cycling seasons. If the chimpanzee anticipated the arrival of human visitors in the spring, it could have amassed a large store of stones. Instead, the arrival of visitors at the zoo might have served as a contextual stimulus for storing rocks to be thrown at people (semantic memory) without the anticipation of doing so at any specific time in the future.

We re-emphasize that a crucial comparative test of future planning in animals should include a choice in which one response will prepare the animal to obtain a reward at an earlier time and the other response will prepare the animal to obtain a reward at a later time. If temporal organization of future plans is crucial to animals, as it is to humans, the animal should choose the response that prepares for the appropriate future time.

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1364-6613/$ – see front matter
doi:10.1016/j.tics.2009.11.009 Available online 22 December 2009

Letters

Some puzzles relating to the free-energy principle: comment on Friston

Chris Thornton

COGS/Informatics, University of Sussex, Brighton, UK, BN1 9QH

In Friston's recent article [1], the structure of an agent's world is taken to be represented by a 'conditional density', a probabilistic mapping from 'causes' to sensory stimulation. Friston argues that the brain can arrive at an approximation of this mapping by minimizing 'free energy', which is a function of sensory stimulation and brain states. A generative model of causal structure in the environment is then obtained, on which basis the agent is able to infer the 'causes of sensory samples' [1]. What is unclear is how this mechanism would function when sensory samples are ambiguous. In general, there are multiple interpretations for the causes of any sensory data, and these cannot be resolved on the basis of inspecting the data alone [2].

For any sense data, there will also generally be causes at multiple levels of description, with causes at one level of description being embedded in causes at higher levels. Sensory stimulation is the result not of distinct causes, but of causal structure. How would a mechanism that acts to infer causes measure up to the task of inferring causal structure?

Friston asserts that almost 'any adaptive change in the brain' can be viewed as resulting from minimization of free energy [1]. On the face of it, no particular stand is taken on the emergence of the structures that mediate minimization. However, by looking at the definition of free energy [3], one finds a significant part being played by the variable ϑ. It is values of ϑ that encapsulate the representation of 'environmental causes' by the brain [3]. The range of ϑ then dictates the gross structural form of any representation acquired. With the framework providing no principle for deciding this range, the representation by the brain of the conditional density is inevitably a 'slightly mysterious construct' [4].

The expectation might be that ϑ will be fixed through instantiation of fortuitous 'matches' between internal and external structures. 'Those systems that can match their internal structure to the causal structure of the environment will attain a tighter bound.' [3]. However, there is a problem of circularity here: agents are posited to be able to form an internal structure matching the environment just in case they already have it. Neither it is clear whether this is intended to be the 'mechanism' for fixing ϑ. If there is no principle deciding this crucial designator of representational capacity, then one can only assume that it is fixed at random.

It seems right for Friston to emphasize that the entropic basis of surprise reveals a deep connection between processes of knowledge, behavior and life. However, this idea has been in common currency for some time (e.g. Refs [5,6]) and it is unclear how introduction of the 'free energy' concept, specifically, adds any explanatory content. Free energy is taken to be a 'good proxy' for surprise: surely it is minimization of 'surprise' that is explanatorily salient. The inability of the present formulation to address the issue of structure emergence also

Corresponding author: Thornton, C. (c.thornton@sussex.ac.uk).

poses difficulties with regard to the specification of ϑ ranges, resolution of sensory ambiguity and inference of causal structure.

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Letters Response

Some free-energy puzzles resolved: response to Thornton

Karl Friston

The Wellcome Trust Centre for Neuroimaging, University College London, Queen Square, London, WC1N 3BG, UK

Chris Thornton [1] poses some simple but key questions about the free-energy principle reviewed in [2]. These puzzles have simple and clear answers:

Puzzle: "A generative model of causal structure in the environment is [then] obtained, on which basis the agent is able to infer the 'causes of sensory samples' [ibid. p. 294]. What is unclear is how this mechanism would function where sensory samples are ambiguous" [1].

