CEN) (Sridharan, Levitin, & Menon, 2008) was phylogenetically more recent and supported the new role of frontal feedback, which gave rise to distinct human cognitive functions (see Fig. 5). Thus, it can be said that the principal brain network associated with the frontal feedback system is the CEN, especially since a true CEN appears to be found only in humans (Rilling et al., 2007).

While a good first approximation, the above interpretation may be a bit oversimplified in that other brain networks may have been recruited into the frontal feedback system along with the CEN once the bifurcation occurred, including the DMN or at least a portion of the DMN. The only way to tease out which specific regions of the human brain are feeding forward or feeding back at any given time is to conduct more targeted studies. While some existing studies related to this issue are reviewed in Section 3.2.2, a comprehensive analysis of the topic is outside the scope of this paper. Therefore, for our purposes here, it is best to view the frontal feedback system as a network or collection of networks residing generally in the more phylogenetically recent cortical regions of the human brain biased largely in the dominant hemisphere.

3.2. Evidence of the enlargement of the hominin frontal cortex reversing the preferred direction of information flow in the human cortex

In order to demonstrate that a fundamental reversal of information flow did, indeed, occur in the human neocortex, it is, of course, necessary to compare and contrast brain data from human and non-human primate species. Comparative anatomical, physiological, and behavioral evidence has been reviewed in support of the thesis in some detail in earlier papers (Noack, 1995a, 2006c, 2007b). Here, we will expand on those earlier studies by incorporating more recent data.

To begin, it will be useful to make some important qualifications in order to help digest the data. The first qualification is that, when talking about preferred directions of information flow in human and non-human cortices, it is the *adult* individuals of these species that is being referred to. The second qualification is that it is best to look at the human frontal feedback system as a system that *grew out* of the PAC and complemented its function rather than replaced it in its entirety. Thus, although it is important to keep in mind that the frontal feedback system eventually gained controlling dominance over the PAC in governing cortical dynamics, the actual waking experience of the human is governed by the *interplay* between these two systems, as a form of the PAC continues to be conserved in humans (Noack, 2007b; see also Fig. 5 and Section 3.1). Finally, there is evidence that some great-ape species, chimpanzees in particular, may, indeed, possess a rudimentary frontal feedback system (Parker & Jaffe, 2008; Parker & McKinney, 1999; Rilling et al., 2007). That possibility is not ruled out under the general framework of the model. However, if a frontal feedback system does exist in some non-human species, the *strength* of that feedback is extremely weak and comparable to that of a human child under 2 years of age (Noack, 2007b; Parker & McKinney, 1999). Thus, the strength of frontal-feedback driving in these species did not cross the important threshold that positioned the frontal cortex to be the main driver of cortical activity, which marks the test of humanity.

3.2.1. Anatomical evidence

The first line of evidence for a reversal in information flow in the human brain comes from studies in the comparative anatomy of human and non-human brains. As discussed above, cortical development in the line of mammals leading to hominins was decidedly biased to that of the caudal sensory systems. In hominins, however, this bias begins to reverse, as also discussed above. As we will see shortly, this reversal in the relative development between frontal and posterior cortical regions was hugely significant in the subsequent development of the hominin brain. Although researchers have, in the past, proposed that the increasing size of the prefrontal cortex in hominins resulted in its commanding greater executive control (e.g., Llinas, 2001; Pribram, 2006), no one has postulated that this increase caused a fundamental bifurcation in brain dynamics in general. The reason most contemporary brain researchers have missed the significance of this development in modeling global brain function is unclear. However, one reason might be that the significance of frontal cortical development in humans has recently been played down by reports that the size of the human frontal lobe scales proportionately to that of all other primates (Bush & Allman, 2004; Holloway, 2002; Schenker, Desgouttes, & Semendeferi, 2005; Semendeferi, Lu, Schenker, & Damasio, 2002). The implication of these studies is that human frontal-lobe development is *not* a significant factor to consider when trying to model the unique functional properties of the human brain (Schenker et al., 2005; Wood & Grafman, 2003). However, even if it were to be demonstrated that the human frontal lobe *as a whole* is no larger than what would be expected for a primate its size, the critical factor in frontal-lobe development as far as the frontal feedback model is concerned is not its gross size per se. Rather, the critical factor is the development of the prefrontal cortex, or anterior MAA, *relative* to associated regions in posterior sensory cortex. Indeed, here we see compelling evidence for a significant shift in phylogenetic development favoring the anterior MAA over posterior-cortical sensory regions.

While cross-species studies in primates that specifically target the relative phylogenetic development of anterior versus posterior MAA regions are scarce, some do exist. One interesting series of studies comes from the comparison of gyrification patterns in human and non-human primates (Rilling & Insel, 1999; Toro, Perron et al., 2008; Zilles, Armstrong, Moser, Schleicher, & Stephan, 1989; Zilles, Armstrong, Schleicher, & Kretschmann, 1988). Although a seemingly crude technique compared to today's sophisticated neuroimaging techniques, studies in gyrification patterns can be a reliable indicator of which cortical regions have undergone more or less development within the phylogeny of a given mammalian order (Toro, Perron et al., 2008; Wosinski, Schleicher, & Zilles, 1996). What is especially useful about this technique for the present discussion is that it provides, at a glance, the relative cortical-developmental trends of each species along a single axis, the gyrification index (GI), which runs the entire rostro-caudal extent (Fig. 6). In this series of studies spanning two decades, it was found that there was a disproportionate development of human frontal-cortical regions relative to posterior regions, especially the anterior MAA versus the posterior, when compared to each of the other primate suborders (Rilling & Insel, 1999; Toro, Perron et al., 2008; Zilles et al., 1988, 1989). In fact, it is apparent from the graph of these differences that not only does the human GI show a peak around the prefrontal area where there is no peak in any other species, but it also shows a relative *flattening* of the GI over posterior regions when compared to the other species (see Figure 6; Schenker et al., 2005; Zilles et al., 1988). One way to interpret this data, of course, is that a shift occurred in the development of the hominin brain that favored the development of the frontal motor systems over that of the posterior sensory systems.

