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Chapter 3

BRAIN ENDOGENOUS FEEDBACK AND DEGREES OF CONSCIOUSNESS*

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ABSTRACT

We present a model able to account for the mechanisms supporting different degrees of consciousness. We support our proposal with recent evidence from brain morphology and physiology, which indicate that the central nervous system contains two parallel networks (neuronal and astroglial) establishing positive and negative feedback loops. The resonance between the distinct networks can occur in the absence of salient external stimulation and, even when such stimulation occurs, the response of the coupled networks is always dependent on the previous state of their interaction domain. We also explain complex processes occurring below the threshold of awareness as those that deploy the brain's computational resources, although without producing resonant states of sufficient magnitude to determine the individual's overt acknowledgment. Our model, exemplified through the "Stadium analogy", affords a plausible account of phenomenal and self-consciousness which, by resting at the outskirts of reportable cognitive activity, traditionally compound the 'hard problem' of consciousness.

1. INTRODUCTION

Most neuroscientific experiments employ external stimuli to induce and consequently measure eventual behavioral responses, to describe associated patterns of brain activity, and to infer from such data the neural routes that follow the processing of the specific stimuli.

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However, in everyday life we continuously process endogenous and exogenous stimuli, which form a processual continuum involving both conscious and unconscious mechanisms. For instance, in the processing of verbal language we are often aware of the meaning we intend to convey, as well as of the sentences we utter in order to express it. However, the sophisticated cognitive operations required to choose our words, and to assemble them in a grammatically correct manner are clearly beyond our accessible reach. We usually become aware of the sentences we construct at the moment of utterance, or by means of our inner speech.

In the pre-Freudian era, philosophers and scientists tended to disagree about the possibility of unconscious thinking. In the cartesian tradition, rationality was associated with having clear and distinct ideas, while bodily sensations and the so-called “gut-feeling impressions” were judged to be the obscure and confused products of our mental machinery. Under the influence of this heritage, contemporary psychology and cognitive science tend to study consciously and unconsciously acquired knowledge, and the respective neural and behavioral correlates, as depending from separate processual operations. However, understanding brain mechanisms of unconscious processing may be closely related to understanding those dedicated to conscious processing, as in fact such distinct mechanisms may be regarded as two sides of a same coin. In such sense, once we understand one of these mechanisms, we are likely in good conditions to understand the other one (Pereira Jr and Ricke, 2009).

In this chapter, we summarize a recently raised hypothesis (Endogenous Feedback Network, Augustenberg, 2010) about how specific brain mechanisms might operate to determine both the broadcast of implicit information (i.e. unconscious mental activity), and the subjective access into the contents of such broadcast (conscious cognitive activity). We demonstrate that our framework can indeed contribute to explain a number of issues left unresolved by other theories, among which those concerning the emergence of phenomenal- and self-consciousness. In order to support our model, we present relevant evidence from experimental psychology, morphology and physiology, the latter two indicating that the brain deploys two parallel networks able to generate positive and negative feedback loops. We propose that degrees of consciousness are affected by the resonance of these two networks, and we explain complex processes occurring below the threshold of awareness as those unable to produce resonant states of sufficient magnitude to determine the individual’s overt acknowledgment. Although the resonance can occur in the absence of salient external stimulation, the response of the coupled networks is always dependent on the previous state of their interaction domain. At the core of our enterprise is the understanding of the extents of cognitive and behavioral flexibility in absence of awareness. In fact, the EFN model affords an explanation of how remarkable processual complexity can unfold below the thresholds of awareness, and how the contents of awareness are dependent on such pre-existing and coherent flow of implicit information.

2. DEGREES OF CONSCIOUSNESS

Consciousness is traditionally considered one of science's outmost frontiers. Besides methodological limitations and conceptual intricacies, one of the features that likely

contributes to make it such a complex topic of research is its multifaceted profile. Consciousness can emerge according to different degrees, which can then be described both in quantitative and qualitative terms. Degrees of consciousness can in fact be accounted for in terms of the activity of specific brain structures, but also on the bases of the level of interaction with the environment manifested by the individual. Such distinction finds one of its most cogent debates within the matter of assessment of patients in coma and persistent vegetative state (see Coleman *et al.* 2009). The occurrence of brain activations following the detection and processing of a stimulus may in fact be in some cases identified in patients suffering from disorders of consciousness¹ by means of brain imaging methods. However, the matter concerning the extents of correlation between the neural activity determined by the presentation of stimuli (*external* consciousness), and the patients' faculty to subjectively acknowledge and appraise such stimuli (*internal* consciousness) is far from being settled.

The very definition of consciousness is therefore both a compelling neuropsychological issue, and an abiding philosophical topic. Libet (1987) noted that:

"consciousness as a neuroscientific concept has been loosely employed to encompass several different meanings or aspects of cerebral function in humans and nonhuman animals. The term is often applied to states of responsiveness to the environment - being conscious or in coma, awake or asleep, and being alert or aroused within the waking state. These states can be described behaviorally by observing the human or animal" (p.272).

Furthermore, in a contribution to the Encyclopedia of Neuroscience, Libet (1987) also defined consciousness in terms of subjective experience:

"we restrict ourselves to the meaning of consciousness as one of subjective awareness and experience, whether it be sensory experiences of our environment, external and internal, or subjective experiences of our feelings and thoughts, or simple awareness or our own existing self and presence in the world" (p.273, own emphasis).

Libet's annotation underlines that the scientific study of consciousness is traditionally *restricted* to those processes which can be explicitly accessed and objectively observed. This tendency, which is likely also determined by limitations of methodological nature, leads to the confinement of a significant repertoire of behavioral and phenomenological events within the relatively ill-defined boundaries of unconsciousness.

