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Review article

Dyadic Brain - A Biological Model for Deliberative Inference

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Abstract: The human brain is arguably the most complex information processing system. It operates by acquiring data from the environment, recognizing patterns of events' occurrence, anticipating their re-occurrence and in turn generating appropriate behavioral responses. Through the lenses of the free-energy principle any self-organizing system that is at equilibrium with its environment must minimize its free energy either by manipulating the environmental sensory input or by manipulating its internal states thus altering the recognition density of the outside stimuli. However, several sets of challenges interfere with the human brain's ability to learn and adapt in such a theoretically optimal fashion. These may include, and are not limited to, functional inconsistencies related to attention and memory processes, the functions of "fast" and "slow" thinking and responding, and the ability of emotional states to generate unintended behavioral outcomes that are less adaptive or inappropriate. This paper will review literature on the subject of how ideal learning viewed from the free-energy principle perspective may be affected by the above mentioned limitations and will suggest a model of information processing that may have developed as a way of overcoming these challenges. This neurobiological model stipulates that a neuronal network is formed in response to environmental input and is paralleled by at least one and possibly multiple networks that activate intrinsically and represent "virtual responses" to a situation that demands a behavioral response. This model accounts for how the brain generates a multiplicity of potential behavioral responses and may "choose" the one that seems most appropriate and also explains the uncanny ability of humans to socialize and collaborate. Implications for understanding humans' ability to learn from others, deliberate on opposing constructs and access and utilize information outside of individual minds are also discussed.

Keywords: deliberation; active inference; free energy principle; neuronal synchrony; dyadic brain; attribute substitution

1. Introduction

The human brain is arguably the most complex information processing system. Its main function may be simplistically described as one of acquiring data from the environment, recognizing patterns of events' occurrence, anticipating their re-occurrence and in turn generating appropriate behavioral responses. This proposition has been conceptualized under the free-energy principle (FEP) [1], which suggests that the process of minimizing free energy is bound to the detection of novelty and resolution of uncertainty by minimizing (expected) surprise. FEP postulates that any self-organizing system that is at equilibrium with its environment must minimize its free energy *via* two possible mechanisms a) by interacting with the environment thus changing sensory input or b) by changing the system's internal states thus altering the predictions of external stimuli. Both processes effectively reduce the discrepancy between sensory samples and predictions of the samples (*i.e.*, they reduce surprise). As with any other self-regulating biological system – and in accordance with the FEP – the brain must minimize free energy as part of maintaining equilibrium with its environment. The FEP therefore can help explain any adaptive functions in the brain as it is striving to reduce surprise by either modifying the external world or its internal state. In other words, the brain will either reconfigure its sensory system to sample inputs that are predicted by its internal representation or will act on the environment to minimize uncertainty, which in turn enforces sampling of sensory data that is consistent with the current representation.

The proposition that the process of minimizing free energy is bound to detection of surprise is also consistent with Claude Shannon's conceptualization that "Information is the resolution of uncertainty." It follows that a more accurate sampling of the environment should ultimately diminish expected surprise, suppress expected prediction error, and in turn minimize expected free energy, which can all be summarized in terms of resolving uncertainty. Interestingly, this means that the opportunity to resolve uncertainty through the active sampling of salient and uncertainty reducing information becomes itself attractive (*i.e.*, salient). Put simply, novel and potentially surprising outcomes become attractive, in virtue of affording the opportunity to gain information about states of the world generating outcomes [2-4][1]. If all of these conditions are aligned and executed in concert they will ensure what we will call "optimal responding." However, several sets of challenges interfere with the human brain's ability to adapt in such a theoretically optimal fashion.

One can easily create a list of hurdles that may impede the process of behavioral adaptation as considered from the FEP perspective. These hurdles are related to the unstable nature of complex memories as these are reconfigured in the processes of perception and memory consolidation, thus providing ever-shifting reference points. In turn, recall of events will be inaccurate, as the memory of these past events has been modified and reconsolidated. These shifting internal representations nevertheless form the matrix that furnishes reference points for interactions with the environment, including social interactions. Cognitive processes including attention and memory exhibit considerable functional inconsistencies and produce less accurate representations than thought previously [5]. It is possible that biased attention and perception and distorted memories, far from providing veridical data to the system, may reduce free energy in order to maintain equilibrium, which may result in inappropriate or suboptimal responding.