Corroborating the above gyrification data are more recent comparative studies using an MRI-based technique known as *surface-based atlas*ing (Orban, Van Essen, & Vanduffel, 2004; Van Essen, 2004). What was found in these studies provides additionally compelling anatomical evidence for the control over cortical dynamics shifting to the frontal motor areas in humans. Simply put, what was found was that, while the visual-network cortical regions of the macaque monkey *alone* occupy roughly 50% of the total cortical volume, the MAA region occupies only 25%. In the human, on the other hand, the

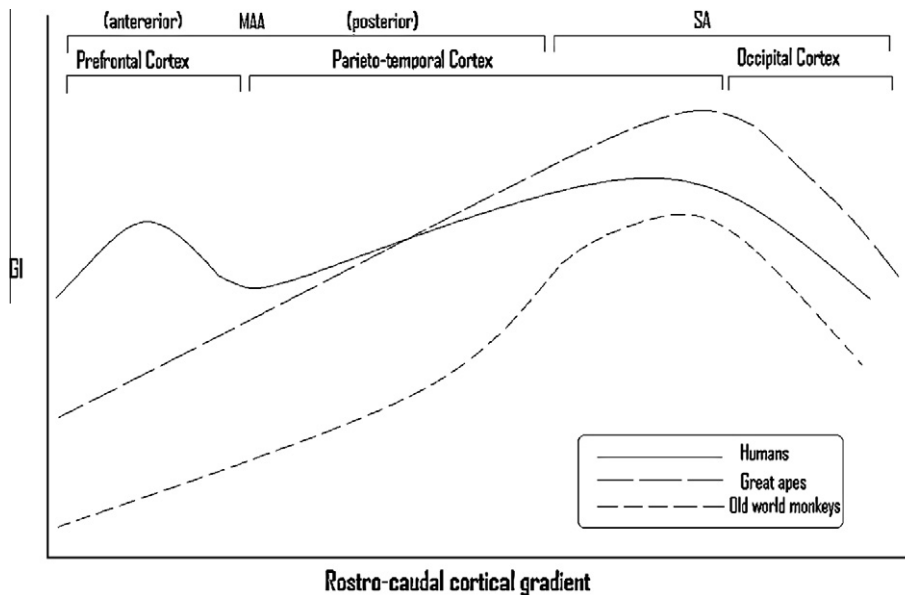


Fig. 6. The gyrification index (GI). Note the conspicuous peak of the human GI over the prefrontal cortex (anterior MAA) and its relative flattening over the SA as compared to the other primate suborders. Graph adapted from Zilles et al. (1988).

situation is exactly the opposite. That is, in the human brain, it was found that, while the visual regions occupy only 25% of the total cortical volume, the MAA occupies 50% of that volume (Orban et al., 2004; Van Essen, 2004). Thus, a 180 degree shift in the parcellation of cortical territory devoted to the MAA versus that devoted to the visual network exists between these two primate species. The key point to make here is that, with the prefrontal cortex (anterior MAA) alone in the human occupying 30% of total cortical volume and the MAA as a whole occupying 50%, it is highly probable that controlling influence over the dynamics of the MAA as a whole is driven by the heavily motor-related prefrontal cortex. Extrapolating the same argument to the neocortex as a whole, it is highly likely that the prefrontal-controlled MAA, composing 50% of the total cortical volume, in turn exerts a significant influence over wave-packet formation in the visual network, which composes only 25% of total cortical volume. In the situation with the macaque, on the other hand, all one needs to do is the same math to reach the conclusion that it is highly unlikely that there is any significant frontal feedback occurring in this species. In conclusion, the anatomical evidence supports the contention that the preferred direction of information flow in the human cortex is rostro-caudal, while in the non-human it is caudo-rostral.

3.2.2. Physiological evidence

Using the framework of the previous section as a model, it is useful to ask what type of activity one might expect to find in the MAA and cortex, in general, in a frontal-feedback architecture versus a PAC architecture. The answer to this question is fairly straightforward. In the non-human PAC, one would expect to see activity reflective of the feedforward processing of sensory-related signals along the entire caudo-rostral extent since the sensory systems are driving the motor systems in these species. In the human frontal feedback system, on the other hand, one would expect to see exactly the opposite: activity reflective of the feedback manipulation of posterior sensory regions by the frontal motor cortices. Indeed, this is exactly what is observed.

Before techniques were developed in recent years to directly study causal influences in the cortex, the only way to determine patterns of information flow in the brain was to *infer* them largely by analyzing single-unit studies. For instance, in the original formulation of the frontal feedback model (see Noack, 1995a), a caudo-rostral bias of information flow in the non-human cortex was inferred from the fact that single-unit recordings all along the monkey's occipito-temporal visual pathway responded in some way to the presentation of a given visual stimulus (Felleman & Van Essen, 1991; Fuster, 1989). In fact, the caudo-rostral feedforward driving effect of visual stimuli in the monkey cortex is so robust that single-unit responses to visual stimuli are found even in prefrontal cortices (Freedman & Miller, 2008; Freedman, Riesenhuber, Poggio, & Miller, 2003; Freedman et al., 2002; Fuster, 1989). Thus, not only can the temporal-cortical stream be considered a visual association area in the non-human (monkey), but so can the prefrontal cortex. Contrary to the case in the monkey, single-unit activation from visual cues is *not* generally robust in human temporal cortices (Ojemann, Creutzfeldt, Lettich, & Haglund, 1988), let alone prefrontal cortices. Instead, single-unit activity in human temporal cortices reflects almost exclusively cognitive and language processes. Ojemann et al. (1988) state:

Thus, the identification of changes in activity related to visual perception in only 1 of 17 populations is . . . suggestive evidence of a lack of visually excitable neurons in human . . . temporal cortex. This is somewhat at variance with findings

in monkeys, where the . . . temporal cortex has been generally considered a visual association area Of the sampled (human) neuronal populations, 76% had significant changes in activity during either language and/or memory. These changes, related to language and memory, were not secondary to changes related to visual perception, speech or arousal, per se Thus, the memory and language changes reported here reflect cognitive processes. (pp. 1397–1398).

The reason Ojemann et al.'s (1988) finding is significant is that, as will be discussed later, cognitive and language processes are hierarchically and sequentially organized, which is exactly how the prefrontal cortex organizes its wave-packet dynamics in order to produce motor behaviors. The sensory systems, on the other hand, do not organize the processing of information in this way, as discussed in Section 2.2.1. This distinction is crucial because it implies that the cognitive and language activity known to dominate both human prefrontal and posterior-temporal association areas is driven in a “top-down” fashion by motor action schemes originating in the prefrontal cortex rather than in a “bottom-up” fashion by sensory information originating in the visual RSN.