A general conceptualization of consciousness derives from the work of the pioneer ethologist Jacob von Uexkull (1934), who applied the term *functional cycle* to the systematic relationship between the perceptions and the actions of an organism in a given environment. By means of recurrent functional cycles, organisms have perceptions that inform their next actions, which in turn will influence their next perceptions, and so on. Accordingly, the content of the world ("*umwelt*") perceived by the organism is defined, both in phylogenetic and ontogenetic respects, by constant functional cycles involving interaction between perceptual and behavioral systems. The processes carried on by these networks are merged during the ongoing experience, allowing the organism to attain various degrees of perceptual

¹ Disorders of consciousness (DOC) describe neurological conditions such as coma, vegetative states (persistent and minimal), and Locked-in Syndrome (LiS).

awareness. A relevant consequence is in fact that different sensory modalities of functional cycles, integrated by different brain systems, may generate different kinds and degrees of consciousness. These degrees presumably coexist in structurally and functionally juxtaposed "jacksonian" fashion (e.g. like the layers of an onion, see Hughlings Jackson, 1958), as do the underlying cerebral structures.

Although it should not be considered a comprehensive review of all the different facets and roles attributed to the phenomenon, we present hereby a general overview of the main expressions of consciousness. Importantly, a number of studies have suggested the correlations between the different facets of the phenomenon and their respective neural routes. Given the complexity of such matters, we will however not attempt a detailed review of such evidence, and we will rather limit ourselves to annotations of broader nature.

2.1. Primary Consciousness

Edelman (1989) addressed the relatively basic processual level in terms of *primary consciousness*. It refers to the ability to coordinate sensory input in order to achieve a meaningful representation of a perceptual object.

This form of consciousness is closely related to the mechanism of perceptual binding, which is proposed to collate the processual output of specialized areas into single perceptual units. Let's take for example the sight of a blooming strawberry field. The elements composing the landscape are remarkably many: uncountable leaves of different size, each with its own spatial orientation and shade of green, tiny white flowers scattered in all directions, while a grassy lawn and other leafy plants mark the confines of the cultivated area. Yet, given an intact brain, we would have no difficulties in binding spatial lines, associating the object-specific geometrical shapes with their corresponding color, and grouping the numerous tiny leaves into "units" (i.e. single plants). More so, some of us would likely be able to recognize immediately the "green-units" as strawberry plants. In sum, the whole componential spectrum of the visual input – shapes, directions, perspective, movements and colors – appears to merge into distinctly clustered percepts, which we are at once able to broadly categorize (<plants>), to recognize (<strawberry>), and then eventually to associate to a specific experience (<sweetness of berries>), and/or to a subjective feeling (<longing for summer> or <worries for allergy season>). Binding mechanisms appear therefore to involve also emotional mediation and memory retrieval. More so, the perceptual richness of our strawberry field can be processed, categorized and organized in seemingly automatic fashion, meaning that we do not need to direct an intentional thought to any of the stimuli that comprise our <strawberry-field-percept>, for it to eventually lead to a complex and nuanced experience.

In terms of brain structures significantly involved in the emotional and behavioral responses on the bases of primary consciousness, Arendes (1994) had suggested that the superior colliculus is crucial for ascribing connotative meaning to stimuli. More recent studies of inter-modal integration have further confirmed the role of superior colliculus, pulvinar and amygdala in the modulation of appropriate responses in lack of awareness of relevant stimuli (Mulckhuysen and Theeuwes, 2010; Mulckhuysen and Theeuwes, 2009; Fecteau and Munoz, 2005; LeDoux, 2000; Bechara *et al.* 1995). These structures have in fact appeared to be

specifically involved in modulating involuntary attention toward those visual stimuli which had failed to elicit participants' explicit acknowledgement.

How binding takes place is however a question still open to debate². A string of evidence has proposed that synchronicity between the firing rates of specific neuronal clusters lays at the bases of binding mechanisms (e.g. Gruber *et al.* 2006; Supp, *et al.* 2007). However, compelling evidence has also been produced to show that neurons involved in the processing of different perceptual elements do not show synchronicity during the merging of such information-bits into an unitarian percept. For example, Thiele and Stoner (2003) had argued against the role of synchrony in perceptual binding, and more recently Dong and colleagues (2011) have further rejected the binding-by-synchrony hypothesis. In the next sections of this chapter, we will argue that our model, pivoting on continuous broadcast, may indeed offer an effective solution to the binding problem.

In sum, we describe primary consciousness as the neural phenomenon responsible for merging single informational-bits into coherent perceptual units. The resulting data-clusters come to shape a background of implicit knowledge which, although remaining not explicitly accessible by the individual, is nevertheless sufficient to potentially enable a response, both at behavioral and at emotional levels.

2.2. Phenomenal Consciousness

Phenomenal consciousness has often been addressed as the most challenging degree of the phenomenon (Chalmers, 1995, 1996). Damasio (1999) has described it in terms of the "feeling of what happens", suggesting that it emerges from the functional cycle between the brain and the body. In Damasio's words, "*I conceptualize the essence of feelings as something you and I can see through a window that opens directly onto a continuously updated image of the structure and state of our body*" (Damasio, 1995, p. xiv). However, phenomenal consciousness is more than a representation of body states in the brain: it reflects the body-state variations which accompany the perception and processing of stimuli. In the case of tissue damage for example, the nociceptive stimuli will determine in the brain the neural representation of the bodily modifications, which will cause additional body-state changes. According to Damasio, "*It is from the subsequent body-state deviations that the unpleasant feeling of suffering will be formed*" (Damasio, 1994, p. 278).

In our words, phenomenal consciousness identifies the strictly experiential dimension of perception that emerges from the processing of stimuli which – contextually and/or historically – possess subjective relevance for the organism. While the stimulus may be explicitly described on the bases of its physical properties (color, shape, location, etc), the *feeling* that it determines is bound to an individual-specific internal representation and experience. Such specificity can be based on the contextual status of the organism, such as in the feeling of satiety that substitutes hunger after an enjoyable meal. Conversely, the sense of discomfort we might experience while looking at a blooming field of flowers would be subjectively determined by our history of allergic reactions to pollen.

² In fact, some would also argue that binding is not necessary to extrapolate a meaningful experience from an otherwise complex perceptual source (see Zmigrod and Hommel, 2011).