A recent review of the FEP in complex (random dynamical and Markov decision) processes has addressed a number of issues that speak to the applicability of the FEP in understanding behavioral responses; especially, the distinction between habitual behaviors (*i.e.* fast responding) and behaviors resulting from active inference and planning (*i.e.,* slow thinking and responding) [6]. For instance, the concept of active inference considers constructs like reward, utility, and epistemic value in terms of prior beliefs and preferred outcomes, which one expects to be realized through action. In this setting, cost or utility driven behaviors are contextualized in terms of a more general imperative to minimize expected free energy. This combines pragmatic or utilitarian imperatives used in

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[1] The sort of free energy we are dealing with here is an information theoretic variational quantity that plays the role of surprise (or log marginal likelihood). Strictly speaking, this is distinct from thermodynamic free energy of the sort entailed by neuronal energetics and metabolism. However, there is a very close relationship between variational and thermodynamic free energies that follows from fundamental laws in physics; namely Landauer's principle and the Jarzynski equality [2, 3]. In brief, this means that when variational free energy or surprise is minimized, the metabolic and computational cost of inference is also minimized. This fits nicely with the imperative to minimize complexity costs – that is implicit in the free energy principle and the resolution of uncertainty through contemplative planning [4].

reinforcement learning with intrinsic motivation and epistemic value found in perception and robotics. Efficient, automatic (*i.e.,* state-action) behaviors can become incorporated in the armamentarium of behavioral policies as "habits". Moreover, the authors advance the notion that habitual behaviors can emerge by observing one's own goal-directed behaviors. Further work from the same group addresses the subject of free energy in relation to explorative behavior in terms of epistemic imperative to reduce uncertainty [7], where transitions among uncertain (hidden) states generate observed outcomes. In brief, it is proposed that active inference entails inferring one's own behaviors on encountering new observations *via* the minimization of expected free energy[2]. As this conceptualization of active inference can clearly be generalized to even more complex behaviors, here we propose that active inference is applicable in the special case of uniquely human cognitive processes.

Specifically, we suggest the phenomenon of slow deliberative thinking (see below), has the unique feature of information processing and contemplation of various possible actions before any action has been undertaken. In other words deliberative purposeful planning necessarily calls on deep generative models of the future consequences of action – models with counterfactual depth. In the case of active inference, the uncertainty about what is referred to as "hidden states" resolves with subsequent observations. More formally, the actions that minimize expected free energy will maximize epistemic value or information gain, under prior beliefs about (preferred) outcomes [8]. Heuristically, this means that the system (*e.g.,* human brain) will search out observations that resolve uncertainty about anticipated outcomes; conversely, when there is no uncertainty about the outcome of one's actions there can be no further information gain and behavior becomes dominated by prior preferences.

What makes the case of slow thinking (and subsequent action selection) unique, is that humans have the ability to "play out" in their minds a variety of possible scenarios and to estimate probabilities of different outcomes without taking any action. In other words, a KL divergence can

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[2] Our reference to free energy minimization is in the sense of variational inference. In brief, this provides a formal (information theoretic) formulation of how we avoid surprising and unpredicted (*i.e.*, costly) states of affairs. In this setting, surprise codifies the improbability of an outcome under a particular model or set of beliefs about what should happen. Technically, it is known as self-information or surprisal (which may or may not relate to the psychological notion of subjective surprise). Free energy is an approximation to surprise that – unlike surprise itself – is possible to evaluate; given a model of how outcomes are generated and sensory evidence for that model. Therefore, minimizing free energy is (approximately) equivalent to minimizing surprise. Crucially, from the point of view of Bayesian statistics, surprise is the negative logarithm of model evidence or marginal likelihood. This means that minimizing free energy corresponds to approximate Bayesian inference.

be estimated for virtual actions with hypothetical outcomes (*i.e.,* "if I do this, that may happen.") in the absence of any actual new experiences and observations. In this review, we propose a model that may account for those unique cognitive abilities and discuss the possible biological substrates that underpin this type of counterfactual contemplation, without actual action or observations.

For the purpose of the current discussion we will examine the phenomenon of fast *vs* deliberative responding, which depend upon fluid attention and memory processes and are related to the resolution of uncertainty. Further, while fast responding seems well suited to serve the purpose of quickly decreasing the free energy in the immediate environment, the slow deliberative thinking will presumably increase the free energy in the system, an issue that will be specifically addressed later. We will also review literature on the subject of how optimal behavioral adaptation viewed through the perspective of FEP may have developed within shared processes of information processing and error detection in an interpersonal context.

2. Fast *vs* deliberative behavioral responses

Kahneman has described two main systems of behavioral responding, fast, automatic responses (*e.g.,* reflexes, instincts, habits) and slower "deliberate" responses (*e.g.,* planning, goal formulation) [9]. Fast thinking predominates mental activity and is based upon rapid appraisal of environmental stimuli which are compared to existing internal representations. When stimuli are familiar, free energy is low and behavior responses follow rapidly and automatically.

Fast automatic thinking is in accordance with the hypothesis that humans need relatively little *a priori* information in order to respond to their immediate environment [10]. This tendency to resort to the (reflexive) use of heuristics has been hypothesized to operate through a process called *attribute substitution* [11]. These unconscious substitutions occur when a difficult problem is addressed by formulating and answering a simpler problem without conscious awareness of the "switch" [12]. Thus, in cases when the "best possible solution" is impractical, heuristic methods based on prior learning and assumptions can be used to expedite the process of finding a "satisfactory" outcome [13].

