Prediction, Perception, and Imagination

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The Conclusions (!)

'Predictive Processing' offers a promising neurocomputational account of perception, understanding, and imagination

They all arrive as a kind of 'cognitive package deal' in brains that are constantly trying to **guess** the evolving sensory flow.

This blurs the intuitive boundaries between **perception, imagination, and thought.**

So What Is Predictive Processing?

Core of PP is the **active** use of a **probabilistic generative model**

= an inner organization that has the resources to **construct plausible versions** of the sensory data for itself, using what the system has learnt about the **probabilities of different patterns in the data.**

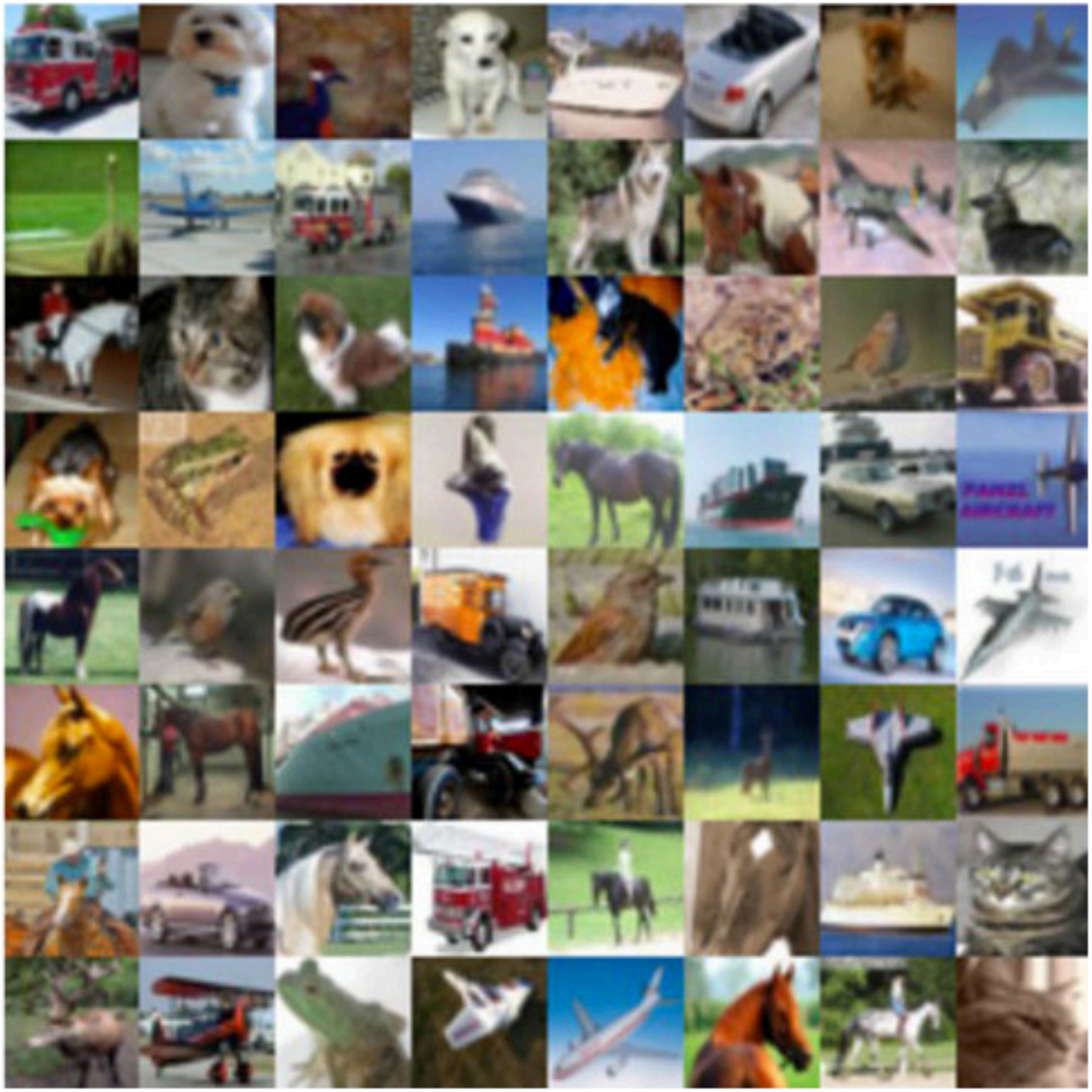
That means working **more like a computer graphics program** than a standard pattern recognizer - generating probable patterns 'from the top-down' rather than via a feed-forward sweep of increasingly complex feature detection.

