New Scientist

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DARK QUARKS
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YOUR QUANTUM BRAIN

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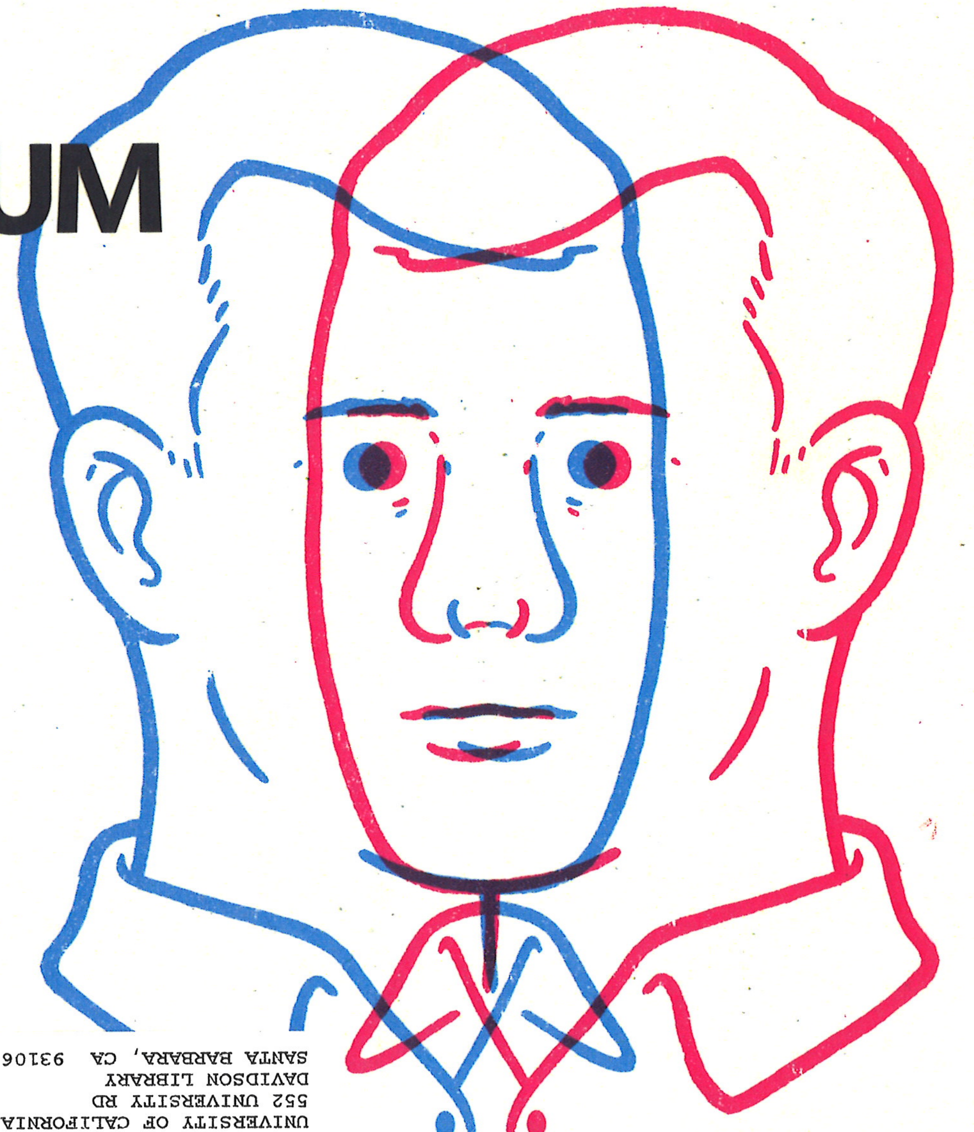

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A bit in two minds

Could quantum fuzziness be behind the peculiar computing abilities of the human brain, asks **Michael Brooks**

MATTHEW FISHER was wary of how his peers would react to his latest project. In the end he was relieved he wasn't laughed out of court. "They told me that this is sensible science – I'm not crazy."

