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John McCrone is a freelance writer based in London, who edits a Website on the dynamics of brain processing at **http://www.btinternet.com/~neuronaut/**

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STANDING by a pond at London Zoo, grabbing a moment to talk shop with an American colleague on what was supposed to be a family outing, Karl Friston tried to describe a new vision of the brain. Traditional thinking held that the brain was some kind of computer, crunching its way through billions of inputs each second, outputting consciousness. But said Friston, a theoretical neurobiologist at London's Institute of Neurology, it is more as if the arrival of those inputs provokes a widespread disturbance in the brain.

Look, Friston told his Harvard friend, the brain is like this pond. You throw in a pebble—the sensory input—and you get ripples. That's the neurons responding. Sure, the pattern says something about the way the pebble hit the surface. But the pond is already covered in ripples caused by other pebbles, so the pattern appears a little chaotic. And then once the ripples spread out far enough to begin bouncing off the sides, he continued, the shape of the pond begins to affect what is going on. The whole thing keeps evolving and becoming more complex.

Yes, replied his friend, nodding furiously, and as we throw more and more pebbles—or rather experiences—into the pond, we change the kind of patterns it produces, and even the shape of the pond itself. This system has a memory!

In the early 90s, in hundreds of private conversations like this, mind scientists were groping their way towards a fresh view of the brain—one based on the idea that mental states are dynamically evolved rather than clinically computed. Back then, the arguments were little more than hand-waving exercises. People were familiar with the new ideas about chaos, complexity and nonlinear systems coming out of places like the Santa Fe Institute, but unsure how they applied to the brain. Today, however, the dynamic revolution is beginning to roll. At workshops and meetings around the world, researchers like Friston are talking publicly about dynamic models of the brain, and the evidence to support the new theories that is beginning to fall into place.

A replacement for the brain-as-computer model certainly seems overdue. The textbook view has been that brain cells are simple logic gates, adding and subtracting input spikes until some threshold level of charge is breached, at which point they convulse to produce a spike of their own. The all-or-nothing nature of a cell's firing promised to lift neurons clear of the usual soupy sloppiness of cellular processes, allowing the brain to carry out digitally crisp, noise-free calculations.

The task for researchers was simply to discover how the output of each cell encoded a message. In a chase likened to the hunt to crack the genetic code, neuroscientists became obsessed with finding the "neural code". They tried to discover whether the message was contained in the strength of a spike, the average number of spikes produced each second, or in the timing of the firing, with information carried only on those spikes which were synchronised with spikes from other cells [(see "Dot dot dot, dash dash dash", New Scientist, 18 May 1996, p 40)](http://www.newscientist.com/article/mg15020304.200-dash-dot-dash-dot-dash-dot.html).

But the neurons have proved slippery customers. "For 30 years we've been going along quite nicely, with lots of expensive equipment, lots of expensive people and lots of papers being produced, but finally the answers aren't there. We can't even say what it is about the spike train of an individual neuron that counts," says Rodney Douglas of the Institute of Neuroinformatics in Zurich. Much worse for the idea of a simple, crackable neural code are the smattering of recent findings which show that the output of any individual neuron also depends on what the brain happens to be thinking at the time. It's as if rather than the spikes combining to produce conscious awareness, consciousness is able to decide how the cells should spike.

The search for the neural code began in earnest in the 1960s with David Hubel and Torsten Wiesel's Nobel prizewinning demonstration that certain cells in the primary visual cortex—the first part of the higher brain to receive sensory input from the eyes—fired only in response to the sight of a line or edge, indeed, only to a line of the correct slope. The neurons represented every possible orientation of a line at each point of the visual field, and were lined up in the brain like dots on a TV screen, creating a physical "map" of the input from the eye.

Other researchers soon showed that cells in different areas of the sensory cortex made maps of the frequencies of sound, and even, in the case of touch, of the contours of the body. In fact, the entire wrinkled surface of the cortex seemed to be a mosaic of mapping, with the primary sensory areas being the first rung of a hierarchy of processing. The primary maps were reworked, as the message from one layer of cells, supposedly encoded in the neurons' spike trains, fed into the next. So, for example, about halfway up the visual hierarchy, cells might fire in response to movement in a certain direction and with a certain speed, or a certain shape of a certain colour. Sensory qualities began to emerge. At the very top of the hierarchy, neurons would react only to complete objects—say, the sight of a face or a hand. Each rung of the hierarchy was built on the digital clarity of the spike pattern of the neurons below, providing a way for the brain to compute a precise, conscious representation of the real world. That, at least, was the theory.