Example:

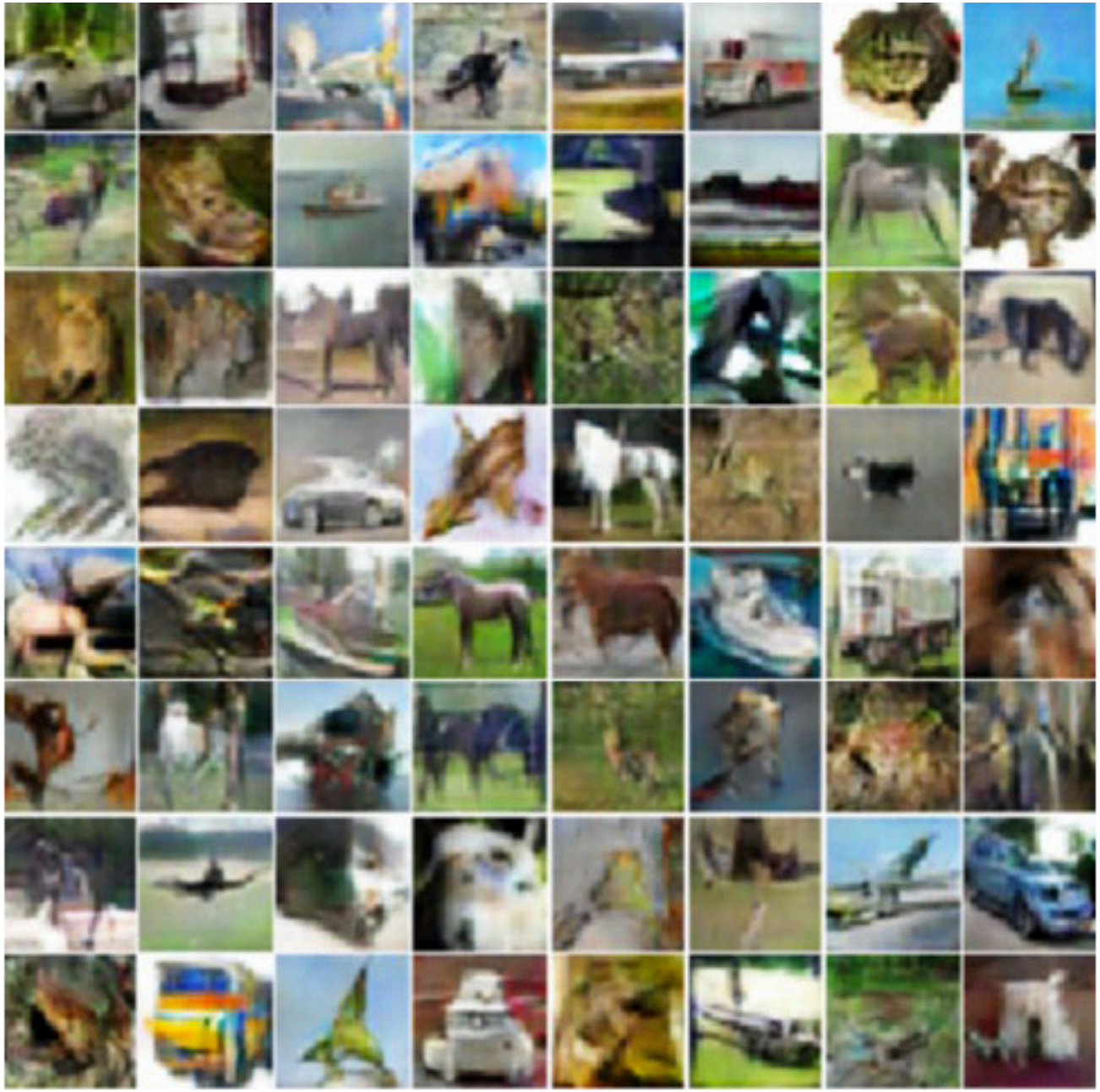
An '**image grammar**' - a (simple, low-dimensional) probabilistic model that can generate plausible images of real-world states of affairs

- can be **learnt** by exposing multi-level neural networks to lots of training images and getting them to **try to generate** similar images for themselves.