Recent neuroimaging data supports the frontal feedback model's interpretation of the Ojemann and Fuster data discussed above. In one particularly relevant MRI study, Denys et al. (2004) presented the same visual stimulus to both monkeys and humans while simultaneously measuring the cortical activation responses in each. What they found was that, while the entire caudo-rostral visuomotor pathway was highly activated in the monkey, only a restricted, far-caudal region of the human visual SA was highly active, a region known as the lateral occipital complex. In fact, the caudo-rostral “throughput” of visual activation in the monkey was so robust that it was largely unattenuated even in the prefrontal cortex. The human, on the other hand, had almost no activation anywhere in the MAA region during the presentation of the visual stimulus. These results suggest that some processes other than sensory related are primarily driving activity in the human MAA. These “other” processes have, through many recent neuroimaging studies, been demonstrated to be cognitive and language related (Friederici, Ruschemeyer, Hahne, & Fiebach, 2003; Humphries, Love, Swinney, & Hickok, 2005; Vandenberghe, Nobre, & Price, 2002), supporting both the Fuster and the Ojemann results and the main thesis of the frontal feedback model.

While the above-discussed single-unit and neuroimaging studies lend largely circumstantial support to the argument for frontal feedback in the human brain, more recent studies in the burgeoning field of *effective connectivity* lend a more direct support (Noack, 2007b). In essence, effective connectivity measures are designed to determine how the activity in one cortical region or RSN affects or drives activity in another region/RSN at rest or during a controlled event. While several techniques have recently been developed to determine effective connectivity measures (Bressler, Richter, Chen, & Ding, 2007; Brovelli et al., 2004; Kounieher, Charron, & Koehlin, 2009; Mechelli, Price, Noppeney, & Friston, 2003; Penny, Stephan, Mechelli, & Friston, 2004; Roebroek, Formisano, & Goebel, 2005), the currently most popular technique uses a measure called *Granger causality* (Bressler & Seth, 2011; Hwang, Velanova, & Luna, 2010). Granger causality determines the effective connectivity between any two given cortical regions by comparing time series data between the two regions during a controlled event. Through a statistical analysis, it can be determined to a high degree of confidence whether a given cortical region/RSN is directly driving another region/RSN or not. Indeed, several recent Granger-causality studies appear to support the existence of a frontal feedback system in the human brain and its absence in the non-human brain.

For example, in the auditory domain, strong top-down Granger driving from frontal MAA regions to the auditory RSN was found during the presentation of ambiguous words to human subjects (Gow et al., 2009). Presumably, this top-down driving resulted from the cognitive effort involved in finding an appropriate match in memory to the ambiguous sound. In a similar study, also in the auditory domain, strong top-down Granger driving was again found to accompany the cognitive effort involved in phonological decoding (Frye, Wu, Liederman, & Fisher, 2010). In the somatosensory domain, strong frontal-to-parietal and then to somatosensory RSN driving was found during a motor-imagery task (Chen, Yang, Liao, Gong, & Shen, 2009). In another somatosensory study, Zhang and Ding (2010) found that strong frontal-cortical to S1 driving correlated with the anticipation and accurate detection of a tactile stimulus. In a study similar to Zhang and Ding, only in the visual domain, Bressler, Tang, Sylvester, Shulman, and Corbetta (2008) found strong top-down Granger driving extending from the dorsal motor cortex through the parietal MAA and into the visual RSN during a visual-attention task. Finally, in another study in the visual domain, Ozaki (2011) found that strong top-down Granger driving correlated with volitional attentional control, a measure of cognitive effort.

What is significant about these Granger-causal studies in relation to the present discussion is that each identifies a strong tendency of the human cortex to direct its activity in a rostro-caudal, top-down direction during *any* form of cognitive demand. This strong, top-down Granger-driving bias is generally *not* found in non-human primate brains such as the macaque brain (see Section 3.3.2 for exceptions). In fact, hemisphere-wide (crossing the central sulcus) Granger-directional driving in the monkey appears to be almost exclusively caudo-rostral no matter what the task (Bressler, 2009; Bressler et al., 2007; Brovelli et al., 2004; Tsujimoto, Mima, Shimazu, & Isomura, 2009, p.24b).

To end this section, it will be instructive to mention one particularly relevant Granger-causal study that ties together many of the concepts of the frontal feedback model discussed thus far. Although not elaborated on in this paper, the frontal feedback model can essentially be deemed a *recapitulation* model (Noack, 1995b, 2006c, 2007b). The recapitulation model hypothesizes that the *evolution* of the non-human primate/mammalian brain is roughly recapitulated in the *development* of the human brain from infancy to adulthood (Parker & Jaffe, 2008; Parker & McKinney, 1999). The prediction that the frontal feedback model makes, then, is that the early form of the brain (both phylogenetic and ontogenetic) utilizes the caudo-rostral PAC in the global regulation of its dynamics which, through phylogenetic/ontogenetic development, reverses its bias to a rostro-caudal frontal feedback regulation. Ontogenetically, this reversal occurs at some point during the second year of

the human infant's life. From there, cognitive development in the child is synonymous with a progressively increasing top-down Granger-driving component in cortical dynamics. In fact, an explicitly stated prediction along these lines was made in a paper I published several years ago (Noack, 2007b). Under the section heading "Experimental Predictions," I wrote,

Using as a guide the [effective-connectivity] framework discussed above. . . as well as the concepts of the frontal feedback model discussed so far, some predictions can begin to be made as to what type of activity might be found in the developing child's brain upon examination. The first prediction is that the strength of the rostral-caudal, or top-down, driving activity seen in [effective-connectivity] studies during cognitive/imaginative processes will be relatively weak in pre-adolescent children. In. . . children 2–6 years of age, this top-down component of activity will be especially weak, gradually increasing in strength only as the child moves through adolescence and then into adulthood. (p. 247)

Indeed, Hwang et al. (2010) have recently conducted a study which appears to support this prediction. In that study, Hwang et al. identified the human's ability to inhibit saccadic movements as a measure of maturing cognitive control. They found that this measure of cognitive control was directly related to the strength of top-down Granger driving running from the frontal MAA toward the posterior SA. The strength of this top-down driving, in turn, was directly related to the development of the prefrontal cortex and, accordingly, was most marked in adults, less so in adolescents, and even less so in children. This study, then, supports the frontal feedback model in that it implies that frontal feedback/cognitive control is directly related to a progressively increasing rostral-caudal information-flow bias in the developing human brain as driven by the progressive development of the prefrontal cortex.