In relation to social interaction, fast thinking may have evolved to detect danger versus cooperation in brief interactions with other humans. Such judgments rely upon biases derived from observable features as well as nonverbal cues and vocal expressions. Therefore, automatic processes simplify social interactions by removing the need to acquire new information for every interaction. The lack of *a priori* information is then substituted with expectations about a particular interaction. These presumptions will generate specific preparations for possible responses. This overall pattern for the resolution of uncertainty is formally related to Hamilton's principle of least action where minimizing expected surprise (or free energy) is formally equivalent to reducing uncertainty. The mathematical presentation of this principle is presented as:

$$\delta S = 0, \tag{1}$$

It can also be stated that a system will choose the path between times t_1 and t_2 for which action is either minimal (*e.g.,* δ equals small change) or stationary (*e.g.,* δ equals no change) [14-16].

As noted above, attribute substitutions are utilized unconsciously for the purpose of simplifying interactions with the environment, including interpersonal interactions. As fast responding is linked to the sense of self, particularly in situations perceived as threatening, then responses which serve self-preservation may be preferentially selected even if they do not provide optimal long-term free energy minimization. Moreover, fast responding is intimately coupled with emotions, which in turn introduces more unpredictability in perceptual synthesis and subsequent responding. In sum, all of these may interfere with the process of minimizing free energy of the system and may in turn even contribute to higher free energy (*i.e.*, surprises) in an interpersonal context. In such cases when the fast behavior response results in an unexpected outcome (*i.e.*, surprise is detected), slow thinking (and responding) is initiated. Those processes are deliberate, logical, and more time consuming. Altogether, these arguments imply that rapid processing may be efficient, yet it is prone to (generalization) error.

The possible relations of these two response types suggest that fast thinking will predominate in situations when the free energy of the environment is low (*i.e.*, no surprise) whereas slow thinking will reflect the brain’s efforts to minimize unexpected surprise *via* shifts in internal (hierarchical) representations or behavior to effect environmental changes. These purported relationships between free energy and fast and deliberative responding are illustrated schematically in Figure 1.

Next we suggest that the human brain may have developed a system to minimize the negative consequences of fast responding that relies not exclusively on individual experiences but on a combination of individual experiences and interactions with others.

3. The dyadic brain

It is well accepted that the brain maintains parallel systems of information processing so that stimuli that engage different sensory systems will process information influx through neuronal pathways, which will create a memory trace of any particular stimulus. Repetitive stimuli will be the

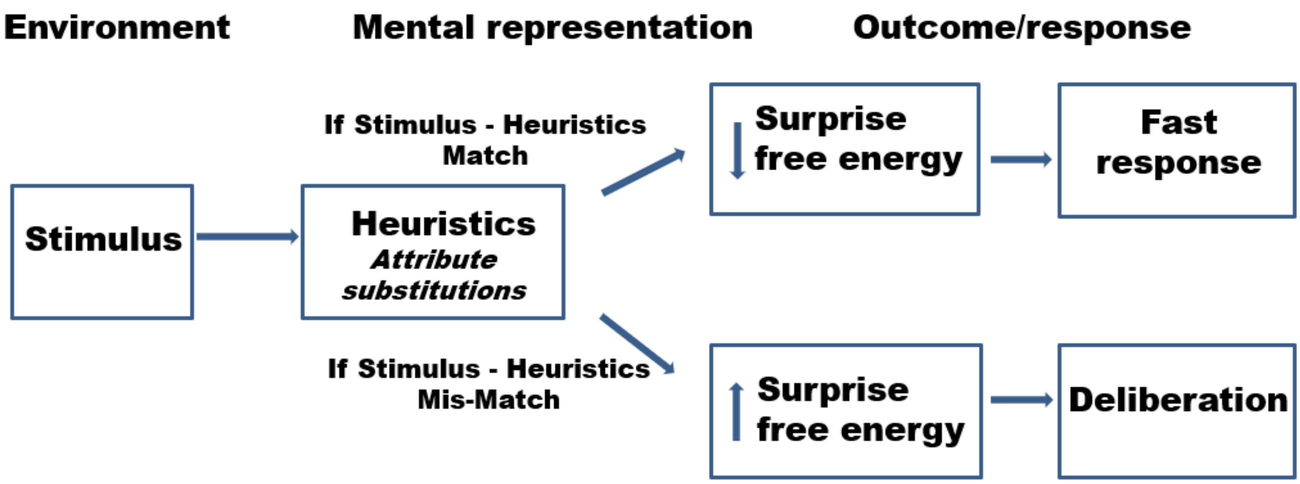

Figure 1. Schematic of fast and slow thinking. The figure outlines the consequences of events that initiate deliberation in relation to free-energy principle. Environmental stimuli that match heuristics induce low surprise and free energy – and entail fast behavioral responses. Conversely, novel stimuli that do not match existing heuristics cause high surprise and free energy – and induce the process of slow deliberative thinking – in order to ultimately reduce (expected) free energy in the future.

most likely to generate a stable representation, or template, as proposed by the Seeking system model [17] according to which environmental stimuli will be coded, remembered, learned, and assigned a mental representation. This Seeking system model further suggests that the emotional experience associated with a particular stimulus will be assigned a valence of emotional arousal, thus creating a "value system" that will in turn provide context and guide future actions.