To do so, they must learn about the visual patterns characteristic of different kinds of object at different spatial scales.



Real images (CIFAR-10)



Generated images

Same technique can generate **short moving 'hallucinated' videos of scenes** – nice examples at:

http://web.mit.edu/vondrick/tinyvideo/

The trained-up generative model can also take a static image and **hallucinate a plausible future unfolding** of the same scene.

See Vondrick, Pirsiavash, and Torralba (2016)

Vondrick, Pirsiavash, and Torralba (2016) Generating Videos with Scene Dynamics
29th Conference on Neural Information Processing Systems (NIPS 2016) Barcelona, Spain

Crucially, In PP, the trained-up **generation engine** is used for **online perception (recognition)**

The brain **recognizes** what is 'in' the current visual scene by finding the **best way to predict (match)** the current raw sensory evidence using the resources of the probabilistic generative model

The goal is for the cascade of top-down construction (prediction) to match, and thus '**explain away**', the incoming sensory signal up to some level of tolerated noise.

Friston, K. (2005). A theory of cortical responses. *Phil. Trans. R. Soc.* B 360: 815-836.

Lee, T.S., Mumford, D. (2003) Hierarchical Bayesian inference in the visual cortex. *Journal of Optical Society of America, A.* . 20(7): 1434-1448

Rao and Ballard (1999) Predictive coding in the visual cortex: a functional interpretation of some extra-classical receptive-field effects *Nature Neuroscience* 2, 79- 87

This is where you need to make an appreciable **leap of faith.**

If PP is right, the core of cognition and understanding is using that kind of trick, **writ very large and very wide**.

The key thing is:

There's no limit on **what kinds of information, accumulated over many interacting time-scales**, can be used to inform the current **multi-level, multi-area, top-down** active construction of the sensory signal.

Fair game includes:

Information at **many scales** of space and time about the **nature and properties of objects** (Rao and Ballard (1999))

Information about the kind of **affective response** they typically elicit (Barrett and Bar (2009))

Information about and the **kinds of behaviors that you might want to launch** in their presence (Pezzulo et al (2015))

Information about your own **current physiological states and needs** (Seth (2013))

Rao, R and Ballard, D. (1999). Predictive coding in the visual cortex: A functional interpretation of some extra-classical receptive-field effects, *Nature Neuroscience* 2, 1, 79

Barrett, L. F., & Bar, M. (2009). See it with feeling: Affective predictions in the human brain. *Royal Soc Phil Trans* B, 364,1325-1334

Pezzulo, G., Rigoli, F., & Friston, K. (2015). Active Inference, homeostatic regulation and adaptive behavioural control. *Progress in Neurobiology*, *134*, 17–35

Seth, A K (2013) Interoceptive Inference, Emotion, and the Embodied Self *Trends in Cognitive Sciences* 17, no. 11: 565–73.

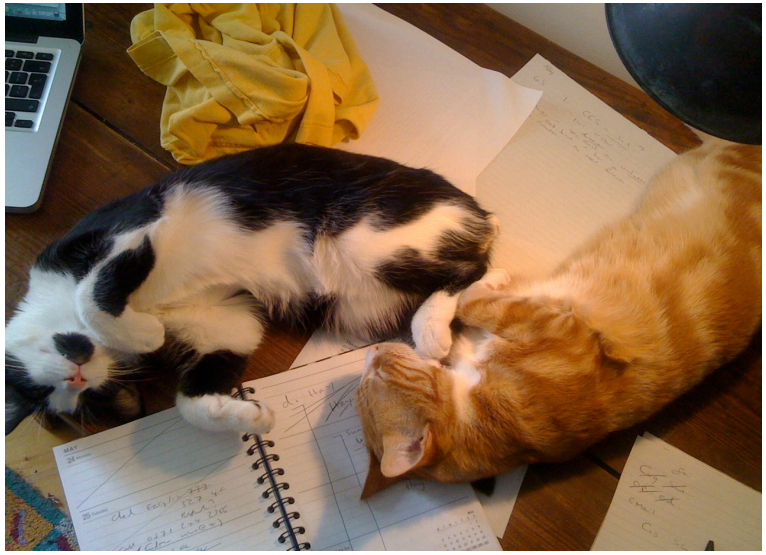
….all of these can **inform and nuance** the PP process of 'top-down construction'…

They must settle into the **coherent whole** that best accounts for (predicts) the current waves of **task-salient sensory information**.