3.2.3. Cognitive and behavioral evidence

The most concise characterization of the nature of cognition comes from our understanding of our own human thought, which is best described as being *symbolic* (Deacon, 1997). Thus, when researchers talk about the birth of the human mind, many often use this event interchangeably with the appearance of symbolic, or "semiotic," thought (Penn et al., 2008; Piaget, 1971b). As a basic definition, symbolic thought refers simply to the human's ability to *represent* one sensory form as a different sensory form as well as to *manipulate* those represented forms in a characteristic manner (Gazzaniga, 2008). The representation can come in the form of a written or spoken word, such as the word *apple*, to represent, or stand for, the wave packet in visual sensory cortex characteristic of a red, circular object with a brown stem. Alternatively, the representation can come from a source other than a word, such as a stylized drawing of an apple, a hand sign that signifies an apple, and so forth. The particular symbol that represents a given stimulus/object is not as important as is the brain's ability to symbolize it, which the human brain can do. As impressive as this symbolic ability is, the human brain's ability to manipulate these symbols is even more impressive insofar as that ability appears to be essentially limitless. Thus, simply through using written words, the human brain can construct literary works that not only serve to symbolize the many subtle, static properties of human experience, such as particular sights, sounds, scents, and emotions, but that also symbolize temporal relations between these sensations. The temporal sequencing of these events can proceed indefinitely, giving rise to short stories, novels, computer programs with millions of lines of code, and historical documents of encyclopedic length.

In terms of the frontal feedback model, the significance of human symbolic thought is that it appears to be primarily a *motor*-driven process. Almost a century of research by child-developmental Piagetian and neo-Piagetian scholars has demonstrated that the organization of essentially all forms of human thought, whether it be storytelling, mathematical analysis, musical composition, art creation, or others, are related in that each is characterized by an internally active construction that is hierarchical and sequential in nature (Greenfield, 1991; Inhelder & Piaget, 1958; Molnar-Szakacs & Overy, 2006; Parker & Jaffe, 2008; Parker & McKinney, 1999; Piaget, 1952, 1971a, 1971b; Piaget & Inhelder, 1969; Sawyer, 2007/1943; Schrock, 2009). More specifically, as a child develops and learns to use its mind to think, what is actually happening is that the child is continuously combining or recombining its earlier sensorimotor experiences in some novel way in order to meet some new challenge. We will discuss this process in more detail later, but for now, the important connection to make is that the only cortical brain region that represents information in a hierarchical and sequential fashion is the frontal motor cortex, which organizes information this way in order to effectively manipulate objects in its natural environment. Therefore, it is not a huge conceptual leap to draw the conclusion that symbolic thought in humans arises from frontal-motor action schemes feeding back on and *reaching into* posterior sensory cortical regions with the effect of manipulating the reconstruction of stored sensory scenarios there.

Contrast the above scenario, where the actions of frontal motor areas are the dominant driver of cortical activity (frontal feedback), with the scenario where the posterior sensory systems are the dominant driver of cortical activity (the PAC). In the former scenario, sensory information is represented as a temporally extended *construction* of recombined sensory scenarios in posterior cortices as governed by the hierarchical and sequential organization of action schemes in frontal cortex. In the latter scenario, on the other hand, sensory information is represented simply as a *series* of temporally related cinematographic frames (i.e., the film reel metaphor discussed in Sections 2.2 and 2.4; see also Freeman, 2006; Noack, 2006c). Thus, and importantly, the serial relationship between the wave packets, or frames, in posterior sensory cortices that are triggered during a recalled event are very different in a brain governed by frontal feedback than in one governed by the PAC. In the PAC brain, each frame will be related to the previous frame only as a movie camera might record it: one frame after the other in a forward, temporal succession, in essence faithfully representing the temporal evolution of the natural scene. In the frontal-feedback brain, on the other hand, sensory scenarios may be created and stored in the PAC-type fashion, but they may also be created and stored as constructions of temporally discontinuous sensory events through internal recombination.

In terms, then, of what salient behavioral differences may manifest from these differences between the human frontal-feedback brain and the non-human PAC brain, the conclusion should be quite obvious: Humans will tend to continually demonstrate behavior that utilizes the novel and creative construction or reconstruction of past sensory events in their attempt to solve certain problems whereas non-humans simply will not. While the non-human PAC brain can learn associations between objects to approach and objects to avoid, and can even learn complicated behavioral repertoires with which to interact with these objects (Noack, 2006c), the important distinction between human and non-human animals is the human's ability to internally construct uniquely novel behaviors without external training. Though "animal-cognition" researchers have tried on many occasions to demonstrate such internal construction in non-human mammals, most notably the efforts of the ape-language project of the 1970s (Preuss, 2006), all of these attempts have ultimately failed to demonstrate any significant ability in these animals to do so (Gazzaniga, 2008; Macphail, 1987; Preuss, 2006; Rivas, 2005; Terrace, Petitto, Sanders, & Bever, 1979). While some researchers have demonstrated the ability of some non-human apes to utilize symbols, no one has provided any convincing demonstration that these apes can recombine those symbols in any grammatically significant, novel fashion (Gazzaniga, 2008; Penn et al., 2008; Povinelli & Bering, 2002). The exact position that great apes place in the frontal feedback model is still under investigation, so some limited internal combinatorial ability in these species would not be completely unexpected. However, that remains to be seen. The more important point is the general claim asserted here that humans alone possess the ability to internally combine symbols in an essentially *unlimited*, temporally extended fashion. It is this unlimited ability in humans for internal construction that signifies a bifurcation in the governance of brain dynamics between human and non-human animals; it signifies prefrontal dominance in humans and posterior cortical dominance in non-humans (Noack, 1995a).