Similarly, stimuli related to interpersonal interactions will generate internal representations or templates for various types of human behaviors that can in turn be quickly identified during social encounters. In other words, these templates are generated based on heuristics; meaning that complex external stimuli will be "simplified" thus making them appropriate to engage quick responding. In many instances, this process will result in adequate, if not optimal, behavioral responses. On a neurobiological level, any interpersonal encounter will activate a set of neuronal circuits. Firstly, one set of networks will activate to retrieve internal representations relevant to the stimulus. A set of networks will activate in parallel in order to generate appropriate responding. These networks will activate in order to retrieve information from the most relevant past experiences that corresponds to the perceivable features of the current interaction, which includes emotional experience as well as observable features. When the most relevant past experience is identified it will also retrieve information about past outcomes linked to that particular experience. This information is then used to create heuristic template for a behavioral response and expectations for the outcome of the current encounter.

It is this pair of networks activating in parallel that are hypothesized to generate a fast type of responding to a particular interaction. When the expected and actual outcomes match, the competition between these parallel networks will be resolved. However, since heuristic templates carry intrinsic biases and disregard stimulus' complexity, in some instances there will be a discrepancy between the expected outcome and the resulting outcome of a response. Such discrepancy, or "conflict," will trigger slow deliberative thinking that will account for these "conflicts" and will initiate a series of problem solving iterations that will entertain possible outcomes in one's mind. In instances when the expected outcome and the current outcome do not match, a person will attempt to revise his response by playing out alternative responses, generating a series of dyads in his mind without bringing these into action until an optimal match between the activation of the parallel networks is achieved; on a psychological level this might manifest as a decision to actively respond when one has devised an optimal plan for response. It is further hypothesized that the activation of these sets of parallel network underpins deliberative responding. Deliberation further increases the repertoire of possible responses and thus leads to a greater range of behavioral choices. We will refer to this model as the Dyadic Brain (Figure 2).

Clearly, any discrepancy between the expected and actual outcome is itself an anticipated or contemplated 'discrepancy'; because the actual outcome is not observable, until one commits to a particular course of action and acts. This 'discrepancy' is therefore an 'expected discrepancy' that, mathematically, corresponds to an expected surprise or uncertainty (*i.e.*, entropy). In other words, although we cannot, by definition, be surprised by outcomes in the future, we can be uncertain about outcomes under different courses of action and select those actions that resolve the greatest uncertainty – particularly in relation to preferred outcomes.

Therefore the term Dyadic Brain refers to a dyad of neuronal systems that activate in relation to a discrepancy between expected and actual outcomes in relation to complex social interactions. The premise here is that these neuronal networks will activate in concert as one set of networks will activate in relation to an environmental stimulus and another set of networks will process