(So we already glimpse how this kind of perception phases seamlessly into understanding…)

Perhaps this is how a **structured, meaningful world** comes into view in perception – we see the world by finding out how to **build** the present sensory signal for ourselves using all manner of stored knowledge –

In this way, we **build our percepts out of predicted 'meanings'**, rather than the other way around.



+ Predictive Coding – a rather specific claim about the way top-down meets bottom-up…

Idea is that moment-by-moment we need only bother about **whatever escaped the predictive net**.

What needs to drive further processing is just the residual difference **(aka the 'prediction error')** between the actual current signal and the predicted one.

PE carries the news!


The Philadelphia Inquirer CITY EDITION

MAN LANDS ON MOON

'Eagle Has Landed,' Astronauts Say

Crater Avoided In Touchdown; 2 Stay in Ship

Tension Highlights Landing

Such a process is **computationally feasible** (there are many small-scale proofs-by-simulation)

For reviews, see Clark (2013) (2016), Hohwy (2013)

And crucially there are increasingly detailed proposals for its **neuronal implementation** (see e.g. Barrett and Simmons (2015), Bastos et al, 2012)

Barrett, L. F., and Simmons, W. K. (2015). Interoceptive predictions in the brain. *Nature Reviews Neuroscience*, 16, 419–429

Bastos AM, Usrey WM, Adams RA, Mangun GR, Fries P, Friston KJ. (2012) Canonical microcircuits for predictive coding. *Neuron* 76:695-71

Clark, A (2013) Whatever Next? Predictive Brains, Situated Agents, and the Future of Cognitive Science *Behavioral and Brain Sciences* 36: 3: p. 181-204

Clark, A (2016) *Surfing Uncertainty: Prediction, Action, and the Embodied Mind* (Oxford University Press, NY)

Hohwy, J (2013) *The Predictive Mind* (Oxford University press, NY)

Summary So Far.

Perception (rich, world-revealing perception) occurs when the downward cortical cascade succeeds at **generating the sensory data for itself** using everything we know about the world

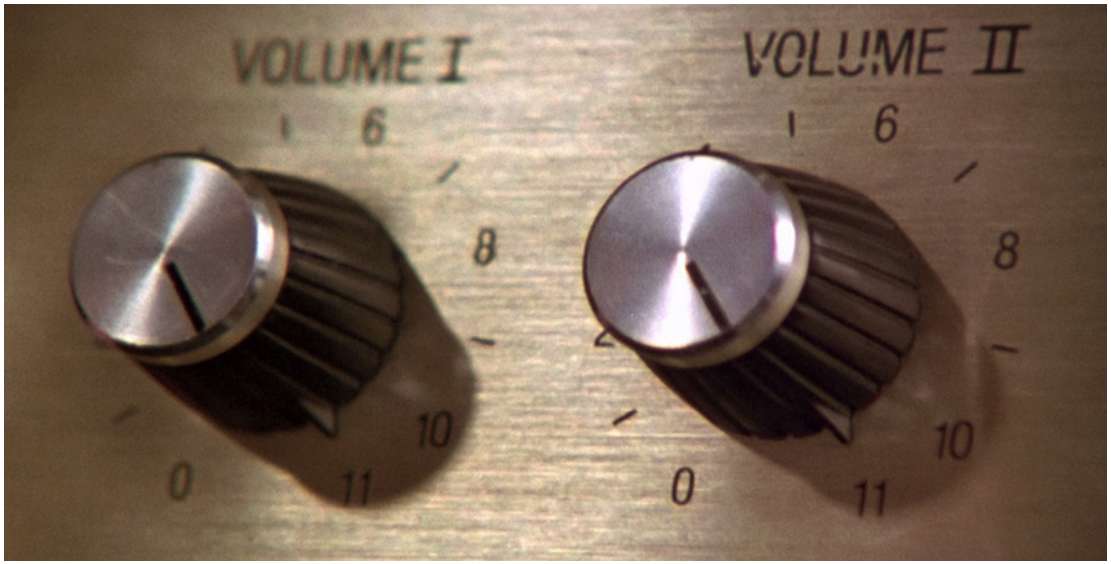
Recalls the slogan (Max Clowes/ Ramesh Jain) that **perception is controlled hallucination.**

You might say : our brains try to guess what's out there, and to the extent that that **guess matches (hence 'explains away') the evolving sensory data**, we perceive the world.