A number of studies (e.g. Vlachos *et al* 2011, Behrendt, 2010, LeDoux, 1994) have highlighted the involvement of the hippocampal system and of the amygdala in the emergence of phenomenal consciousness. Additional to such structures, the dorsolateral prefrontal cortex, right lingual gyrus and posterior cingulate cortex have been indicated as areas involved in the retrieval of memories possessing emotional valence (Maratos *et al.*, 2001).

2.3. Access Consciousness

Due to the fact that it can be explicitly and intentionally probed, access consciousness is one of the facet of the phenomenon that can be approached by means of direct investigation (e.g. verbal reports, self-confidence rates, questionnaires). Access consciousness can be described as the window into our cognitive mechanisms: it allows us to isolate specific stimuli for further evaluation, it enables the manipulation and strategical deployment of information, and it supports intentional behavioral responses. Say for example that you are traveling by car across a foreign city. You have a map and you know the name of the street you need to reach. As you cruise the unfamiliar roads, you pay attention to all directional posts, you read carefully the names of the streets so not to miss the one you are looking for, and you are also aware of the sense of apprehension determined by your fear of getting late to your destination. Every turn you will take will depend on your evaluation of its orientation toward the specific goal, and the decisions will be taken on the bases of the knowledge you have gained from the reading of the map, but also from the previous mistakes in choosing the wrong directions. The conceptualization of access consciousness embraces your ability to intentionally access during your journey the meaning of each stimulus that impinges your perceptual systems, and to strategically deploy the knowledge you derive from them in order to better fulfil the task. The Global Workspace Theory (Baars, 1988; 1997; 2007) is among one of the most consensually accepted models that describe the processes likely governing access consciousness.

The role of attentional mechanisms and the involvement of a fronto-parietal network (e.g middle frontal gyrus, bilateral inferior frontal junction, and intraparietal sulcus) are plausibly pivotal in supporting the presence of a stimulus in working memory (Gazzaley, 2011). According to other recent studies (Johnston *et al.* 2011; Benedet *et al.*, 2009; Ranganath, 2006), the retrieval of task-relevant information, and the strategic deployment of knowledge also determines increased neural activity in fronto-temporal structures. Finally, the emergence of inhibitory intermediary layers, compatible with Posner's (1995) mechanism of selective attention, likely contributes to the increased mobilization of mental resources toward the processing of contextually relevant information.

2.4. Self-Consciousness

As you are driving your car through the unfamiliar surroundings, your attention is focused on the specific stimuli (e.g. streets' names, lights, etc), and your mental resources are generously allocated to your challenging spatial task. However, a complementary mechanism is also consistently granting you the faculty to recognize yourself as the subject of perception,

and as the brewer of each decision. This mechanism allows in fact the emergence of self-consciousness, which refers to the individual's ability to implicitly and/or explicitly recognize ownership of own perceptions, thoughts and actions. Self-consciousness is historically, culturally, and linguistically constructed, and it emerges as a sense of coherence between our body and our mind (e.g. when your intention to drink is reflected by your hand reaching for the cup).

One aspect that further characterizes self-consciousness from other facets of consciousness is its developmental profile. Phenomenal consciousness and primary consciousness are assumedly present in all humans from birth, since both the emergence of feelings and the ability to perceive object-units are indeed hardly arguable in babies³. However, it is still a topic of debate whether self-consciousness is a faculty present at birth (e.g. Legrand, 2007), or it rather develops gradually during the first years of life (e.g. Lewis, 2011; Tagini and Raffone, 2009). Two conditions appear necessary for the emergence of self-consciousness: the capacity for self-reference, and the competence in practicing symbolic language (inner and/or outer speech). The maturation of frontotemporal brain structures, together with the progressive development of intra-hemispherical connective pathways cover therefore a role of crucial relevance by mediating language production needed to manifest self-consciousness (Perani *et al.* 2011). However, while the ability to address oneself by means of appropriate linguistic distinctions ("I"-entity vs. "others"-entity) is certainly a necessary tool of self-consciousness, such symbolic representations are first of all rooted in the implicit faculty to associate our perceptions (internally and externally triggered) to a correlating emotional and/or behavioral response. This self-referential mechanism is supposedly the product of a tightly connected neural network able to merge the output of specialized areas into meaningful perceptual units, and to measure these data-clusters against the organism's contextual intentions. Self-consciousness is therefore crucial to our ability to interact efficiently with our physical and social environment, since it conveys the feedback about the effects that our responses determine in the surrounding contexts and in ourselves. In the previous example of the car driving, a wrong turn would determine your awareness of having misjudged the distances, and such knowledge would consequently weigh on your next decisions concerning the best route toward your destination. Accordingly, our ability to interact socially is also dependent on the comparison between our actions and the effects they achieve on contextual situations. In sum, we can say that self-consciousness is the vehicle that modulates our sense of agency.

As previously mentioned, self-awareness reflects the emergent phenomenon of a significantly large neural network able to pool the processual output of both cortical and subcortical structures. Not surprisingly, it has therefore often been suggested that the rich connectivity between prefrontal areas and other specialized structures in the brain grants to the former a critical role in the emergence of self-consciousness (Tsakiris *et al.*, 2007; Sturm *et al.* 2006). However, further evidence indicates the equally pivotal role of temporo-parietal cortex in multisensory integration, and in the resulting emergence of first-person perspective

³ Recent studies have employed fMRI method to explore the neural network involved in the processing of emotional stimuli in 3-7 months old babies. The results have showed that selective activation of the anterior temporal cortex correlated with emotionally positive stimuli, while orbitofrontal cortex and insula activations accompanied the detection of negative stimuli. Similar patterns of activations occur in the adult brain exposed to stimuli of emotionally comparable valence (see Blasi *et al.*, 2011).

(Ionta *et al.*, 2011; Blanke and Arzy, 2005)⁴. Rather than opposing findings, the data can be taken to confirm the contributions of a remarkably broad neural network in the shaping of self-consciousness.

In the next section we summarize the Endogenous Feedback Network theory (Augustenberg, 2010). The model accounts for a global mechanism able to broadcast the outcome of perceptual processes, to merge them into meaningful representations, to modulate both emotional and behavioral responses, and to mediate the emergence of the different degrees of consciousness outlined in the above sections.