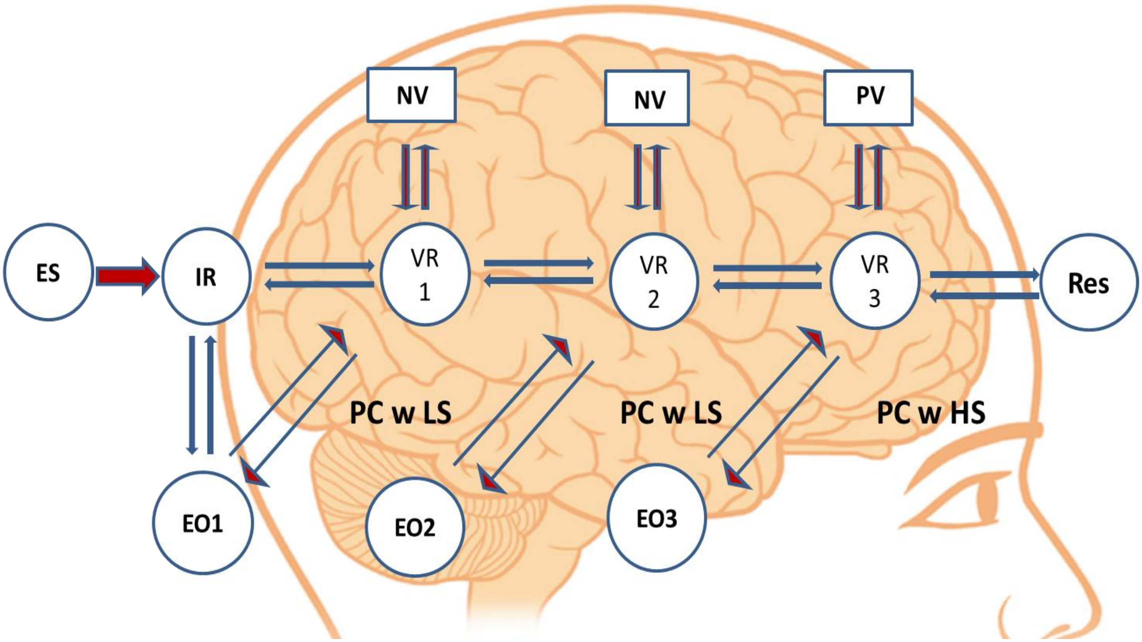

Figure 2. Schematic of deliberative thinking. A novel stimulus causes simultaneous activation of internal templates called parallel activation networks. After detected discrepancy between an environmental stimulus (ES) and internal representations (IR – *e.g.*, attribute substitutions) multiple virtual responses (VR) are generated and – through inferential processes – an optimal behavioral response is selected. Predictive coding (PC) is used to ascertain the compatibility between the initial observation *e.g.,* ES from the environment and VR. If the VR is assigned a negative emotional valence (NV – *i.e.*, a high expected free energy) and if parallel activation networks show low synchrony (LS) the process is repeated with the generation of more VR against newly created expected outcomes (EO). This iterative process proceeds until parallel activation networks obtain high synchrony (HS), which signifies that the response selection closely approximates an optimal response (Res). This optimal response is assigned a positive emotional valence (PV – *i.e.*, a low expected free energy) and thus selects an internal representation (of a policy) that will be utilized for future action.

information related to the development of a virtual response that is not accompanied by a physical action until a particular plan for action is reached.

For these processes to occur in the described manner it is necessary for the system to determine the probability for optimal outcome associated with each individual "plan of action" before the action is executed. This is in turn related to the principle of maximum mutual information, which refers to maximizing the mutual information between external or environmental states and a system's internal states. In this sense, the human brain will have high mutual information with its external milieu by virtue of having higher entropy[3], which can be expressed as the entropy of sensory impressions minus the conditional entropy of those sensations (S) conditioned upon internal states (Int).

$$\mathrm{I}(S,Int)=\mathrm{H}(S)-\mathrm{H}(S \mid Int) \tag{2}$$

It follows that reduction of uncertainty about a possible outcome is linked to knowing a system's internal states. Therefore a high mutual information is achieved when the internal states provide a good resolution of uncertainty about environment that is richly structured and complex (*i.e.*, $H(S)$ has a high entropy). Crucially, the time average of variational free energy is the entropy of the sensations $H(S)=<-\log R(S)>=F$. This can always be decomposed into complexity minus accuracy.

$$\begin{aligned} <-\log P(S)> &= D\lfloor P(Int \mid S) \| P(Int) \rfloor - <\log P(S \mid Int)> \\ &= <-\log P(S \mid Int)+\log P(Int \mid S)-\log P(Int)> \\ &= <-\log P(S,Int)+\log P(Int \mid S)> \\ &= <-\log P(S)> = <F> = H(S) \end{aligned} \tag{3}$$

In the above equation $P(S)$ denotes the probability of some (*e.g.,* sensory) state S, while $P(Int \mid S)$ corresponds to the conditional probability of some other (*e.g.,* internal) state given S. The term $D\lfloor P(Int \mid S) \| P(Int) \rfloor$ denotes the (Kullback-Leibler) divergence between two probability distributions – and is a measure of their overlap. The brackets < > denote expectation or average. Therefore, $<-\log P(S)>$ corresponds to the expected self-information (*i.e.,* entropy) because the negative log probability of an event is self-information, surprisal or surprise.

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[3] The term *entropy* refers to the number of potential states within a system [18], and therefore indicates the quantity of uncertainty and disorder within that system [19]. Mathematically, entropy is the expected surprise or self-information of the system generating outcomes or observations. Hirsch et al. proposed an inverse relationship between entropy and the potential of a biological system to successfully adapt and perform the work of transforming current states into desired states [20]. In our treatment, we associate uncertainty (*i.e.*, entropy) with expected surprise. This means that, by definition, acting to resolve uncertainty is the same as acting to avoid expected prediction errors.

In other words, the decision to choose among response options for a conflict that was not resolved by a fast response should *a priori* lean towards a plan of action that would model a rich and high entropy world, whilst doing so in the simplest possible way. We suggest that this objective is achieved by the functions of networks that activate in parallel to process simultaneously information related to the features of the environmental stimulus and sort through possible behavioral responses to choose the one that would provide maximal free energy reduction, expected when pursuing that response.

For the purpose of the current discussion it is crucial to establish if both fast and deliberative responding relate to FEP in similar versus distinct ways. Fast responding seems designed to facilitate interactions that are sufficiently efficacious without the demand of extra resources. In that sense fast responding may facilitate quick resolution of any given interaction thus minimizing surprise.