In PP, the whole process is orchestrated and nuanced by **self-estimated sensory uncertainty** ('precision').

This **weights** selected predictions/prediction errors according to how reliable (for task, in context) they are deemed to be.

= the estimated **inverse variance** of the prediction/prediction error



Upshot

These stories make the estimated **precision** of predictions and prediction errors into one of the major players on the cognitive stage

Assign **too much precision** to sensory PE and you won't be able to detect **faint patterns** in a noisy environment

Aside: interesting recent work on possible **disturbances to this balance** in **autism** – e.g. Pellicano and Burr (2012)

Pellicano, E. and Burr, D. (2012) When the world becomes too real: a Bayesian explanation of autistic perception. *Trends Cogn. Sci*. 16, 504–510

Image from Mike Specian, astrophysics

Assign **too little precision to sensory PE** and you will start to **hallucinate patterns** that are not there, just because you strongly expect them

e.g. the Bing Crosby experiments… (Merckelbach and van de Ven (2001))

Merckelbach, H., & van de Ven, V. (2001). Another White Christmas: Fantasy proneness and reports of 'hallucinatory experiences' in undergraduate students. *Journal of Behaviour Therapy and Experimental Psychiatry*, 32, 137–144.

As a way of showing what a huge difference apt top-down prediction can make to perceptual experience, listen to these **clips of sine-wave speech** - degraded replicas of recorded speech that have been stripped of most of the normal speech attributes and acoustics.

The replica preserves only a kind of skeletal outline in which the core (and rather coarse) pattern of dynamic changes in the speech signal is coded as a set of **pure tone whistles** –

sounds kinda like
The Clangers….

Sound clips from Leo Nordwall: https://vimeo.com/leonordwall - and see http://www.mrc-cbu.cam.ac.uk/people/matt-davis/sine-wave-speech/

Or consider hearing a **familiar song** playing on a **poor radio receiver**, or **in the shower**

The familiar song will appear to sound **much clearer** than an unfamiliar one.

But whereas we might have thought of this, within a **simple feed-forward** framework, as some kind of **add-on memory effect**, it now seems more reasonable to think of it as a **genuinely perceptual** one.

The clear-sounding percept for the familiar song, after all, is constructed in **just the same way** as the fuzzy-sounding percept of the unfamiliar one.

It is just that the familiar one invokes a **better set of top-down predictions** (priors, in the Bayesian translation of the story).

Under those conditions – I suggest - the familiar song ***really does*** sound clearer.

It is not that familiarity makes a **fuzzy percept merely seem clearer**

It is not that memory ***later*** does some filling-in affecting, in some backward-looking way, how we **judge** the percept to be

Rather, the **percept itself is altered** by our multi-level expectations

This is not just a philosopher's thought experiment.

Teufel et al (2010) show that predictions of other people's **mental states** influence **how we physically perceive them to be,** affecting our perceptual experience of (e.g.) their **gaze direction in a court-room setting…**

(For many, many more examples of the effects of top-down knowledge upon perception, see work by Gary Lupyan)

Teufel, Fletcher and Davis (2010) "Seeing other minds: attributed mental states influence perception" *Trends in Cognitive Sciences* 14 (2010) 376–382

The Moral

Perceptual experience reflects not the sensory stimulation but the sensory stimulation **relative to ongoing predictions**.

This neatly explains why (for example) **unexpected absences** can seem so **experientially vivid**

If you hear a familiar (or regular) series of notes and one is unexpectedly omitted, **prediction error spikes.**

In PP simulations (Adams et al (2015)), that spike comes **just after a faint 'hallucination'** of the **onset** of the missing item – a note, or a bird chirp…

– like 'half-seeming to just start to see' your recently deceased dog emerge when the door opens in just the right way….

Perhaps this is not simply a **grief-based malfunction**.

Instead, it is just the prediction machine working as it should, constructing experience by **balancing** ingrained expectations against incoming sensory evidence.