3. ENDOGENOUS FEEDBACK NETWORK: THE STADIUM ANALOGY

The Endogenous Feedback Network theory proposes consciousness as the phenomenon emerging from a distributed mechanism responsible for the broadcast of the neural changes determined by the sensorial detection and processing of internal and external stimuli. It is important to underline that the broadcast depends from the output of the specialized processual areas, but it is not involved in the processing of stimuli. An analogy might hopefully help to clarify such conceptualization. Imagine a crowded football stadium. Scattered at a number of focal nodes, *specialized agents* are responsible for monitoring the bleachers. Since each figure composing the crowd moves constantly around, the *specialized agents* unceasingly gaze the wide environment, ready to detect any anomaly, to recognize a known figure, to anticipate a predictable situation, or just to take in whatever input is contextually detectable. However, the complexity of the open environment and the multiplicity of targets do not allow the *specialized agents* to follow up automatically on every input. Therefore, by means of a constantly open port, they encode in real time their informational burden into a *global broadcast device*. Although not able to draw input directly from the crowd, such *global broadcast device* is responsible for circulating the continuous rapports of the *specialized agents*, and therefore for broadcasting across the stadium each node's status-quo at any given time. In this way, it is possible for every *specialized agent* to be alerted if an event has occurred at a different focal node, to anticipate an approaching situation, and to coordinate joined actions when needed. However, within such dynamic environment it will still difficult to isolate given figures: Specific elements can therefore be singled out by being placed in the stadium mid-field. Every *specialized agent* will then be able to inspect it with ease, and consequently to report the results of its assessment into the *global broadcast device* with enhanced clarity and richness of details. However, the ability of the *specialized agents* to adequately survey also the crowd during the detailed mid-field examinations will likely suffer, and eventually some figures – likely those least worth attention – might escape notice. A crucial detail in our stadium analogy has to be underlined. As soon as the *specialized agents* have completed their rapport, their focus will shift toward a new input, and they will no longer be concerned with their previous element of interest.

⁴ Others have also suggested that the frontoparietal network should identify the “observing self” (Baars *et al.*, 2003).

Truly, the activation in such areas appears to correlate with the processing of conscious stimuli, while it decreases instead during coma, persistent vegetative state, sleep and anaesthesia. Nevertheless, since frontoparietal activation emerges also during the processing of unconscious stimuli (van Gaal *et al.*, 2010), it could be argued that such structures most likely do not play a stringently causal role in the emergence of self-consciousness.

Nevertheless, their rappings – more so if they contain data of contextual or eventual future relevance – will remain (for variable periods of time) within the contents of the global broadcast⁵. This feature entails that new information is added into an existing pool of data⁶, which is dynamically build and maintained on the bases of the information's contextual relevance, of their frequency of retrieval, and of their adaptive value. Within such plastic network, related input will cluster, new 'files'⁷ will be created (if the incoming information has potential relevance), old 'files' will either be erased (if they have become obsolete), or they will increase in size (if new significant data add to their meaning). Additionally, if pre-existing knowledge is probed by new incoming information, the relative cluster can be retrieved, and brought to joint attention within the stadium mid-field where it will be submitted to novel assessment.

Let's see now how such analogy is supposed to apply to consciousness. Say that a visual input reaches your retina. The stimulus determines a change in the firing of the receptive cells, which in turn will activate the route that transmits the signal to the specialized areas in your occipital lobes (in the above analogy, this stage equals to the random figure detected by the *specialized agent*). According to the EFN theory, the neural changes produced by the visual input as it travels along your visual processing pathways will concomitantly produce an effect into a distinct neural network (the *global broadcast device*). As described in the analogy, the global broadcast is not relative to the processing of the stimulus per se: its purpose is rather to circulate the “news” that a stimulus as been detected, and that it is being processed at specific focal nodes. Say now for example that you are traveling on a crowded train on your way to work. While your eyes absent-mindedly sweep the crowd, a person's face determines a sudden attention shift, and your eyes make a saccadic movement back toward the stranger's face. Supposedly, as the passenger's face was being visually processed, some of its features have determined an informational match. In fact, after a few moments, you realize that the stranger vaguely resembles someone you have met some time ago. The EFN theory proposes that, as the neural changes produced by the processing of the specific feature had been encoded into the global broadcast mechanism, the input had found a partial match with the data-cluster relative to the person you had met before. This occurrence had determined the attentional enhancement of the contextual stimulus which translates into your consequent saccadic sweep back to the passenger's face⁸. In the stadium analogy, we would say that the specific item has now been removed from the crowd, and it has been placed mid-field to be jointly assessed from every focal node. At some point, you might be able to remember who the stranger resembles, where you had met your acquaintance, and other

⁵ It is not suggested that the representation of a stimulus is actually kept within the mechanism and repetitively broadcast. The hypothesis is rather that, for a variable interval of time, the neural connections that have reflected a specific representation will be more predisposed to re-establish their connective bonds. This mechanism would therefore enhance the probability that a specific representation might emerge within the “attentional mid-field”. Frequency, emotional valence and relevance could all be possible elements to enhance such likelihood by contributing to maintain the cluster at increased levels of excitability.

⁶ Pools of data refer to neuronal coalitions linking specific representations, and leading in such way to the shaping of concepts or experiences.

⁷ The creation of new files refers to the shaping of connective neural patterns, i.e. coalitions of neurons.

⁸ The emergence of data from the background broadcast into the attentional spot-light identifies the emergence of access-consciousness. Among the criteria that allow such enhanced allocation of resources, it has been hypothesised that the stimulus' relevance and meaning, its perceptual saliency, and the contextual availability of the individual's cognitive resources, can all play a role in the acknowledgement of a specific stimulus above others (Augustenborg, 2010).

possible details of the encounter. While such mnemonic reconstruction might take time since it rests on the shaping of only weakly probed connective patterns⁹, you would likely be able to immediately determine whether or not you know personally the passenger on the train. In this latter instance, the probing of a complete data-cluster would have in fact maximized your faculty to recall.