Certainly nothing in Fisher's CV says crazy. A specialist in the quantum properties of materials, he worked at IBM and then at Microsoft's Research Station Q developing quantum computers. He is now a professor at the Kavli Institute for Theoretical Physics at the University of California Santa Barbara. This year he won a share of the American Physical Society's Oliver E. Buckley prize in condensed matter physics, many recipients of which have gone on to win a Nobel.

The thing was, he had broached a subject many physicists would rather simply avoid.

"Does the brain use quantum mechanics? That's a perfectly legitimate question," says Fisher. On one level, he is right – and the answer is yes. The brain is composed of atoms, and atoms follow the laws of quantum physics. But Fisher is really asking whether the strange properties of quantum objects – being in two places at once, seeming to instantly influence each other over distance and so on – could explain still-perplexing aspects of human cognition. And that, it turns out, is a very contentious question indeed.

The most basic objection comes from Occam's razor, the principle that says the simplest explanation is usually the best. In this view, current non-quantum ideas of the brain's workings are doing just fine. "The evidence is building up that we can explain everything interesting about the mind in terms of interactions of neurons," says philosopher Paul Thagard of the University of Waterloo in Ontario, Canada. Physicist David Deutsch of the University of Oxford agrees. "Is there any need to invoke quantum physics to explain cognition?" he asks. "I don't know of one, and I'd be amazed if one emerges."

Fisher is less sure, pointing out that current ideas about memories are far from watertight – for example, that they are stored in the architecture of neuron networks or in the junctions between neurons. "My gut instinct is that neuroscience has lots of things that remain puzzling," says Fisher. So why not see if there are better quantum explanations?

Perhaps because we've been here before. In 1989, Oxford mathematician Roger Penrose proposed that no standard, classical model of computing would ever explain how the brain produces thought and conscious experience. The suggestion intrigued a lot of people, not least an Arizona-based anaesthetist called Stuart Hameroff, who suggested a specific way for quantum effects to get involved.

The crux of the idea was that microtubules – protein tubes that make up neurons' support structure – exploit quantum effects to exist in "superpositions" of two different shapes at once. Each of these shapes amounts to a bit of classical information, so this shape-shifting ›

EIKO OJALA

quantum bit, or qubit, can store twice as much information as its classical counterpart.

Add entanglement to the mix – a quantum feature that allows qubit states to remain intertwined even when not in contact – and you rapidly build a quantum computer that can manipulate and store information far more efficiently than any classical computer. In fact, Penrose suggested, the way such a computer can arrive at many answers simultaneously, and combine those answers in different ways, would be just the thing to explain the brain's peculiar genius.

Penrose and Hameroff collaborated on the idea, and they and others kicked it around as a sensible proposal for a while. But holes soon began to appear.

From a physicist's perspective, the most fundamental problem was coherence time. Superposition and entanglement are both extremely fragile phenomena. Think of a human pyramid of performers crossing a high wire on a unicycle and you get the idea. The slightest disturbance and their grip slips. In the case of a quantum system, it will "decohere" to a bog-standard classical state if disturbed by heat, a mechanical vibration or anything else. The information stored in the quantum states is generally lost to the surrounding environment.

This problem has hampered attempts over the past two decades by physicists, Fisher included, to engineer a quantum computer of any significant size. Even in cryogenically cooled and mechanically isolated conditions, it's a struggle to keep qubit networks coherent for long enough to do anything beyond the capabilities of classical computers.

In the warm, wet brain, with its soup of jiggling, jostling molecules, it becomes almost impossible. Neurons hold information for microseconds at a time or more while processing it, but calculations suggest that the microtubule superpositions would last only between 10^{-20} and 10^{-13} seconds. Neurophilosopher Patricia Churchland summed up what came to be the mainstream view: "Pixie dust in the synapses is about as explanatorily powerful as quantum coherence in the microtubules," she wrote in 1996.

"Maintaining quantum effects in the warm, wet brain should be impossible"

Fisher shared that scepticism. "When they started talking about microtubules, I knew immediately it didn't make sense," he says. "It's impossible to work with quantum information unless you can control it and keep it from entangling with the environment."