Answer: One of the main motivations for the free-energy principle is its appeal to [approximate] Bayesian inference where ambiguities are resolved by priors [3]. Priors are mandated by the (ill-posed) problems created by ambiguity and empirical priors are an integral part of hierarchical inference [2,Box 3]. This is not theoretical hand waving; in biophysics, the free-energy formulation is used routinely to solve difficult ill-posed inverse problems (e.g. [4]).

Puzzle: "On the face of it, no particular stand is taken on emergence of the structures that mediate minimization. But looking at the definition of free-energy, we find a significant role being played by the variable ϑ. It is values of this variable that encapsulate the brain's representation of 'environmental causes'" [1].

Answer: The representations are not environmental causes ϑ but the sufficient statistics μ of the brain's recognition density $q(\vartheta;\mu)$; these include synaptic activity and

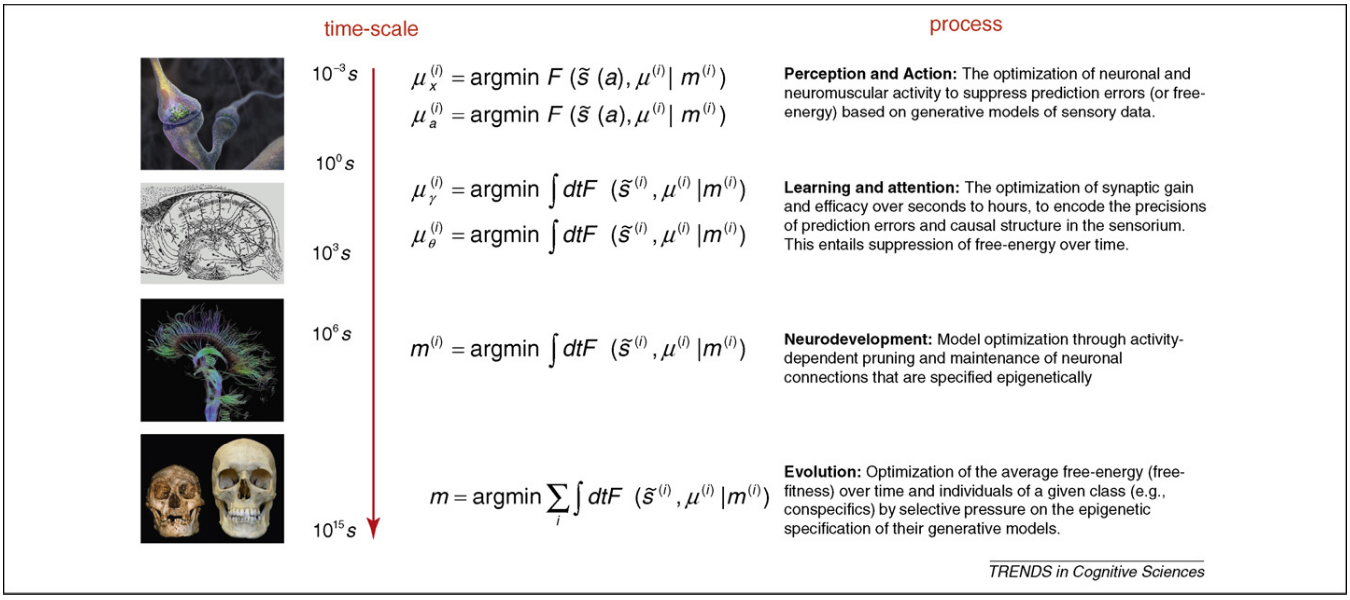

Figure 1. This schematic summarises the various timescales over which minimization of free-energy can be considered as optimizing the state (perception), configuration (action), connectivity (learning and attention), anatomy (neurodevelopment) and phenotype (evolution) of an agent. Here, $F(\tilde{s}, \mu^{(i)}|m^{(i)})$ is the free-energy of the sensory data (and its temporal derivatives - $\tilde{s}(a)$) and states of an agent $m^{(i)} \in m$ that belongs to class m. The states $\mu \supset \mu_x, \mu_\gamma, \mu_\theta$ correspond to synaptic activity, gain and strength, respectively, whereas a action determines the sampling of sensory data.

Corresponding author: Friston, K. (k.friston@fil.ion.ucl.ac.uk).