So far, the analogy of the stadium could seem to overlap with other known examples that have attempted to translate the difficult conceptualization of consciousness into more affordable terms (e.g. the theatre analogy proposed by Baars, 1997). However, if we were to follow the model of the Global Workspace Theory, we would conclude that the stadium's mid-field (i.e. Baars' 'stage') frames the phenomenon of consciousness. On the contrary, according to the EFN model, this element of the stadium analogy reflects mere attentional enhancement. More so, by allowing a conceptual ambivalence between variably accessible cognitive processes modulated by attention, and the experiential degrees that may derive from them, we might obtain only the illusion of tacking consciousness. This reasoning would in fact call for Goethe's warning: when we look for what we know (i.e. accessible information), we see what we are looking for (i.e. consciousness)¹⁰. The result is therefore a theoretical framework relatively inadequate to account for the many degrees of consciousness (exception made of course for access consciousness, which hardly can be dissociated from attention). Additionally, the workspace-conceptualization of consciousness implies that virtually all non-human animals possess consciousness. It may in fact be hard to deny that sensorial permeability to the environment, and ability to select specific stimuli from it are faculties possessed by all organisms. However, the essential question concerning whether or not all animals *are aware of perceiving and experiencing* has so far been left unsatisfied.

The distinction between the ability to *process* stimuli, and the faculty to *experience* the contents of such processes is at the core of the stadium analogy. As previously described, we suggest that the information processed by each focal node is encoded into a global broadcast mechanism¹¹. This means that information emerged from our cognitive processes with regard to a stimulus' physical features and to its meaning converges into the relative data-cluster. However, emotional tags derived from the involvement of subcortical structures contribute as well to the specific 'informational folder'. These strictly phenomenal tags are likely more rapid to gain explicit acknowledgement than other more factual features of the stimulus. In order to eventually acquire a space in our "attentional mid-field", the latter type of information would in fact require the shaping of a broader range of neuronal coalitions coding for many proprieties (shape, color, meaning, etc). Let's consider an example. If you were arachnophobic, you would likely experience sudden fear at the mere glimpse of a 'spider-like'-shape at the edges of your visual field. Before you might be able to collect further data, the crawling movement would in fact be sufficient to trigger the phobia-sensitized "spider-cluster". This emotional reaction would therefore anticipate the more precise (but also more time-consuming) outcomes of the cognitive processes, which might eventually either inhibit

⁹ This delay could support the Tip-of-the-Tongue phenomenon, which refers to our ability to experience the feeling of knowing or remembering something, although we are not actually able to recall it explicitly.

¹⁰ Accordingly, every computation estranged from the global workspace is considered "unconscious" (Baars, 1988).

¹¹ It is not suggested that every single stimulus impinging our sensory systems is automatically broadcast. Specific criteria, e.g. the occurrence of an eventual mnemonic match, the perceptual saliency of the stimulus, the attribution (albeit rudimentary) of meaning and relevance, have to be met in order to access the broadcast (see Augustenburg, 2010 for a more detailed discussion of access criteria).

(if the stimulus is in fact a dust bunny blown by the breeze) or enhance (if the stimulus is indeed a spider) the emotional reaction.

These suggestions are broadly supported by studies presenting both behavioral and electrophysiological evidence of increased efficiency in the processing of feared stimuli (e.g. Kolassa *et al.*, 2005, 2006, 2007; Becker and Rinck, 2007; Gerdes *et al.*, 2008; Öhman and Mineka, 2001). Kolassa *et al.* (2007) presented their participants with pictorial images which gradually transformed from schematic pictures of flowers to schematic pictures of spiders. The task consisted in determining whether the images resembled more spiders or flowers. The results showed that spider-phobic participants, compared to non-phobic participants, tended to associate the ambiguous pictures more often and more rapidly to spiders than to flowers. Furthermore, the electrophysiological data collected during similar experiments had showed larger parietal late positive potentials in phobic participants when the schematic images were associated to spiders, than when the picture were thought to resemble flowers (Kolassa *et al.*, 2006). These results are congruent with those obtained from phobic participants observing real-life pictures of spiders, and they support therefore the interpretation that the ambiguous image of a spider is sufficient to “*trigger meaning-related evaluative processes in the brains of spider phobic persons*” (Kolassa *et al.*, 2006). Kolassa and co-workers also suggested that the speed by which phobic participants processed the schematic images of spiders might have reflected “*a higher level of expertise*” in processing these stimuli above others (Kolassa *et al.*, 2007). This interpretation is compatible with our hypothesis that an increased level of excitability contributes to the likelihood that the specific coalitions of neurons re-establish their connective bonds, and consequently emerge within the “*attentional mid-field*”. In other words, practice would appear to facilitate the gaining of the necessary level of activation needed to trigger specific representational coalitions.

Although it might be tempting to ascribe the behavior of the spider-phobic group to an autonomic response strictly mediated by the amygdala, other studies appear to contrast such interpretation. Alpers *et al.* (2009) have employed fMRI to study amygdala activations in participants who had been asked to identify the moving animal in a double-exposure display. The results showed that, while the amygdala was strongly activated by spider-congruent images (two spiders, one of which moving), no significant responses resulted from the presentation of mixed displays (bird and spider, former moving). In other words, rather than on the presence of the feared stimulus, the amygdala's arousal appeared to depend on the allocation of attention to the spider. This interpretation supports our hypothesis that the sudden fear experienced by a phobic person is determined by the retrieval of the specific data-cluster¹² (comprising therefore also a subjectively acquired emotional valence) operated on the basis of a perceptual cue, i.e. the crawling shape at the edge of your visual field. Attention – and consequently amygdala's arousal - appears in fact to follow the perception of the crawling movement, as it is also demonstrated by the fact that the assessment of the true nature of the stimulus (whether a real spider or a dust bunny) *follows* the emotional response. We suggest therefore that the amygdala's involvement in the fearful responses might result from its participation to the neuronal coalition activated by the probing of the specific spider-cluster. In this light, the model based on the stadium analogy can account for the adaptive

¹² This hypothesis is also supported by evidence of arachnophobia in a congenitally blind person (see Musial *et al.* 2007). The person's emotional reaction (fear and disgust) appeared to be triggered by mental pictures, by history of encounters with the spider (e.g. touching the web), and by what she had been told by others.

value of feelings, which - on the basis of previous experiences - can rapidly convey immediate responses to specific stimuli also in absence of attention. Furthermore, on the premises of our current hypothesis, our ability to deduce and generalize would consequently emerge from our ability to elaborate also on the bases of partial data-matches.