But equally, he thought, wouldn't it be odd if evolution hadn't worked that out? Life has had billions of years to "discover" quantum mechanics, and its exquisite molecular apparatus gives it the means to exploit it. Even if electrical impulses among neurons within the brain – something well described by classical physics – are the immediate basis of thought and memory, a hidden quantum layer might determine, in part, how those neurons correlate and fire.

Fisher's personal interest in the subject began in a rather roundabout way, while wondering about the persistence of mental illness among people close to him, as well as the efficacy of the drugs used to treat them. "No one truly knows how any of the psychiatric pharmaceuticals work," he says. There's a reason for that. It would require a much better understanding of what the drugs are trying to modify: the human mind.

The initial focus of Fisher's interest was lithium, an ingredient of many mood stabilising drugs. As he combed the scientific literature, he happened across one particular report from 1986 that gave him pause for thought. It described an experiment in which rats were fed one of the two stable isotopes of lithium: lithium-6 and lithium-7. When it came to grooming, nursing of pups, nest-building, feeding and several other measures, those fed lithium-6 were enormously more active than control groups or those fed lithium-7 (*Biological Psychiatry*, vol 21, p 1258).

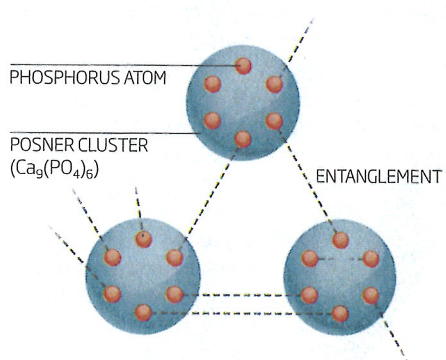
It was this paper that led Fisher to think it might be time to open the whole quantum cognition can of worms once again. All atomic nuclei, like the fundamental particles that make them up, have a quantum-mechanical property called spin. Crudely, spin quantifies how much a nucleus "feels" electric and magnetic fields; the higher the spin, the greater the interaction. A nucleus with the very lowest possible spin value, 1/2, feels virtually no interaction with electric fields and only a very small magnetic interaction. So in an environment such as the brain, where electric fields abound, nuclei with a spin of 1/2 would be peculiarly isolated from disturbance.

Spin-1/2 nuclei are not common in nature, but here's the thing. The spin value of lithium-6 is 1, but in the sort of chemical environment found in the brain, a water-based salt solution, the presence of the water's extra protons is known to make it act like a spin-1/2 nucleus. Experiments as long ago as the 1970s had noted that lithium-6 nuclei could hold their spin steady for as long as 5 minutes. If there is an element of quantum control to the brain's computation, Fisher reasoned, lithium's calming effects might be down to the incorporation of these peculiarly coherent nuclei into the brain's chemistry.

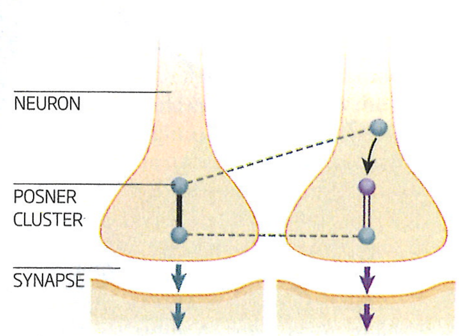
And not just that. Lithium-6 does not occur naturally in the brain, but one nucleus with a spin-1/2 does, and it is an active participant in many biochemical reactions: phosphorus. The seed in Fisher's mind was beginning to sprout. "If quantum processing is going on in the brain, phosphorus's nuclear spin is

Joined-up thinking

Posner clusters thought to be found in the brain contain six phosphorus atoms whose nuclear spin states can be quantum entangled – perhaps influencing how we think and remember



Change the spin state of one entangled phosphorus atom and the state of its entangled partner changes too – regardless how far apart they are



Entangled Posner clusters involved in chemical signalling in one brain neuron could **induce similar reactions in another neuron** the only way it could occur," Fisher says.