3.3. Reversal of information flow in the neocortex: The creation of the frontal feedback system

At this point in the discussion, we can begin to ask the question: Just how did reversing the functional dynamics of the PAC produce the remarkable panoply of mental capacities humans came to possess? In order to address that question, it is necessary to once again review the functional architecture of the PAC in order to investigate just what sort of dynamic state(s) of operation might result from such a reversal. Before we do that, however, it will be useful to introduce what neurodynamacists refer to as the cortical "attractor landscape." The attractor landscape defines the current state of wave-packet dynamics in the cortex that guides the PAC and ultimately the frontal feedback system.

3.3.1. The attractor landscape

The attractor landscape that exists in the mammalian cortex at any given moment reflects the current sensitization of that cortex to current sensory influences/stimulation. That sensitization is governed mainly by the interaction between subcortical reinforcement centers of the brain (Kouneiher et al., 2009), which signal changes in homeostasis, and cortical neurodynamics. More specifically, the nerve-cell assemblies that bind individual sensory representations/wave packets to their associated category attractors and action schemes in neocortical regions also bind those representations to their associated *affective* components in subcortical limbic regions. These associations between cortical cell-assemblies, which represent specific objects, and limbic cell-assemblies, which reflect the biological significance of those objects, are a two-way street, and the activation of either will trigger the other (Cohen et al., 2012; Damasio, 1994; Noack, 2006c).

For example, the visual stimulus of a banana may serve to engage an animal's PAC in a consummatory behavior through the *banana* wave packet's triggering of a reward-appetitive component of the animal's affective limbic region, or "salience network," as defined by Menon and colleagues (Bressler & Menon, 2010; Seeley et al., 2007; Sridharan et al., 2008). In like fashion, the endogenous activation of the animal's salience network, enacted through the animal's simply being hungry, may, in reverse order, trigger a banana wave packet in the cortex, even though a banana may not be present in the animal's immediate environment. This endogenous triggering of cortical wave packets through homeostatic changes in the internal state of the organism has been referred to as *reafference* by Freeman (1995) and serves as the general mechanism through which attractor landscapes are managed in the mammalian brain (McCrone, 1999; Noack, 2006c).

As an illustration, if an animal is hungry, its salience network sends signals to the neocortex that serve to trigger wave packets and category attractors there related to food items. If the animal is in estrus, the salience network sends signals that serve to trigger wave packets related to conspecifics, and so on. In the former example, it can be said that the animal manifests a *hunger* attractor landscape. In the latter example, the animal manifests a *copulation* attractor landscape.

The functional utility of the attractor landscape is that it guides the interaction of the animal's PAC with its environment in order to maintain homeostasis in the animal. Thus, an animal manifesting a *hunger* attractor landscape will ordinarily find itself interacting with food items, such as bananas, since that interaction is facilitated and, therefore, reinforced in the PAC. Similarly, an animal *not* manifesting a hunger-related attractor landscape may find itself largely ignoring food items since their representation in the PAC is not reinforced. To put it simply, the current, cortical attractor landscape an animal manifests at any given moment reflects the current needs, drives, and motivation of the animal as governed by the current state of its salience network.

3.3.2. Revisiting the perception–action cycle

In Section 2.4, the PAC was broken down into four stages. In the first stage, sensory information from the environment reaches the primary receiving area of the cortex and, from there, triggers a feedforward sweep of activity through the

unimodal sensory networks. In the second stage, the combined activity of each of the unimodal sensory networks merge with activity in the posterior MAA in order to form a category attractor, which reveals the important features of the current polymodal sensory field. In the third stage, activity in the posterior MAA merges with activity in the anterior MAA. Here, the category attractor serves to enact the initiation of an associated action scheme whose purpose is to negotiate the current sensory situation. In the fourth stage, new sensory information reflecting the change in the environment appears in the primary sensory cortices, beginning the next cycle in the loop.

Using the above model of PAC function, it will be helpful to demonstrate how the presence of an attractor landscape in cortical dynamics helps the PAC do its job. Utilizing again the example of a monkey eating a banana, the PAC is first “prepped” through the presence of a *hunger* attractor landscape in the animal’s cortex. The presence of this attractor landscape then engages a generalized exploratory behavior in the animal in the attempt to place it in the presence of food-related items such as bananas, other fruits, seeds, leaves, small reptiles, and so forth. Because the attractor landscape is hunger related, the monkey’s cortex is teeming with wave-packet representations of these food items in SA, their related category attractors in posterior MAA, and their associated action schemes in anterior MAA.

In the SA, food-related wave packets are likely maintained in cortical dynamics through the salience network triggering category attractors in posterior MAA, which then feed back their influence to earlier SA regions. Thus, top-down feedback effects do, indeed, exist in all mammalian cortices, human and non-human, and can be especially robust *within* the SA regions (Bressler et al., 2007; Saalman, Pigarev, & Vidyasagar, 2007). In fact, top-down feedback effects in non-humans can even run the extent of the hemisphere, running from anterior MAA frontal regions back toward the SA (see Buschman & Miller, 2007). Such an effect would occur through the salience network triggering action schemes endogenously through its association with the ventrolateral prefrontal cortex (Sridharan et al., 2008). The important distinction to make between the human and the non-human condition, however, is that top-down feedback effects in the non-human cortex are *transient* and exist largely to maintain some particular attractor landscape active in the cortex in preparation for an expected, rewarding stimulus. In the human, on the other hand, these top-down feedback effects can be sustained.

From a chaotic-dynamics perspective, the presence of these food-related wave packets in the absence of an actual stimulus “flit about” in the cortex in a largely disorganized, high-dimensional fashion. Once an actual food item is encountered in the environment, however, that external sensory stimulus acts to “catch” one of these endogenously generated dynamic representations in the SA, reinforcing it and locking in the PAC. In our example here, the monkey’s coming across a banana in its natural environment acts to (1) catch and lock in a banana wave packet in SA which, in turn, (2) locks in the *objects-to-peel-and-consume* category attractor in posterior MAA which, in turn, (3) locks in the *peeling-and-consuming-an-object* action scheme in anterior MAA.