Adams R, Stephan K, Brown H, Frith C, and Friston K (2013) The computational anatomy of psychosis. *Front Psychiatry*.30;4:47

Some Attractions (more goodies in the 'cognitive package deal')

1. The PP schema shows why we perceive a structured **external world** and not just 'sense data' or patterns of light and sound.

Our brains must meet the sensory barrage with a top-down cascade of guesses at the **interacting wordly causes** that most probably **generated** the sensory evidence (see Helmholz, Neisser, Gregory…).

Clark, A (2016) *Surfing Uncertainty: Prediction, Action, and the Embodied Mind* (Oxford University Press, NY)

The so-called '**transparency**' **of perceptual experience** (that we seem to **simply see** bananas, cats, and burritos not pixels or any sensory intermediaries) seems to fall quite naturally out of such a process.

2. PP delivers **perception and understanding** at a single stroke

To perceive like that is to guess how the sensory evidence was generated by means of **interacting worldly causes,** and how perceived events are likely to **change and evolve** over time.

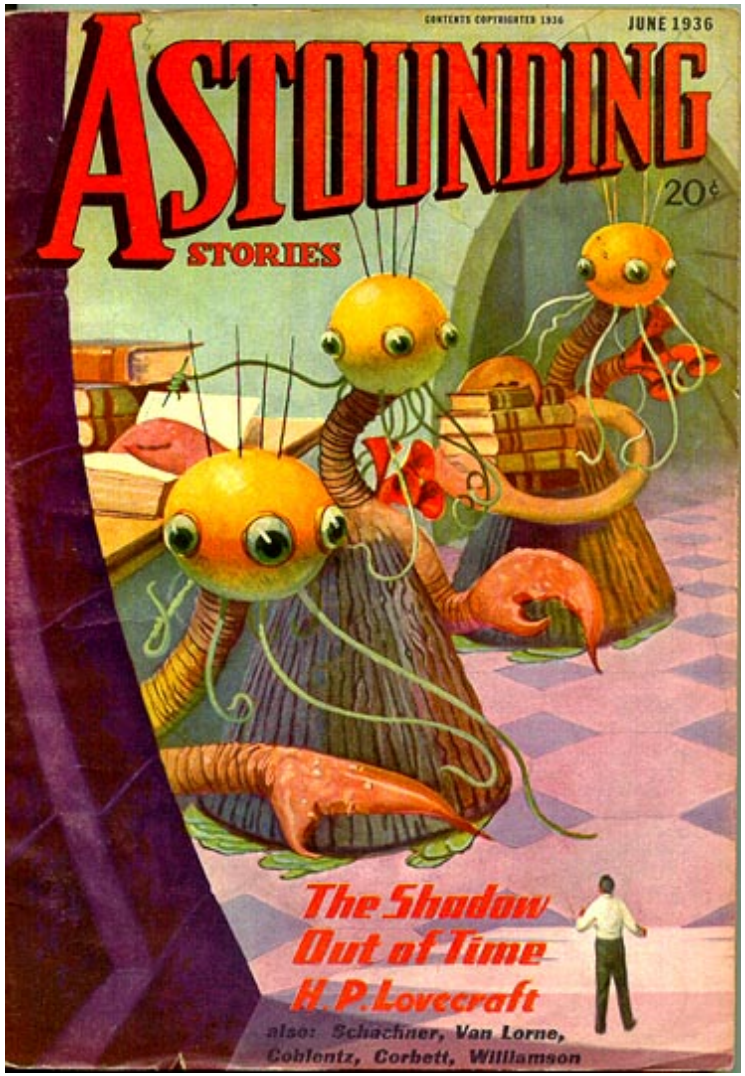
This, surely, is to make deep inroads not just into the explanation of **effective perception** but also into the origins of **meaning and semantics**

= the elusive realm of **'aboutness'** itself.

3. Perception and imagination are co-emergent too.

A crucially important feature of the probabilistic internal models that power these approaches is that they are **generative** in nature.

That means that the perceptual system can be 'run from the top-down' and is capable of **creating 'virtual sensory data'** for itself.