Detecting conflict after a fast response has failed to resolve any particular interaction is also an indication that the information available for the purpose of fast responding was insufficient and that additional information is needed to resolve uncertainty or epistemic conflict. In that sense the emergence of parallel activation networks may be seen as necessary in order to access such additional information. Therefore, the relations between deliberative responding and FEP are complex. As discussed above, the dyad between the mental representation of an environmental stimulus and the mental representation of responding without action engages different brain neural circuits that activate with the purpose of resolving a cognitive conflict – therefore the resolution of conflict without action will serve the purpose of decreasing the free energy that emerges in the process of deliberation. When, however, a decision to act is reached and physical action ensues, the result of this action will be the reduction of free energy that is underwritten by uncertainty reducing epistemic foraging.

In accordance with the FEP, the ultimate result of this complex deliberative process will be a plan of action that will influence the environment on the one hand and on the other will generate new internal representations that are more informed by selecting actions with epistemic affordance. These processes will create a more diverse armamentarium that will in turn increase the probability of adaptive outcomes, thereby reducing both prediction error and the likelihood of future surprise. One may further suggest that slow deliberative thinking has developed as an evolutionarily advantageous mechanism to compensate for the insufficiencies introduced by quick responding, which can be mitigated by generating action repertoires that will minimize free energy in the future (*i.e.*, expected free energy or uncertainty).

4. Evidence to support the model

What is known from the field of neuroscience that may suggest that such a model could have biological substrates? First, our proposition is analogous to the concept of mirror neurons, which are seen by some as essential to the human experience of empathy, emotional and physical attunement, and the ability to learn by mimicking, repetition, and “virtual learning.” Mirror neurons have been identified in animals and possibly in humans. These are neurons that are located in proximity to other cortical neurons [21-23], and are hypothesized to activate when an action is observed or contemplated in contrast to regular neurons that activate only if actions are carried out [24, 25]. The point here is that the brain has the capacity for neural activation in direct response to stimulus registration and also for neural activation for potential action. This pattern of brain activation may extend beyond individual neurons and may occur at the level of neural ensembles and hierarchical networks.

Another brain function that has been extensively studied and might be linked to the above proposed model is the synchrony between the oscillation frequencies that accompany neuronal activation. We further suggest that the activation in the different sets of neurocircuits will occur in different frequencies. For instance, it is accepted that prediction error estimation is associated with activation in particular neuronal circuits (supra-granular layer of the cortex) that generate forward signaling in fast gamma rhythms [26]. The forward signaling of the prediction error will generate feedback from infra-granular layers (also known as predictive coding) that are thought to engage slower beta rhythms, which in turn will suppress the fast gamma rhythms. This basic scheme can be used as a foundation to further elaborate on the proposed model for deliberative thinking.

For instance, as deliberative thinking requires retrieval of relevant memory information from past knowledge and experiences it will need to engage separate brain regions and long-range networks. In turn, it has been shown that slow brain rhythms (beta and theta) are capable of propagating and synchronizing networks across brain regions including cortical and subcortical structures [27]. In addition, cognitive processes that are linked to deliberation (short and long term memory formation and retrieval) have been linked to gamma-theta coupling [28]. Thus it seems logical to suggest that identifying conflicts between stimuli and fast response outcomes will generate a representation that will continue to reactivate until a mental solution is reached. Such reactivation will occur in the fast gamma rhythms [29-31] and these will couple with slower theta rhythms thus ensuring long-range activations that will access relevant prior knowledge (*e.g.*, memories). It is here speculated that when activations related to processing information from external stimuli and activations due to the internal representations are closely matched, the corresponding psychological experience may be related to something like “making sense of the stimulus.” In contrast, when any stimulus generates neuronal activation in one particular system that is poorly synchronized with the activation of the parallel “response” system, this may entail the development of ongoing re-entry activation loops that will continue to process information in parallel but will not synchronize. When the processes continue to reactivate this will reach a point of finding a solution with the highest probability for optimal outcome and action selection can take place. Figure 2 illustrates this iterative process. It is suggested that the registration of a stimulus may activate in high frequency whereas the development of mental response without action might be processed in low frequencies. As long as this discrepancy is maintained it may correspond to the psychological experience of anxiety, which is well known to accompany states of uncertainty and ambivalence. In turn, the successful smoothing (*i.e.*, slowing) of high frequencies may be experienced as diminished anxiety – also well known to occur when a person is able to "make sense" of a particular conflict.

We will also consider some phenomena that may provide indirect support of our hypothesis. First, neuroscience research on the neurochemistry of working memory has described activation currents that create distinct neuronal "states" [32]. These states are dependent on the activity of different dopamine receptors. For instance, one such state designated as "state 1" is linked to the activation of the intra-synaptic dopamine 2 receptors. Another state, defined as "state 2" is linked to the activation of the extra-synaptic dopamine 1 receptors. State 1 is described as a condition in which "networks exhibit less stimulus-dependent tuning because many items are represented nearly simultaneously but none are represented particularly strongly." Also "State 1 may be important in situations requiring response flexibility, during which many options for action must be held in memory and compared." In short these suggest that the brain is capable of creating functional states that facilitate the simultaneous processing of many representations so that each representation may be linked to a separate stimulus or alternatively that one stimulus may generate many parallel representations. This is analogous to the proposed states of parallel activation of neuronal systems whereby different responses are "deliberated" without any accompanying physical action.

