Notes on Pezzulo and Friston (2015)

> *Our aim is to offer an integrative perspective by contextualizing classical formulations of adaptive behaviour within the Active Inference framework, which extends predictive coding from the domain of perception to cover action (Friston et al., 2009).*

Glossary: Direct (homoeostasis) or indirect (allostasis) control of bodily states.

Purpose: Tie together Active Inference (AI) and assosiative theories of learning (AoL).

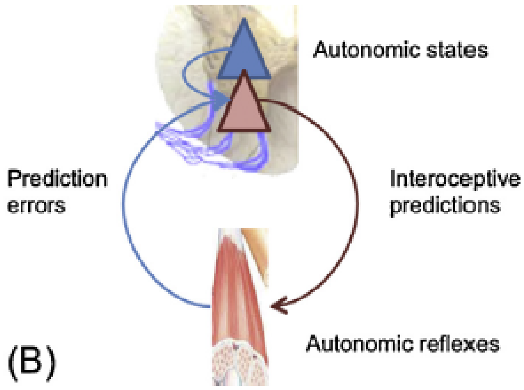
AoL relies on multiple forms of control: **Pavlovian:** Classical conditioning. Outcome (food) triggers unconditioned reflex (salivating) paired with a neutral stimulus (sound). After conditioning, the neutral stimulus now triggers the unconditioned relfex. **Instrumental:** Maximises some goal or value function. Behaviour is only goal-directed if and only if it is sensitive to reward contingencies. This gives flexibility and context sensitivity, but the animal must learn causal effects (model). Forward associations learns action/outcome pairs while backwards associations learns outcome/action pairs.[1] Because action to outcome is many-to-many it poses a difficult inverse problem, such as tree searches (MDP).[2] *Habits* are a simple kind of instrumental control.

Homeostatic states and allostatic processes requires: **Interoceptive signals:** Signals homeostatic levels (blood glucose). Autonomic regulation control bodily processes, which is not sufficient to keep homeostasis. To do this they must acquire an adequate behavioural repertoire and learn to select from currently available actions or sequences of action (policies). This is the main focus of associative learning theories in psychology and biology. Contemporary AoL assumes that cooperation and competition between several behavioural controllers "Pavlovian" and "instrumental" (goal-directed and habitual).

Behavioural reflexes: Calls on a limited set of unconditioned responses. **Pavlovian (classical) conditioning:** The process by which an unconditioned stimulus (say, food), that triggers an unconditioned reflex (say, salivation), is repeatedly paired with a neutral stimulus (say, a bell).

Active Inference assumes that the brain is a statistical organ that learns a generative model of its environment.[3] Extends predictive coding (PE) to action and perception. In PE perception is inference and the aim is to minimise PE between empirical priors (representations or expectations that privide top-down predictions in hierarchical models) and current sensations.[4] PE of every level of the hierarchy are minimised by adjusting (empirical) prior expectations. Crucially, Active Inference considers another way to minimize prediction errors; namely, through action.

In the simplst form, *peripheral reflexes* that suppress proprioceptive or interoceptive prediction errors through closed loop control. Descending predictions project to prediction error populations send efferents to neuromuscular junctions. This efferent outflow will cease when the interoceptive or proprioceptive feedback matches the descending prediction associated with arc reflexes and the suppression of proprioceptive prediction errors through action.[5] In addition, the same loop can perform homeostatic regulation through autonomic reflexes instead of costly negative feedback loops.[6]



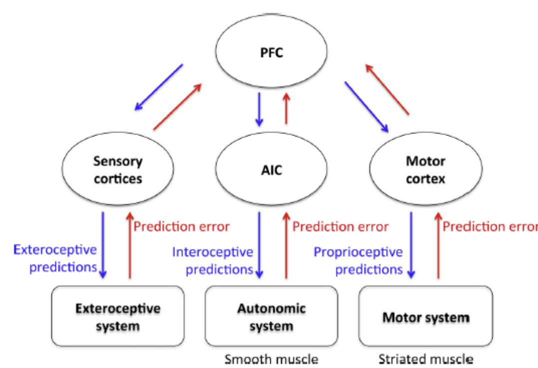
The AI loop shows how interoceptive predictions minimise interoceptive predictions errors and thus assure 'good' levels of autonomic states. This induces a circularity between homeostatic states and autonomic reflexes as one tiggers the other etc. Pavlovs example of this is how salivation (autonomic) facilitates ingestion (homeostatic).

Although autonomic reflexes keep certain homeostatic states within narrow bands, animals must take action to survive. Allostatic control is a complex problem because of temporal correlation between actions and future outcomes, this is the *credit assignment problem*. These kinds of problems are not solved well by closed-loop homeostatic control (of interoceptive prediction errors) because action/outcome are not deterministic. The best way to finesse the *credit assignment problem* is to learn (hierarchical) models of how interoceptive signals are generated. Much like perceptual hierarchies, these interoceptive models predict interoceptive events over different timescales and thus anticipate homeostatic needs.

Suggested solutions to this problem has been: Re-representiong bodily events centrally, via. interoceptive channels[7] or feelings.[8] Authors suggest that the best way to finesse the credit assignment problem is to learn a hierarchical model of how interoceptive models predict interoceptive events over different time scales and thus anticipate homeostatic needs.