Finally, the EFN model depicts a mechanism able to account for self-consciousness. Let's take a step back at the earlier example of you driving the car. You are implicitly aware of being the driver of the vehicle, you might also be explicitly aware of reading the name of every street trying to identify the one you are looking for, meanwhile you are surely aware of getting increasingly anxious about being late to your destination. According to the EFN model, each of these outcomes depends on the fact that specific cognitive processes have determined a consequent flow of data into the global broadcast mechanism. In fact, by allowing the merging of new information into a stream of pre-existing knowledge, the broadcast mechanism endows us with the ability to shape internal "data-threads". Your implicit knowledge of being the driver of the vehicle matches therefore your previous knowledge of having entered the car, which matches your previous knowledge of intending to reach a specific destination, and so on. In sum, the bonds between intra- and inter-coalitions mediated by the global mechanism shape the unique neural profile of an individual. Self-consciousness defines the experiential expression of such constellation, in which the individual's emotional and cognitive processes at any one time will be affected by the emotional and cognitive outcomes determined by the processing of previous information. For example, your sense of anxiety for getting late to the destination is strictly subjective since it is based on the specific emotional responses you have linked to such occurrences. If - on the basis of previous experiences - you implicitly associate being late to the emotional response of embarrassment, your anxiety might reflect the effort to avoid such outcome. The level of discomfort produced by the retrieval of such experiential clusters shapes then the strictly subjective way in which the contextual situation affects you. In other words, the "what-it-feels-to-be-you" while you are driving the car is determined by the completely unique data-thread you have built until that specific moment. At functional level, self-consciousness mediates therefore our ability to learn from previous experiences by allowing us to profit from the correlations between our actions, their consequences and the feelings we derive from them. It can consequently be suggested that the gradual shaping of a biographical archive of cognitive (i.e. the significance we learn to ascribe to stimuli) and emotional information (i.e. the emotional component tagging the specific stimuli) may then account for the developmental profile of self-consciousness.

4. MORPHOLOGICAL AND PHYSIOLOGICAL EVIDENCE: NEURO-ASTROGLIAL NETWORKS

The brain is composed of billions of cells of two classes, neuronal and glial. The second class was until recently thought as merely supportive. According to the "Neuron Doctrine" formulated by Ramon y Cajal (in Bullock *et al.*, 2005), neurons were conceived as discrete structural and functional units of the brain, responsible for our mental processes, while glia had only mediating functions, as anchorage and nutrition to neurons. In the modern mapping of brain functions, glial cells are conceived as co-participants in our cognitive and affective

functions, forming a network (additional to the one shaped by neurons) that processes and broadcasts information by means of intercellular ionic waves (Douglas Fields, 2009). This new conception allows for an explanation of mental phenomena executed by means of cooperative neuro-glial interactions.

Among glial cells, one kind that intensely exchanges information with neurons is the astrocyte (for a review, see Pereira Jr. and Furlan, 2010). Neurons receive signals from the world through peripheral and central sensors, and transmit these signals to other neurons and astrocytes. Astrocytes receive signals from neurons, the blood and cerebrospinal fluid, and transmit these signals to other astrocytes and neurons. The modalities of information processing and transmission in neuronal and astroglial networks are different. Neurons have an permeable membrane, which mediates the gradual excitability of the nerve cell. When the neuron's specific threshold is reached, an action potential (discrete pulse) is triggered at the axon hillock, and it travels along the axon. Action potentials are adequate to reliably transmit information in a digital-like manner. Astrocytes have their membranes constantly hyperpolarized, being unable to generate action potentials, and they process information and communicate by means of electromechanical waves of ions. These waves are generated inside microdomains, which are connected by gap junctions. The smaller waves formed in microdomains communicate with other microdomains, and propagate through the astroglial network, possibly broadcasting local activation patterns across the whole brain. These waves possibly embody affective connotations of the signals received from neuronal populations.

The affective network is conventionally conceived as composed of subcortical regions as the periaqueductal gray area, hypothalamus, striatum (the *nucleus accumbens*), limbic structures as the amygdala (LeDoux, 1994) and the cingulate gyrus, as well as insular and orbital cortices (Tsakiris *et al.*, 2007, Volkow *et al.*, 2005). These regions are involved in specific dopaminergic, serotonergic, noradrenergic and cholinergic circuits that modulate the balance of excitation and inhibition, producing affective and emotional conscious states. All these areas contain both neurons and astrocytes. Neurons operate as specialized information processing units, but they do not appear responsible for modulating feelings about the content of the information they process. For example, in the amygdala, neurons fire to emotionally salient stimuli, but the corresponding feelings are not instantiated by them (see Pessoa and Adolphs, 2010). Pereira Jr. and Furlan (2010) proposed that feelings are instantiated by a large astroglial network connected to the above mentioned regions. In this view, the feeling of fear is not limited to the activation of the amygdala, as well as the feelings of pain or pleasure are not limited to the activation of the insula. The feeling determined by a given stimulus is rooted in the whole brain since it is modulated by the activation of the astrocyte network. Astrocytes are in fact in an adequate position to instantiate feelings, since they connect the main signaling subsystems of the living body (blood, cerebrospinal fluid and neurons), and operate in a wavelike fashion analogous to the first-person experience of feeling. In fact, according to a philosophical monist assumption, astroglial ionic waves and feelings are two aspects of the same percept: one experienced from the first-person perspective (feelings), and the other tractable from the third-person perspective (the astroglial wave is – in principle – a component of the scalp EEG register).