Human functional neuroimaging studies comparing time courses of inter-subject neural responses, measured by inter-subject correlation analysis, have shown substantially correlated responses in similar brain regions among different individuals attending to the same narratives, demonstrating coupling between brain regions of independent listeners. These studies also showed that production of narratives is not localized to the left hemisphere but recruits bilateral networks, overlapping extensively with the comprehension system. Moreover, direct comparison between the neural activity time courses during production and comprehension of the same narrative pointed to brain areas coupled across the speaker's and listener's brains during production and comprehension of the same narrative [33]. These studies demonstrate widespread bilateral coupling between production- and comprehension-related processing within both linguistic and nonlinguistic brain areas, exposing the surprising extent of shared processes across these two systems. Thus, generating and receiving representations through language seems to engage a much wider range of networks, even extending beyond the neuroanatomical centers for speech production and comprehension [34]. These findings are relevant to the idea that deliberation will involve communications between wide spread long-range networks that extend beyond specific neuroanatomical structures.

Studies in "prospective" memory may also support the proposed function of mirror activation systems. Prospective memories refer to tasks that one keeps in mind for periods of time that last for hours and days but do not consolidate into permanent memories [35]. These processes seem to engage particular brain regions as the rostral PFC, which has been identified as subserving a system linked to stimulus-oriented and stimulus-independent thinking and responding. This cognitive control function and its product are hypothesized to apply to a wide range of situations linked to competent human behavior in everyday life, such as "watchfulness" (*i.e.*, remembering to carry out intended actions after a time delay). In other words, these are situations that require one to be particularly alert to the environment, to deliberately concentrate on one's thoughts, or that involve conscious switching of responses. One aspect that is particularly relevant to the current discussion includes tasks that a person has to keep in mind for as long as the task remains unresolved and until it is completed or one "gives up." A straightforward example is monitoring a metered parking space. One must constantly reactivate the task (*i.e.*, track the time) and allow time to either reload the meter or to drive away (and thus resolve the task). Similar to the above propositions, multiple tasks appear to be reactivated in one's mind, not unlike the mechanism of reactivation of cognitive conflicts that initiate deliberation.

5. Theoretical implications

Here we will consider examples demonstrating the possible theoretical and clinical relevance of the proposed model. Some of these purportedly apply to more general neurocognitive processes. First, our model supports the notion that memories of complex interactions are not "remembered" per se but are rather reconstructed from individual details similar to the way one assembles different structures using the same set of Lego blocks. Further, complex memories are unlikely to be "remembered" in all of their complexity but are rather assembled and reassembled with each recall, an idea already suggested from basic research [36-38]. In turn, they will be influenced and modified as the narratives about any specific events may change over time. Such fluid features of memory are relevant to therapeutic techniques in treating traumatic memories, such as reframing memories in order to modulate the physiological and emotional responses coupled with such memories.

Second, this model accounts for some of the unique features of deliberation. Deliberation operates through processes that hold opposing concepts (*e.g.,* dialectics) in consciousness which are mentally manipulated for extended periods of time before a final decision for action is reached. As discussed above it is possible that recurrent iterative reactivations of the initial "problem" or "question" will trigger activations in at least two independent networks (*e.g.,* parallel activations) each representing one side of the dialectic. "Holding" the dialectics in one's mind may be underpinned by reactivations in neuronal networks that will activate in high frequencies. Those high frequency activations will eventually be "smoothed" in the process of iterations to produce the optimal frequency synchrony. Psychologically this will translate into choosing the "best possible" behavioral response.

We can also consider the relevance of the proposed model to particular types of human interactions that emerge when a person seeks social support in order to manage complex problems or modulate behaviors. Such collaborative interactions may be clinical, such as psychotherapy; or advisory, such as mentoring. It is beyond the scope of this paper to explain complex constructs of psychotherapy and therapeutic action. However, we will selectively address one particular phenomenon from psychotherapeutic practice that we think is relevant to the current topic. We will consider clinical interventions that seem related to the idea that the brain maintains parallel systems that activate in response to a particular stimulus and interact in order to resolve a conflict (and minimize free energy).