The problem was that most of the evidence for the theory came from studies of anaesthetised animals whose heads had been propped up in front of screens with their eyelids pinned back. When, in the late 1980s, researchers developed techniques that made it easier to record neural impulses from awake animals, the story of brain cells as simple switches, hard-wired to respond to this line or that movement, changed dramatically.

Take an experiment reported in Nature last year by neuroscientists John Maunsell, at Baylor College of Medicine in Houston, Texas, and Stefan Treue of the University of Tübingen in Germany. They studied those neurons about halfway up the visual hierarchy that deal with motion, in monkeys trained to watch moving dots on a screen. When the monkeys did not have to follow any dot in particular, the motion cells simply burst into life each time they spotted a dot heading in their preferred direction. But as soon as the monkeys were asked to concentrate on a single dot—they had been trained to do this without moving their heads or their eyes—the cells became picky. When the target dot came into view, the cells went wild, doubling their firing rate, while the response from the same neurons to non-target dots moving in the correct direction became weaker.

It all makes good psychological sense. The cells turn the volume up in response to movement that is the focus of attention, and mute it in response to other movement. But it also raises the question of how the brain's mental state is managing to transmogrify the cell's spike pattern.

Spooky

Neuroscientists dread any hint that something spooky might be going on. They try to slide past the problem of the brain's mental state interfering with the clarity of the long-sought neural code with euphemisms such as "selective attention effects" or "state-dependent modulations".

Yet Maunsell admits that his findings strike to the heart of the idea that the brain works as an input-driven machine: "We are coming to the end of one generation of effort," he predicts. "The next generation is going to have to look at the whole system [and] understand the effect that plans, decisions and actions can have on what neurons do."

Maunsell and Treue are not the only ones who have been backed into a corner by their own data. A rash of similar findings is emerging from labs run by the likes of Robert Desimone at the National Institute of Mental Health near Washington DC and Richard Andersen at Caltech in Pasadena. One team of researchers has even found that cells right at the bottom of the visual hierarchy—those that take the "freshest" input from the eyes and might be expected to be least influenced by the brain's mental state—are also at its mercy.

David Leopold and Nikos Logothetis, both also at Baylor, reported in Nature last year the results of an experiment in which monkeys looked through stereoscopic displays so that each eye saw a different image—gratings angled in different directions. The brain makes sense of such a conflict by allowing the view of one eye to dominate: the monkey is consciously aware of seeing only a single image.

According to the old view of the brain, the cortex cells that get their input direct from the eyes shouldn't be involved in the mental jiggery-pokery that suppresses the image from one eye—it should happen higher up the hierarchy. Instead, Leopold and Logothetis found that the firing of about a fifth of cells in the primary visual cortex depended on which image the monkeys signalled they were seeing. Even at the lowest level, there was an attention effect.

Booming with the enthusiasm of an outsider who is beginning to be proved right, Scott Kelso, a dynamicist who studies the brain and behaviour at Florida Atlantic University in Boca Raton, claims that results like these will only make sense once the old notion of the brain processing encoded messages through nothing more than a hierarchy of inputs and outputs is abandoned. Instead, he says, neuroscience must make a fresh start and recognise that the brain is a dynamical system—an organ that evolves its patterns of activity rather than computes them.

The very word "dynamic" strikes fear into the hearts of many researchers, relying as it does on the maths of chaos and complexity theory. Jargon such as "metastability", "critical boundaries" and "loosely coupled attractors" litters the papers. Still, the champions of the dynamic view stress that a few simple ideas are key.

Bursting forth

First, says Kelso, stop thinking of neurons as if they are exchanging messages. Instead (to use another of the hydraulic metaphors favoured by dynamicists), the spike patterns of a cell are like a whorl erupting in moving water—a local expression of a much wider balance of forces. After all, it is no secret that most of the 5000 input lines to the average brain cell are actually parts of feedback loops returning via neighbouring neurons, or those higher up the hierarchy. Barely a tenth of the connections come from sense organs or mapping levels lower in the hierarchy. Every neuron is plumbed into a sea of feedback. The signals coming up the chain may provide the seed of a response, but in the end, the cell's spike patterns evolve in concert with how the rest of the brain is reacting to the stimulus. The spike pattern is less a crisp code and more the chatterings of a system forever moving towards an equilibrium.