In this philosophical framework, there should be an isomorphism between each feeling and the corresponding wave, composing a type-type mapping. Put another way, each time the subject feels, say, pain or pleasure, the corresponding waveform occurs in his or her brain, and such kind of wave occurs only when s/he is experiencing that specific pain or pleasure.

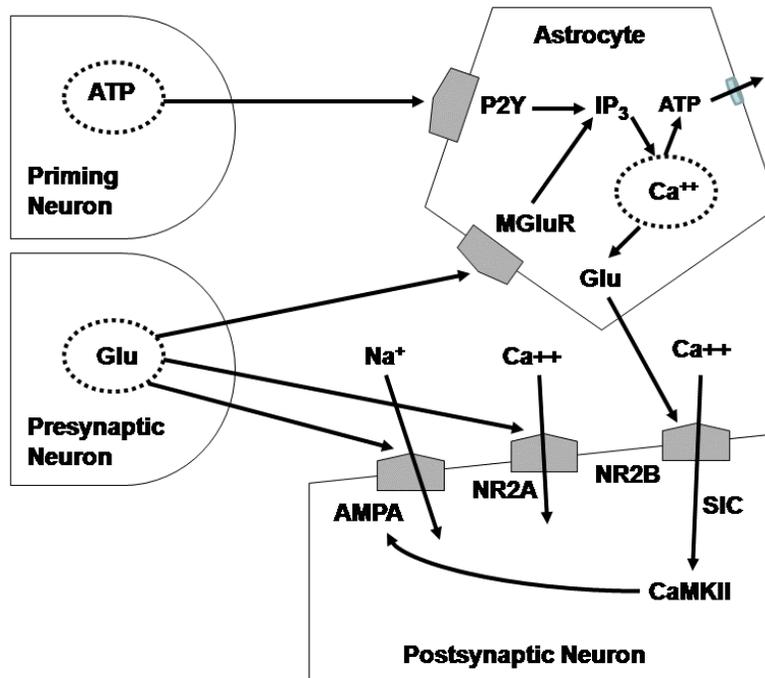


Figure 1. Sketch of the Physiology of Tripartite Synapses: While the brain is awake, astrocytes are primed by purinergic transmission mediated by metabotropic receptors (P2Y), GABAergic, cholinergic and other neurotransmissions (not shown). Glutamate (Glu) released by the presynaptic neuron binds with both astroglial (MGLuR; possibly also astroglial NMDA receptors, not shown in the picture) and postsynaptic neuronal (AMPA and NMDA containing the NR2A subunit) receptors. Synergic action of MGLuR and other astroglial receptors activate the inositol triphosphate (IP₃) pathway, release calcium ions from internal stores (mitochondria and endoplasmatic reticulum) and - when a threshold of activity is crossed - induce calcium waves in adjacent cells, mostly by means of ATP signaling mediation (represented in the figure by the arrow from the astrocyte to the astrocytic network – the latter not depicted). Astroglial Glu binds mostly with neuronal NMDA receptors containing the NR2B subunit (NR2B), causing calcium ion entry (Slow Inward Current - SIC) and binding to CaMKII, then sustaining the excitatory activity of the neuron by means of AMPA phosphorylation.

A more precise picture of how neurons and astrocytes interact requires the consideration of molecular mechanisms of the tripartite synapse (i.e. a type of synapse that contains two neurons and one astrocyte). Neuronal communication requires the transduction of bioelectric output (action potential) into biochemical signals, carried by the transmitters released at the synaptic cleft. Neurons release a considerable number of transmitters which, besides affecting the post-synaptic membrane, reach the astrocyte located in the tripartite synapse. The latter releases in turn transmitters (gliotransmitters) which reach the post-synaptic neuron (Figure 1). Among the many transmitters released by neurons, glutamate (Glu) is the one responsible for carrying sensory information, and it operates in balance with the inhibitory transmitter system (GABAergic). In the tripartite synapse, it operates synergically with purines (the adenosine triphosphate/ATP is an energetic as well as an informational entity; see Verderio and Matteoli, 2011) to activate the astrocyte. The latter can sustain the activity of the post-synaptic neuron by means of the release of astroglial Glu, as well as generate an ionic wave (calcium wave) transmitted to other astrocytes.

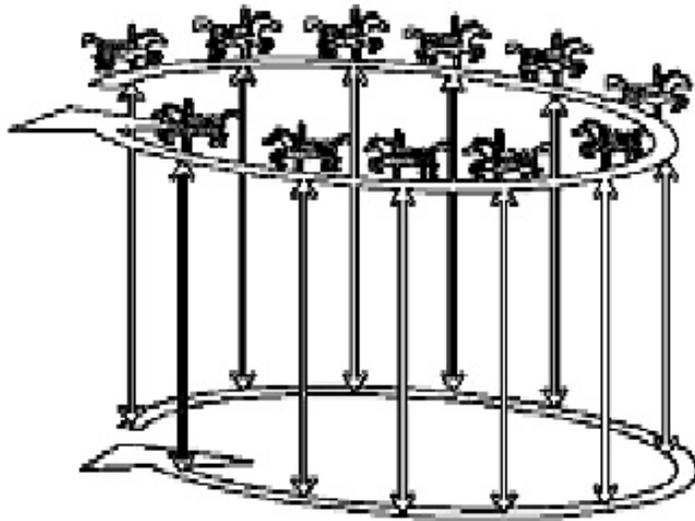


Figure 2. The Carousel Effect: The below circle represents a cycle of activity of a population of synchronized neurons, while the above circle represents an intercellular calcium wave in astrocytes. Each horse corresponds to a small calcium wave inside one astrocyte microdomain. The coordination of smaller waves, generating the large wave, is orchestrated by synchronized neurons and feeds back to them (bidirectional arrows) independently of an actual causal relation between the smaller waves (adapted from Pereira Jr. and Furlan, 2010).

One complex dynamical mechanism, the "carousel effect" (Pereira and Furlan, 2010), was proposed to describe how neuronal and astroglial networks interact. The analogy is intended to illustrate how calcium waves in the astroglial network are induced by large populations of synchronized neurons, and feedback (positively or negatively) on the same neurons (Figure 2).