Once the elements of the PAC are locked in, the transient rostro-caudal, top-down feedback in the animal’s cortex is washed away as the dynamics of the brain now shift toward a caudo-rostral bias, which is characteristic of the PAC (e.g., Bressler et al., 2007; Brovelli et al., 2004; Fuster, 1989; Noack, 2007b). An order parameter is established in the animal’s brain, which is synonymous with the action scheme, in that the entirety of cortical dynamics will now be driven by the action scheme until its completion. To put it another way, the principal job of the action scheme, once triggered, is to create the appropriate change in the external environment that will facilitate the completion of the next step in the sequenced scheme. For example, the first sequenced step in the *peeling-and-consuming-an-object* action scheme is reaching out and grasping the object. It is only when the object is secured in the hand and the sensory systems (SA) have relayed that confirmation to the MAA that the next step of the sequence, peeling, can commence, and so on. There must be confirmation, or parity, between the category attractors in posterior MAA representing the current environmental scene and the appropriate stage in the sequence of the action scheme in anterior MAA in order for the action scheme to proceed (see Bressler, 2009; Tsujimoto et al., 2009). It is the maintenance of this parity that the order parameter serves to achieve, and once the action scheme runs to completion, the brain is freed to seek another one.

3.3.3. Introducing the frontal feedback system

The effectiveness of the PAC is in its ability to exercise dominion over cortical dynamics through the establishment of attractor landscapes, action schemes, and order parameters. For it to be effective, the PAC must run in one direction only, caudo-rostral, in order to continue to match the parity of the current sensory scene and its responses to that scene. As such, it would seem that reversing these dynamics would do little more than calamitously “short circuit” the entire operation. Amazingly, however, reversing the dynamics of the PAC is just exactly what is proposed here to have happened to the human brain. While some may argue that the results were, indeed, calamitous, reversing the PAC succeeded in providing the brain with several interesting and biologically advantageous attributes.

These biologically advantageous attributes exist in the human brain because the human brain alone has the capacity to use the action-scheme sequences housed in the anterior MAA to drive the formation of sensory wave packets in the SA through frontal feedback. In the non-human PAC, it is the action scheme currently present in anterior MAA that serves as the order parameter driving cortical dynamics. However, in the non-human, the action scheme serves only to produce behaviors expressed in the musculature that may create, *externally*, sensory wave packets sent back to the SA that will confirm that a certain stage in a sequence has been met. If that condition is not met, the entire PAC is held up until the animal’s coordinative efforts meet that condition. In the human frontal feedback system, on the other hand, the influence of the action scheme not only can feed into the musculature to enact a behavior, but it can also feed back into the posterior MAA and even SA *internally* to enact change there (see Fig. 5). The consequence of such feedback is that the action scheme does not have to

wait for a concrete change in its external environment to facilitate the next sequence in its cycle. It can *create its own internal change* in a fictitiously created internal environment. It is simply this ability of the human frontal feedback system to create these internal environments and manipulate objects within them that resulted in the birth of the human mind (Noack, 2007b).

As an example, imagine a non-human animal that is hungry and, thus, is manifesting a *hunger* attractor landscape. As described above, the manifestation of this attractor landscape will cause the animal to explore its environment until it comes across an external food item in order to lock in its PAC. If the animal never does come across a food item, it is likely to simply continue to explore until it gets exhausted and dies. It is not likely that the animal internally reflects on its predicament and the gravity of the situation.

Contrast the above example to that of a human manifesting a *hunger* attractor landscape. As in the non-human condition, the food-related attractor landscape triggers food-related wave packets including the *foods-to-consume* category attractor and *consuming-an-object* action scheme. In contrast to the non-human condition, however, the triggering of the action scheme in the human locks the frontal feedback system into a stable order parameter as the action scheme begins to feed-back on and manipulate the food-related wave packets active in the SA. Considering that the manipulation of actual sensory stimuli and the manipulation of these internally generated food-related wave packets are played out on the same SA cortical regions (Halpern & Zatorre, 1999; Halpern, Zatorre, Bouffard, & Johnson, 2004; Kosslyn, 2005; Slotnick, Thompson, & Kosslyn, 2005), the effect of manipulating an internal representation creates reinforcement in the salience network similar to that of manipulating an actual food item (Cohen et al., 2012; Kreiman, Koch, & Fried, 2000; McCrone, 1999). As a result, an order parameter is established in the frontal feedback system that will guide the manipulation of these internally derived food-item representations through the entirety of the action scheme. This situation is manifested in the frontal feedback system, and in the human brain as a whole, as a complete “thought.”

For example, when a human becomes hungry, before manifesting an exploratory behavior, he might first “reflect” on what he might want to eat. In the first stage of this thought process, the person’s *hunger* attractor landscape triggers the *consuming-an-object* action scheme. In the second stage, the influence of the action scheme, through frontal feedback, acts to mentally catch, or “grab onto,” one of the many food-related wave packets skirting around in SA regions. At this point, an order parameter is established in the frontal feedback system whereby the representation of the object that was caught or grabbed onto becomes manipulated internally by the action scheme. If the action scheme grabs onto a banana wave packet, for instance, the person may “imagine” himself peeling and consuming the banana. As in the PAC, parity needs to exist between the sensory and motor wave packets at each stage of the action scheme in order for the thought to run through to completion. In contrast to the PAC, however, the frontal feedback system can grab and manipulate sensory wave packets at will through frontal feedback, whereas the PAC must have actual changes in the environment drive the action-scheme sequence.

In short, then, what makes the human frontal feedback system so powerful is that, in contrast to non-humans, the frontal feedback system does not necessitate the presence of actual stimuli-objects in the external environment in order to manipulate them. It can use the enormous body of stored representations in its SA to serve as its objects of manipulation and creation. As a result, the frontal feedback system can utilize essentially any object it has ever experienced—or even ever *heard* of—in its mental constructions, allowing the person to imagine creating elaborate and sophisticated multi-course meals as well simply peeling a banana. The only requisite for the production of any internal, mental construction is that it creates reinforcement in the brain-salience network. As a result, improbable scenarios such as time travel and the creation of anti-gravity machines can be produced within the frontal feedback system. All that the internally created scenarios need to do is generate reinforcement, not satisfy the laws of physics. In the case of the non-human, on the other hand, only real-world, or “physically correct,” scenarios can be played through the PAC since it is only real-world external sensory scenarios that can maintain an order parameter there.