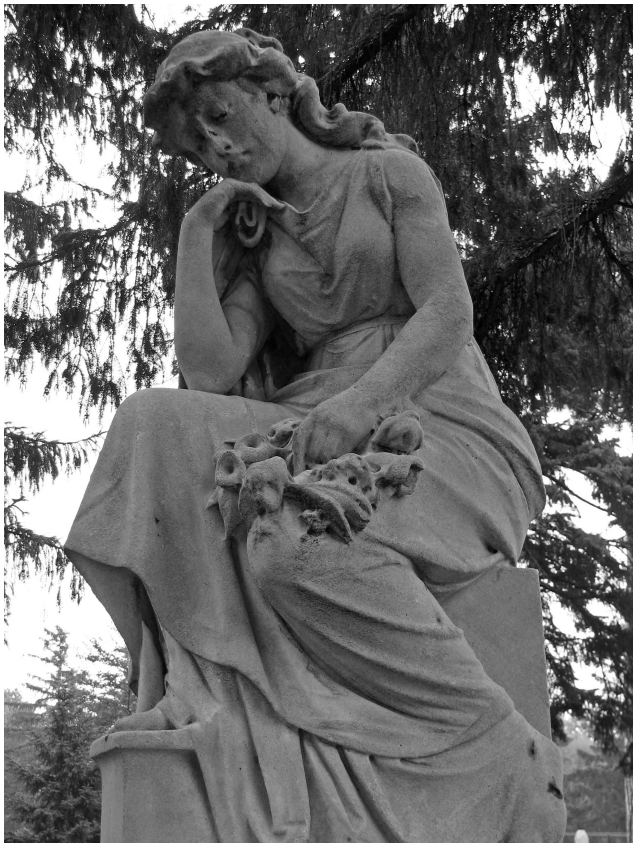


For any creature whose perceptual organization is akin to ours, if it is able to **perceive** some state of affairs X, then it has the neural resources **endogenously to generate (**at least an approximation to) **those same sensory states.**

4. Finally – a bridge towards **reason**?

What we think of as reason may be ushered onto the cognitive scene by **harnessing imagination.**

If we **down-regulate** (=assign low-precision to) **perceptual information**, and somehow **seed** the system by activating a high-level state (prediction), we can 'see' how things **would** unfold **were** we to take such and such an action.



PP thus describes a mechanism that fits very nicely with large bodies of work on **mental simulation** as the bridge between perception and reason

Clark, A, and Grush, R (1999) Towards a cognitive robotics *Adaptive Behavior* 7 (1), 5-16

Grush, R. (2004). The emulation theory of representation: motor control, imagery, and perception. *Behavioral and Brain Sciences* 27:377-442.

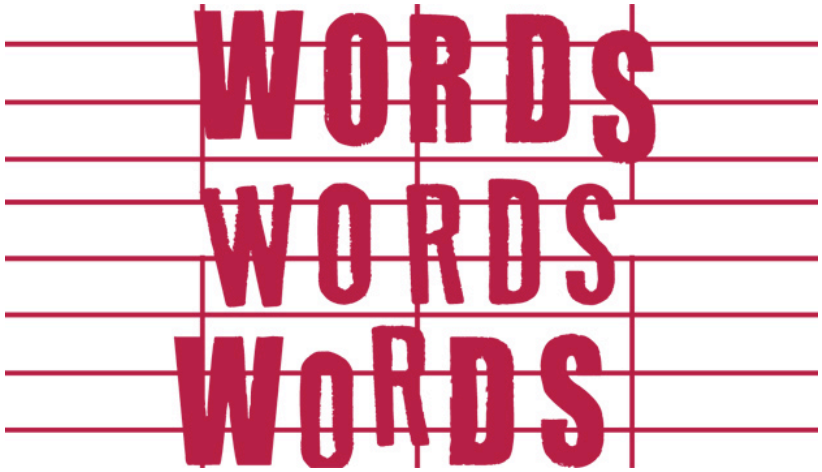
Barsalou, L. (2009) Simulation, situated conceptualization, and prediction. *Philosophical Transactions of the Royal Society of London: Biological Sciences* 364:1281–89.

Friston, K., Mattout, J. & Kilner, J. (2011) Action understanding and active inference. *Biological Cybernetics* 104:137–60.