Animals react to predictions about their own state - not actual hypoglycaemic sensations. This ability can be supported by generative models of how interoceptive signals change as a function of future behaviour. This is easier if the process you are optimising is periodic, such as eating, sleeping etc. Hormones such as ghrelin, insulin etc. trigger anticipatory responses.[9] Essentially, the animal behaves to avoid anticipated losses rather than react to real losses (good regulator theorem).

Interoceptive and proprioceptive channels in the brain are not directly wired (see fig below). While autonomic reflexes can work with reciprocal message passing, arc reflexes work through higher cortical and subcortical sustems. Not possible to use interoceptive PE to enslave action in the same way as proprioceptive PE produce movement. On slower time scales, higher levels in the hierachy integrate information about predicted homeostatic flux and engage action through decending proprioceptive predictions.



In AI central representations of bodily events are hierarical generative models that describe consequences of multiple (exteroceptive, proprioceptive, and interoceptive) levels. They are generative in the sense that they generate (top-down) expected (sensory) consequences of hidden causes.

These models necessarily entail a sensorimotor- to-interoceptive mapping that encodes associations between sensorimotor and interoceptive events; say, “a burger in my mouth” (a sensorimotor event) generates (and predicts) “more glucose in my blood” (an interoceptive event).

In sum, generative models linking sensorimotor and interoceptive events resolve a key aspect of homeostatic regulation. They enable the use (and suppression) of sensorimotor prediction errors as proxies for (the suppression of) interoceptive prediction errors, which are hard to control at short timescales

For example, I can harness the association between ingesting a burger, the sensation of a full stomach and the (future) restoration of blood glucose levels. These associations mean that the exteroceptive prediction errors (that report the fact that I am not currently eating) can be resolved by acting (eating) to suppress interoceptive prediction errors in the future.

This means that agents control their homeostatic states (target of control problem) by solving a sensimotor problem (e.g. eating). A key difference between AI and AoL is that the former UC responses are stimulus-response mappings and in AI they are encoded by generative models that encode stim-stim assiciations where behaviour minimises intero- or propripceptive PE. In this sense a prediction (e.g. sensing a burger) at high levels of the hierachy become an equilibrium or 'reference-point'. Unconditioned responses also work as a scaffolding of more complex behaviour.

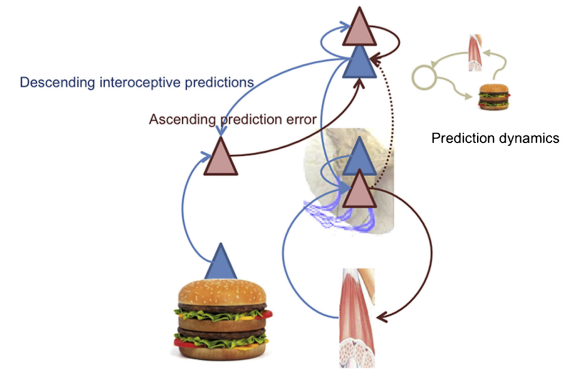


Figure above illustrates unconditioned responses of dynamical control over the equilibrium point of peripheral reflexes that rests on descending peredictions about pro or interoceptive input. Peripheral reflexes are noe contingent (given) top-down predictions that themselves are informed by ascending PE from the gustatory input. PE are red and expectations are blue. In dynamical schemes, these interactions produce an attractor or heteroclinic cycle that models the temporal succession of predicted sensations (here, gustatory and subsequent interoceptive sensations).

AoL describes learning contingencies of action/outcome pairs in terms of multiple behavioural controllers (Pavlovian, goal-directed and habitual). In AI these forms of control are not segregated but work in a hirarical structure (figure above). High levels in hierarchical models contextualize lower level expectations through descending or backward connections, and eventually, at the peripheral level of the hierarchy, nuance motor and autonomic reflexes (which are thus conserved in an evolutionary sense).

How behaviour arises from different processes (control): *Pavlovian responses:* Arises when *descnding* preductions encompass predictive *exteroceptive* cues. Stimulus-stimulus (bell-burger) are instantiated by a high-level representation of a conditione stimulus part of the sequence of expected events. The sound of a bell produces preduction errors that engage top-down predictions of appropriate auditory input. Those inputs themselves predict the emergence of interoceptive sensations (burger) that produce the unconditioned reflex (salavitaing). Descending predictions engage peripheral reflexes – establishing a (vertical) link between the conditioned stimulus and unconditioned response.

References

[1] Hommel et al., 2001; Prinz, 1997) and forward and inverse models of motor control (Wolpert et al., 1998).

[2] Craig, 2010; Damasio and Carvalho, 2013; Gu et al., 2013

[3] Dayan et al., 1995; Friston, 2010; Friston et al., 2009; Helmholtz, 1866)

[4] Gregory, 1980

[5] Feldman and Friston, 2010; Shipp et al., 2013

[6] Pezzulo, 2013; Seth, 2013; Seth et al., 2012)

[7] Craig, 2010

[8] Damasio and Carvalho, 2013

[9] Woods et al., 1970 and Drazen et al., 2006