In the clinical context of psychotherapy, patients develop an understanding of their minds at work and the unconscious, internal templates that contribute to their emotional responses and behaviors. Relevant to the topic of this paper, such understanding develops within the interactions between patient and therapist. We propose that as patient and therapist interact, therapeutic processes may resemble the parallel activation systems described above. Here we can examine a clinical example of the interaction between the minds of patient and therapist when the patient reports a dream and wonders about its meaning. A traditional approach by the therapist would be to assume that the dream conveys a covert message about an already formed idea in the patient's mind and therefore the therapeutic intervention will be designed to help the patient gain insight about this hidden but already existing (in the patient's unconscious) meaning. However, a more contemporary therapeutic approach is based on the notion that the meaning of the dream is not extant and thus waiting to be discovered. Instead, therapeutic intervention will aim to help the patient to recognize the possible meanings of the dream in a collaboration between patient and therapist. A useful analogy is a situation when one is looking at a figure in a fog. While it is evident that the figure represents a person, the details about the person are not obvious and can be a matter of interpretation.

As patient and therapist work together to understand possible meanings of the dream, the processes underlying their interaction may resemble the above proposed parallel activation systems. For the patient, these parallel systems will include an internal representation (*i.e.*, the dream) and the external stimuli (*i.e.*, the therapist's suggestions about the dream). For the therapist the parallel systems will consist of the external stimuli (*i.e.*, the patient's report of the dream) and the internal representations (*i.e.*, the therapist's responses to the dream). Resolving the conflict "what is the meaning of the dream" will be a mutual achievement involving both patient and therapist. For instance they would agree that the figure in the fog is a young woman with blond hair wearing a blue dress.

Under typical conditions, the mind engages in biased perception and selective remembering in order to reduce free energy, resulting in fast responding. Such homeostatic mechanisms fortify and maintain internal templates but often result in the negative consequences of inflexible and maladaptive responding. Therapeutic interventions interrupt fast thinking and responding and draw attention to the operation of such processes. Disruption of the patterned response introduces surprise and thus initiates deliberation. The processes described bear similarities with the correlations of brain activity described by Hasson *et al* [34] and its outcome will diminish uncertainties about the meaning of behaviors and emotional responses, hence minimizing free energy.

In other types of relationships, such as between mentors and mentees, interpersonal processes provide an opportunity for self-discovery and development, as one both learns didactically from the teachings of the mentor and as one identifies with idealized aspects of the mentor's or teacher's attributes that reflect aspects of the self. Subsequently, internalization of new qualities occurs and contributes to change and development in the protégé [39]. Engagement in mentoring activities may be linked to the unique human ability to learn through imitation and to adopt successful strategies already used by other humans. Existing research suggests that humans heavily rely on learning through imitation and "borrowing" of behavioral strategies used by others instead of developing new problem solving strategies [40]. In these particular types of relationships, students or mentors seek guidance due to being uncertain about proper sequence of procedures, the need to organize and systematize great amounts of information and to "make sense" of it. The model provided by the teacher/mentor resolves uncertainties on the part of the student/mentee. This ability to receive guidance and emulate behaviors in order to adapt one's own behavior may also be linked to the emergence of the proposed parallel activation networks. With FEP in mind it is easy to see how such learning preferences may have evolved. Adopting effective behavioral responses from others will eliminate the need for the more costly (in terms of energy) process of finding a solution *via* trial and error approaches.

Another type of interaction which is relevant to the concept of parallel activation networks is collaboration. Collaborations include various creative, productive, and supportive interactions. Regardless of their forms, collaborations differ from short-lived interactions as they require prospective planning, consideration of alternatives, and adjustment of planned actions in accordance to available feedback. All collaborations will involve deliberation and, by extension, deliberation is an essential component of the ability to collaborate. Therefore the processes of reactivation and reiteration of widespread neurocircuits may be seen as the biological basis for the development of skills that facilitate continuous, as opposed to short-lived, communications resulting in collaboration. Moreover, collaborations require these most complex of cognitive processes in order to find solutions to complex problems. When more than one mind is working on resolving a problem, the deliberations can be "shared" among participating individuals since each individual mind will approach the problems differently. Therefore it is economically advantageous for the complex and laborious process of deliberation to be shared among individuals.

6. Conclusion

This paper outlines a neurobiological model of brain information processing that borrows from the mirror neuron hypothesis and generalizes it into a so called "dyadic model." This model suggests that a neuronal network formed in response to environmental input is paralleled by at least one and possibly many other networks that activate intrinsically and represent "virtual responses" (*i.e.*, contemplation without action) to a situation that demands a behavioral response. This model expands the concept of active inference, applicable to explorative behaviors, to the uniquely human case of contemplation without action and thus accounts for how the brain generates a multiplicity of potential behavioral responses and discusses the mechanisms by which it chooses the one that seems most appropriate. This model also explains the uncanny ability of humans to socialize and collaborate, including preserving and accessing information on levels beyond individual memories. Lastly, the model implies that the therapeutic processes of counseling and psychotherapy can modulate self-awareness, understanding of context and enhance decision making *via* influences on an evolutionarily developed biological system that constitutes the basis for optimizing behavioral responses and performance.

Conflict of Interest

All authors declare that there are no conflicts of interest in this paper.

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