3.4. Emergence of the central character, or “self,” within the frontal feedback system

In addition to its ability to construct fictitious, creative thoughts, there is one other interesting and important feature built into the functional architecture of the frontal feedback system. This feature is the appearance of a dynamic entity in human brain activity that can be referred to as a “central character,” or more simply a “self,” which the human individual’s thoughts are centered around. In order to see how this self manifests in cortical dynamics, it will once again be helpful to review how the frontal feedback system works. As described in Section 2.2.2, the frontal feedback system works by manipulating the specific from the general. In other words, the frontal feedback system works by using frontal-cortical action schemes in anterior MAA to manipulate the reconstruction of stored, specific memories in the SA’s unimodal sensory networks *through* the manipulation of their more-general category attractors in posterior MAA. While the wave packets formed in each sensory network are unimodal, the category-attractor wave packets formed in posterior MAA are polymodal. Thus, one principal effect of frontal feedback is that it acts to *position* a polymodal sensory gestalt in posterior MAA *against* the unimodal sensory representations in each individual sensory network. The frontal feedback system accomplishes this task through forcing the influence of a particular action scheme back through the caudo-rostral sensory–representational gradient discussed in Section 2.2.2.

It is proposed here that it is this positioning of the general, polymodal sensory gestalt in posterior MAA against the more specific representations in the unimodal networks that gives the human the *general* sense of self (manifested as a polymodal

situational awareness) manipulating and experiencing *specific* sensory events. This curious effect of frontal feedback is not possible in a non-human PAC-type system because information in the PAC is always moving in a caudo-rostral fashion, from the specific to the general. In the human, however, frontal feedback allows a self to emerge from within the infrastructure of the system itself. It is an automatic effect of frontal feedback and is, in a sense, unavoidable. In the process of reconstructing past experiences or constructing novel ones, the presence of a self as agent in the process will essentially always accompany those constructions.

As a consequence of the above proposal, it can be said that the self, or least the focal region of the self, is housed in posterior MAA. Interestingly, traditional studies in neglect syndrome (Becchio & Bertone, 2005; Bisiach & Luzzatti, 1978; Carter, 2002; Venneri & Shanks, 2004) and recent MRI studies (Baars, Ramsoy, & Laureys, 2003; Vogeley & Fink, 2003; Vogeley et al., 2004) also seem to place the focus of the self in this region. According to the frontal feedback model, the self experiences a thought or sensory perception when there is some change in its activity pattern, that is, change in the internal dynamics of the posterior MAA (Noack, 2006a, 2007b). When the self is thinking or imagining (cognition), that change comes from the behavior of frontal action schemes in anterior MAA manipulating specific sensory representations in the unimodal networks through manipulating the posterior MAA. These specific sensory representations in the unimodal sensory networks compose a virtual environment, or virtual world, in the SA regions that is created internally by the frontal feedback system. Thus, the experience of the self thinking essentially amounts to the projection of the self into the virtual world from the top-down direction (Noack, 2007b). The self experiencing a sensory perception, on the other hand, is exactly the opposite. The experience of a sensory perception involves the projection of the virtual world into the self when sensory stimuli from the external environment invade the posterior MAA from the bottom-up direction through the SA. As revealed in Golland et al. (2007; Golland, Golland, Bentin, & Malach, 2008), the waking experience of the human is composed of the continuous oscillation of this top-down (cognitive) and bottom-up (perceptual) activity, depending on which activity is more reinforcing at the time.

In addition to frontal action schemes in the anterior MAA manipulating cognitive processes in the human, they also manipulate the behavior of the human. The manipulation of behavior is ultimately the principal goal of nervous-system function in any animal organism since that organism continually needs to maintain homeostasis through acquiring food, finding mates, avoiding predators, and so forth (Damasio, 1999; Freeman, 1995; Noack, 1995a, 2006c). The frontal feedback system works to achieve such an effect by continuously running through a variety of fictitious, mental scenarios when presented with a given real-world situation. These fictitious scenarios reflect the manipulation of the self, or central character, in a virtual environment encountering a virtual situation. The continuous running through of many of these fictitious scenarios in any given real-world situation will tend to identify one fictitious scenario that generates a larger amount of reward, or reinforcing, activity in subcortical limbic structures than the others. It is this highly rewarding scenario that is then played out through overt motor expression as that scenario recruits the salience network in order to manifest its execution (Noack, 1995a, 2006a).

In accordance with the model put forth above, then, the self can essentially be seen to exist in the human brain as a passive (perhaps even a *reluctant*) witness of the actions of its frontal action schemes on its early posterior sensory networks. An analogy to illustrate the relationship between the human's frontal action schemes and the self in posterior MAA is that of the relationship between a puppeteer and a marionette. In that relationship, the puppeteer manipulates objects in the marionette's immediate environment *through* manipulating the marionette itself. To an audience watching this display, and ostensibly to the marionette itself, the marionette is "agent" in these actions. However, it is the puppeteer that is really running the show. The situation is essentially the same in the human, only the human self enjoys the added feature of the puppeteer (frontal action schemes) manipulating its thought processes as well as its overt behavior.

One interesting dynamic that emerges when positioning a self as agent against its creative constructions is that the frontal feedback system can construct a copy of itself as an individual human form in these sensory network regions leading to the phenomenon of *self-awareness* (Noack, 2007b). In fact, the frontal feedback system can construct several copies of itself in these sensory network spaces and hold dialogs among these copies, yielding the *metaperspective* analysis of various situations (Noack, 2007b). Some of these created copies can be classified as other similarly self-aware individuals not related to the primary self. Thus, a *theory of mind* can also naturally arise from the actions of the frontal feedback system (Noack, 2007b).

It can be gleaned from the above discussion that the property of frontal feedback in the mammalian brain naturally produces an interesting suite of operational features that are argued here to be uniquely human. This suite of operational features essentially amounts to a system whereby frontal action schemes continually position an internal agent, the self, against the continuous generation of creative symbolic constructions in early sensory cortex. In Section 3.1, it was argued that the subsequent development of the brain post *Homo erectus* (~2 million years ago) was driven by the appearance of this frontal feedback bifurcation. In like fashion, it is reasonable to assume that other changes in body form characteristic of post *Homo erectus* humans was also driven by this bifurcation. These changes include, among others, the loss of body hair, the appearance of a fully opposable thumb, and the lowering of the larynx to facilitate language production. According to the frontal feedback model, these somatic changes in humans were born as a direct result of the adaptive advantage of socially expressing the continuous flow of internal schemes generated by the new frontal feedback system. Some examples of such social expression include (1) visual-system constructs such as body art, cave art, and jewelry making, and (2) auditory-system constructs such as musical compositions and phoneme assemblies in the production of language. The importance of these changes in human body form is that they gave rise to the subsequent post-frontal feedback emergence of a shared *cultural intelligence*, the socialization of which has been referred to as the spreading of "memes" throughout the newly forming human communities (Blackmore, 1999). These memes, as defined here, are synonymous with the internally generated action-scheme constructs of the frontal feedback system.