Hesslow, G (2002) Conscious thought as simulation of behaviour and perception, *Trends in Cognitive Sciences*, 6, 6, 242-247

(Mere) **Speculation**: perhaps **human language** provides a key additional means of **self-seeding** our own imaginative explorations

(See Lupyan and Clark (2015))



Lupyan, G and Clark, A (2015) Words and the World: Predictive coding and the language-perception-cognition interface *Current Directions in Psychological Science* 24, 279–284.

Plenty of Outstanding Issues

A big one is: so why is there **conscious experience at all**?
Can PP really help us there?

Hope so - see our 4-year ERC project 'Expecting Ourselves', now up-and-running – see www.x-spect.org

European Research Council

Established by the European Commission

But end with a word on just one question…. What does all this say about the nature of our **perceptual contact with the world?**

Does the PP strategy threaten to **cut us off from the world in perception** by inserting all those **rich bodies of expectation** between us and the perceived world?

Yes and no!

Folk in this literature speak freely of perception as '**controlled hallucination**' and of the brain as in the business of generating a '**virtual reality**' or '**inferred fantasy**' about the world (see e.g. Paton, Skewes, Frith, and Hohwy (2013), Hohwy (2013), Hohwy (2014))

Paton, Skewes, Frith, and Hohwy (2013) Commentary on Clark in *Behavioral and Brain Sciences*

Hohwy, J (2013) *The Predictive Mind* (Oxford University Press)

Hohwy, J. (2014). *The self-evidencing brain*. *Nous*. doi: 10.1111/nous.12062

But this is the very same process that enables us, when all is working correctly, to **sort out the signal from the noise**, unearthing the varied distal objects casting their rough sensory shadows on the walls of Plato's cave

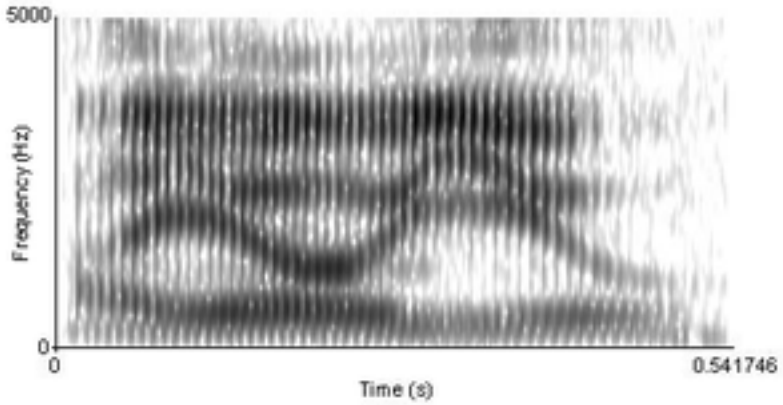
Image from Michelle Henry http://www.michellehenry.fr/cave.jpg

Consider the act of hearing a sentence spoken in your native language.

You hear **words, separated by gaps**.

But the soundstream itself is **perfectly continuous**, so those gaps are added by the listener.

So what we encounter is **in one sense a construct**.



A spectrogram of the phrase "I owe you".

There are no clearly distinguishable boundaries between speech sounds.

But it is a construct that tracks **real structure in the signal source** (other agents producing strings of distinct meaningful words)

Apt prediction helps us **see through** the noisy, continuous, frequently ambiguous, sensory signal to the **human and task-relevant aspects** of the world

This may be a rather good picture of animal perception in general….

If so, then the world we encounter in perception is **no more (and no less)** a virtual reality or fantasy than the **separated words** we hear in a sentence spoken in our native tongue.

PP describes a way of **seeing through the sensory signal** (through the shadows on the wall of Plato's cave) to the **human-relevant aspects of the distal world**.

This is **perceptual openness** for real agents operating in a real (and noisy) world.

Some Sources

Barrett, L. F., and Simmons, W. K. (2015). Interoceptive predictions in the brain. *Nature Reviews Neuroscience*, 16, 419–429

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Hohwy, J (2013) *The Predictive Mind* (Oxford University press, NY)

Conclusions

PP suggests that full-blooded perception is nothing other than **multi-area, multi-scale prediction.**

Perception, understanding, imagination and the rudiments of reason now co-emerge, delivered as a single '**cognitive package deal**'.

Getting to grips with this vision – testing it, challenging it, and working out what it means for standard pictures of mind and reason is a prime task for **21st century cognitive science**