This is good, as it means there is nothing spooky about how thoughts and intentions, that is mental states, shape the activity of a neuron, and vice versa. But it does mean that levels of consciousness matter, especially if you are trying to make sense of a neuron's spike train.

When a cell is firing in relative isolation—for example, when an animal is unconscious—its response will be at its most hard-wired, a simple sum of its sensory or lower inputs. Like a ringing phone, the neuron will announce that it has a message, but no one lifts the receiver to get the conversation going. But as the experiments with wide-awake monkeys show, as soon as a cell becomes drawn into some greater wave of processing, its firing appears far less hard-wired. Of course, it takes time for the wave to build up, which is why attention effects usually show up about a tenth of a second behind the first exposure to the focus of the attention.

The second crucial change needed in the thinking about neural processing, say the dynamicists, is to realise that the brain is always in a state of tension, its circuits drawn tight like the surface of Friston's pond. Computer analogies suggest that the brain is a blank screen until cells fire to light up a picture. But almost every brain cell is constantly firing, a fact that has long troubled neuroscientists. There is a steady tick-over of at least three or four spikes a second even in an area of the brain that seems to be doing nothing. The temptation is to dismiss this activity as meaningless, just a leakage of current. But dynamicists say the spikes bouncing around the brain's connections must be maintaining it at a certain level of tone, giving each new input something to disturb in the first place.

Going a step further, they argue, this background firing presumably creates some meaning. But what? The brain stores memories as patterns of connections between cells—new experiences prompt the strengthening of old connections, or the growth of new ones. The tick-over firing echoing around the brain could be a defocused representation of everything you have ever learnt or known. When the brain processes new information, it is not a matter of lighting up dark circuits but of driving a generalised, weakly defined state of representation towards a specific one. The brain is always on, it just needs tuning in.

Hot spots

As the message of the dynamicists begins to sink in, neuroscientists are having to think again about the way they do experiments and analyse their data. The most obvious change, says Friston, is that researchers must allow enough time to get an accurate fix on what a cell is up to. Indeed, to truly understand a cell's firing pattern, you need to know how far along its feedback trajectory it has gone. At the moment, neuroscientists tend to concentrate on a cell's first reaction to a stimulus rather than waiting another tenth of a second or so until the feedback has had long enough to focus what the cell is saying.

What's more, in a dynamic scheme, cells apparently saying nothing (that show no change in firing rate and therefore go unreported when the time comes to write up a research paper) are still important. "Rather than talking about a hunt for the neural code, we should be talking about a hunt for the metric—the right kind of spatiotemporal measure to give the full picture of how a cell's response evolves," Friston says.

Friston is as good as his word when it comes to his own interest in human brain scanning. The standard approach to scanner studies is to look for brain hot spots, the bits of the brain that have to work the hardest when a subject does some mental or physical task. Like 20th-century phrenologists, researchers look for the brain bump that "does" hand movements or mental imagery. But if the brain really works by evolving patterns of connections, then it is how areas of the brain, even those that appear quite faint on a scan, join together over time that tells the true story.

As part of a two-day symposium on dynamical neuroscience at this October's meeting of the Society for Neuroscience in New Orleans, Friston attempted to prove that the distinction between mapping brain hot spots and patterns of connections is not purely academic. He reported an analysis of brain scan data collected by magnetoencephalography, using a method of correlation that highlights increases and decreases in activity in different parts of the brain that occur over the same period. It turned out that high activity in an area at the front of the brain called the prefrontal cortex, and low activity in an area towards the back called the parietal cortex, are tightly coupled just when the volunteer is deciding to make small hand movements. Usual methods of analysis would have missed the link. What's more, says Friston, it took a twentieth of a second or more for this coupling to appear, a clear sign that the connection had to evolve.

For now, however, dynamicists like Friston and Kelso are keeping a sense of perspective. They know that convincing mainstream neurobiologists to stop looking for machine-like order in a biological organ that thrives on the creative energy of chaos and feedback is going to take more than a few experiments and lots of enthusiasm. As Kelso said after the New Orleans symposium: "If we are serious about the brain as a self-organising system, then we need new tools, new concepts, a new language. Even the way we measure the brain has to be different." That process has started, and once it is complete, the dynamicists say, neuroscience's golden age of discovery will be ready to begin.