The "carousel effect" makes it possible to conceptualize the complex dynamic of interactions between the neuronal and astroglial networks. While the former is responsible for the cognitive elaboration of sensory information, the latter mediates affective evaluations of the content of the information, accordingly to the individual history and to the ongoing processing of somatic markers. The large ionic wave formed in the astroglial network can determine an endogenous feedback by means of at least eight modalities, which can produce opposite effects (potentiation or depression) on neuronal membranes (for details, see Pereira Jr. and Furlan, 2010):

- Glu release by astrocytes activating synaptic NR2A subtype NMDA receptors, causing membrane potentiation by promoting AMPARs transport to the postsynaptic density;
- Glu release by astrocytes activating extrasynaptic NR2B, causing membrane depression by means of inhibition of AMPARs transporters;
- D-serine release by astrocytes potentiating NR2A neuronal NMDARs in the presence of presynaptic Glu release;
- D-serine release by astrocytes depressing NR2A neuronal NMDARs in the absence of presynaptic Glu release;

- ATP release and binding to neuronal purinergic receptors;
- ATP release in extracellular space and degradation into adenosine, causing depolarizations that impact on brain activity and behavior;
- The release of cytokines that mediate pain sensations;
- Astrocytic homeostatic control of ionic concentrations in perisynaptic intercellular fluid.

The double role of astrocytes – i.e. potentiation or depression of neuronal activity – follows the activation of the above modalities. For instance, a reduction of ATP production and/or availability can promote neuronal membrane potentiation by means of binding to neural receptors and reducing the availability of adenosine, or blocking it by means of reducing calcium waves, with the consequent release of astroglial Glu and D-serine to neurons.

On the basis of this neuro-astroglial interaction model, we suggest that variable degrees of consciousness, as well as the conjugation of cognitive and affective operations, may depend on two factors: a) the intensity of activation in each network, in terms of patterns reaching or not the threshold necessary to trigger a broadcast, and b) the degree of resonance between the two networks. The resonance can occur in the absence of salient external stimulation and, even when such stimulation occurs, the response of the coupled networks is always dependent on the previous state of their interaction domain.

Cognitive and affective contents can be associated, forming perceptual "blocks" (e.g. the representation of a house and the feeling of protection). The broadcasting of one kind of content (cognitive or affective) does not compete with the other, since each one makes use of its own network.

According to this proposal, the dynamics of an extended workspace would not be based only on selective mechanisms, but also on cooperative coalitions of cognitive-affective blocks (representations and their associated feelings). The main characteristic of conscious processing would then be the integration of patterns processed in a distributed computing system, in such a way that many activated circuits could contribute to the composition of an explicit episode.

Variable degrees of consciousness occur when patterns reach a specific threshold in one network, but not in the other. Several experimental results indicate that, while a stimulus can be subliminally processed by the cognitive network, it can simultaneously be acknowledged supraliminally by the affective network. For example, in a study carried on by Siegel and Weinberger (2009), participants had been showed visually masked pictures of spiders.

As the time-limited and masked presentation of the images had inhibited the subjects' ability to form the visual representation of the spider, they had therefore not been able to explicitly report its appearance. However, the picture of the spider had been able to elicit a supraliminal effect on the affective network, as demonstrated by the participants' fearful behavioral responses, and by their increased skin conductance (see also Öhman, 1994, 2001). Current paradigms based on a narrow view of GWT have possibly led researchers to classify these behaviors as "unconscious", and the respective memory as being "implicit" (Yang *et al.*, 2011). An extended workspace approach would help to revise these assumptions, leaving the classification of "unconscious" only to those computations which escape global broadcast.

We explain complex processes occurring below the threshold of awareness as those not able to produce resonant states of sufficient magnitude to determine the individual's overt acknowledgment. Implicit feelings (i.e. those of which we are not aware) can occur when restricted calcium waves are formed in the astroglial network without feeding back to neuronal networks. Implicit cognitive processes occur in neuronal circuits when cell assemblies are activated without reaching the threshold to induce the corresponding astroglial calcium waves.

A possibility of transient dissonance between the contents processed by the networks is the case of the so-called "mind-body dissonance" (Huang and Galinski, 2011). This concept can expectably be argued by neuroscientists, who likely tend to defend that the state of the body can only be recognized by the brain. Compatibly, we suggest that there are no dissonances between states of mind and states of the body, rather only dissonances between cognitive and affective contents.

CONCLUSION

In this chapter we have presented a brief overview of some among the main facets of consciousness. Although the different expressions of the phenomenon manifest themselves in quite distinct ways, they are joined by a common feature: they all appear to emerge from a chain of processes relatively inaccessible to the subject.

We have therefore presented a model which aims at describing an underlining mechanism able to determine the emergence of different aspects of conscious activity. Particularly, our model affords a plausible account of phenomenal and self-consciousness which, by resting at the outskirts of reportable cognitive activity, traditionally compound the 'hard problem' of consciousness. In introducing this chapter, we have argued that a theory of consciousness cannot be complete unless it entices also a theory of unconsciousness. Within the frames of the EFN model, we have proposed that a global broadcast mechanism can be taken to describe the otherwise vague conceptualization unconsciousness.

We arrive at the suggestion that the Endogenous Feedback Network may actually compound two interacting networks, (neuronal and astroglial), which form an Extended Global Workspace. In this context, different degrees of consciousness, ranging from complete lack of subjective awareness to full reportability of percepts, correspond to the strength of interaction between the two networks.

Resonating states define the degree of attention in access consciousness, and the main pathways for the construction of self-consciousness. Features outside the focus of attention are however experienced in primary and phenomenal consciousness: these correspond respectively to patterns that reach significant levels of amplification either in the neuronal or in the astroglial network.

In sum, we argue for the existence of a continuum from total unconsciousness (i.e. absence of informational broadcast) to full awareness (i.e. intentional and explicit reportability), which embraces different phenomenological nuances. This framework, which includes therefore both accessible and non-accessible perception, shapes distinct frames to the conceptualization of unconsciousness, to which it grants a broader and more active role in the mediation and modulation of our mental resources.

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