4. Consciousness

Although a proper discussion of human consciousness should enjoy its own treatment as a separate paper, it was promised in the introduction that a solution to this hard problem would be integrated with the proposed solutions to the easy problems that have occupied the majority of the discourse thus far. In Noack (2007b), it was argued that the solution to the hard problem of consciousness, should one arise, would end up being a non-reductionist one. The reason offered was straightforward: by the very nature of the reductionist approach, the solution offered would necessarily have to explain how phenomenal, sentient experience in the brain arises or emerges from non-phenomenal and insentient matter-energy (Smith, 2006; Thomas, 2001). Therefore, by definition, such a reductionist solution cannot cross what is known to philosophers as the *explanatory gap* (Chalmers, 1995; Noack, 2007a, 2007b; Smith, 2006; Thomas, 2001). Of course, that does not stop scholars from publishing a wide variety of attempts to put such a square peg in a round hole anyway, so to speak, almost all of whom model the conscious moment as some sort of unified coherence effect in neural tissue (Globus & O'Carroll, 2010; McFadden, 2007; McKemmish et al., 2009). Each of these coherence models, however, fails to satisfy scientific curiosity because reducing consciousness to a single physical process fails to explain the rich diversity of the sentient phenomena we experience such as colors, emotions, thoughts, sensory perceptions, and so on, not to mention the problem of the explanatory gap (McKemmish et al., 2009; Neafsey, 2009; Segalowitz, 2009; Smith, 2009).

In light of these inherent obstacles in reductionist approaches, the frontal feedback model offers a solution to the hard problem that, once again, simply arises organically out of its operational principles. To review one last time, the frontal feedback system works through the action of frontal action schemes feeding back on and driving fictitious scenario constructions in posterior regions. This operational property is manifested as the central character/self in posterior MAA manipulating objects in sensory regions through the top-down bias in directional driving. From the point of view of adaptive-biological evolution, the assumption in these brain dynamics is that the success of the self in its created virtual world will equate to the success of the actual human organism in the real world. Therefore, what the self needs to do within its virtual world is survive and prosper by exploiting the virtual world and the scenarios it creates within that world. In order to exploit that virtual world, the self as agent needs to experience each of its facets as distinct from one another such as visual objects, auditory sounds, emotions, thoughts, the color red, the sensation of wetness, the sensation of stereoscopy, and so forth. If the central character/self did not experience each of these facets of its virtual world as distinct from one another, it would not be able to manipulate and exploit them to some reinforced end because those facets simply would not exist in its world. Each facet needs to be experienced by the central character/self in order for that facet to exist in the central character's virtual world. Thus, and in conclusion, conscious experience is defined here as *the process by which the central character makes distinctions within its virtual world*. While this proposed solution to the problem of human consciousness may not satisfy the staunch reductionist, some notable scholars of the hard problem have asserted that a non-reductionist solution may be equally as scientifically valid as a reductionist one (Chalmers, 2004). That sentiment is echoed here in that the frontal feedback model, while systems based, at least offers a reason for the existence of consciousness if not a precise way, at this point, to measure it.

5. Conclusion

The main strength of the frontal feedback model lies in the parsimony of its explanation as to what it is that makes humans unique. It is argued in this paper that the problem of human consciousness and cognition, which has puzzled scholars for so long, can be solved simply through modeling a global reversal in the direction of governing neurodynamics in the human brain. Although simple in concept, the conceptual rigor, completeness, and explanatory power of the model is not compromised by the parsimony of its thesis: In comparison to most other currently existing models, the frontal feedback model is remarkably specific as to (1) what it was that happened to the human brain to create the human mind, (2) what it is that the brain does to generate the mind, and (3) what brain areas are involved and how they are involved.

In addition to its parsimony and explanatory power, the frontal feedback model as presented here is also highly testable not only in principle but in practice. Recently developed effective connectivity measures are ideally suited to test the frontal feedback model. As described in Section 3.2.2, many already-existing effective-connectivity studies strongly imply that an information-flow reversal occurred in the human brain, and it is not difficult to conceive how more directed tests might be conducted in the future.

It is precisely this testability of the frontal feedback model that makes it useful in today's uncertain cognitive neuroscience climate. That uncertain climate breeds confusion simply because there currently does not exist *any* formal, testable model, much less a standard model, for how cognition and consciousness are generated in the human brain that can be used to compare species' differences. The result of this confusion is that many animal-cognition researchers simply define for themselves what behavioral cues qualify as "human-like" and then place a given non-human species in that human-like category depending on whether or not that species passes their qualifying "test." Currently, the most popular of these tests is mirror self-recognition and rudimentary symbol manipulation (Pepperberg, 2006; Rajala, Reininger, Lancaster, & Populin, 2010). While seemingly a good place to start an investigation into the differences and similarities between human and animal minds, the problem with this behavioral-test approach lies in the phylogenetic diversity of animals that seem to be passing these tests. For example, membership in the proto-human-mind "club" was initially limited mainly to great apes, particularly the chimpanzee (Gazzaniga, 2008). However, club membership recently has been expanded to include

macaques, elephants, dolphins, and even birds such as parrots and magpies (Pepperberg, 2006; Prior, Schwarz, & Güntürkün, 2008; Rajala et al., 2010).

The bottom line is that, while some or all of the above-mentioned animals may indeed possess some human-like capacities, it is impossible to determine the extent to which this is the case without first defining a systems-level model for how these capacities are generated in the brain in the first place. Furthermore, it is similarly impossible to determine whether the source of these putative human-like capacities in non-humans is the same as that of humans. The source of intelligence and self-awareness in parrots and magpies may arise from a brain mechanism entirely distinct from that of humans. Again, the place to begin this investigation is to first define the source and mechanism of human mental capacities and then proceed from there. The frontal feedback model offers a preliminary attempt to do just that.

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