After exhaustive calculations of the coherence times of various phosphorus-based molecules in biological settings, Fisher has now gone public with a candidate qubit. It is a calcium phosphate structure known as a Posner molecule or cluster. It was identified in bone mineral in 1975 and has also been seen floating around when simulated body fluids – that is, water with added biological molecules and mineral salts – are concocted in the lab. When Fisher estimated the coherence time for these molecules, it came out as a whopping 10^5 seconds – a whole day.

He has also identified at least one chemical reaction in the brain that he thinks would naturally manufacture entangled, coherent states between nuclear spins within Posner molecules. It is a process involved in calcium absorption and fat metabolism that uses an enzyme called pyrophosphatase. This enzyme breaks down structures made of two interlinked phosphate ions, producing two single ions. Theoretically, at least, the nuclear spins in these two ions should be quantum entangled. Release them into the fluid surrounding the cells, and they can combine with calcium ions to form Posner molecules.

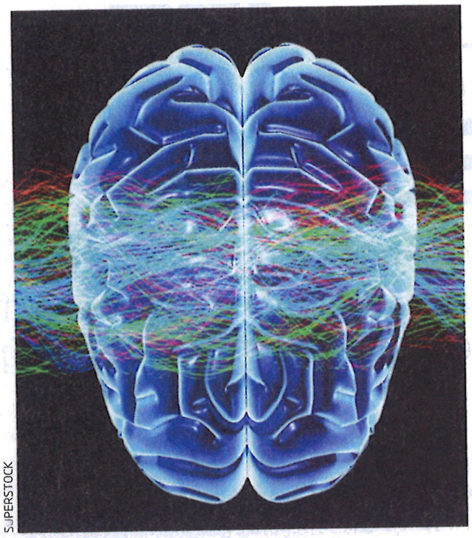
If this is all correct, the brain's extracellular fluid could be awash with complex clusters of highly entangled Posner molecules. Once inside the neurons, these molecules could begin to alter the way the cells signal and respond, starting to form thoughts and memories (see diagram, left).

Fisher published the details of his proposal in *Annals of Physics* last month (vol 362, p 593). Much of it, he admits, is highly speculative. "I'm still at the stage of telling stories," he says. "I have to get some experiments done."

The c-word

The first test will be whether Posner molecules exist in real extracellular fluids. If they do, can they be entangled? Fisher envisages testing this in the lab by inducing the chemical reactions suspected to entangle phosphorus nuclear spins, pouring the resulting solution into two test tubes and looking for quantum correlations between light given out from the two. Observe such correlations, and you might just begin to make a case for quantum cognition. "That test can be done, and I'll make sure it is done," says Fisher.

Penrose is – perhaps predictably – excited by the story so far. "Stuart Hameroff and I have been of the opinion that nuclear spins might be an important ingredient of



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long-term memory for quite a while," he says. "Matthew Fisher's idea could well provide a very positive contribution to this picture."

Penrose still pins his colours to his microtubule hypothesis, however, seeing the new proposal as a mere add-on that allows for lasting memory. "The phenomenon of consciousness is much more likely to be connected with the quantum actions of

> "The idea that the brain is too messy for quantum effects is simple-minded"

interconnected microtubules," he says.

For Penrose, consciousness has to do with gravity acting on quantum states and thus causing them to decohere; microtubules are more massive than nuclei, and thus more likely to be the cause of this interaction, he says. Fisher would rather not go down this road, and says he has studiously avoided any mention of the c-word – consciousness – in his paper, concentrating instead on better-defined concepts such as memory.

His proposal might not be crazy, but does it do enough to convince sceptics to look again for quantum effects in the brain? Thagard declares himself open-minded. He points to evidence that has accumulated in the past quarter-century showing that other biological processes, such as photosynthesis, involve long-lived coherent quantum states. Vlatko Vedral of the University of Oxford also sees some value in Fisher's work. The idea that a warm, wet brain is too messy to have useful coherences is "simple-minded", he says.

Quantum control of the brain is controversial

Beyond that, he is not sure what exact part Fisher's mechanism might play. "But at least he has suggested experiments that might be able to probe this issue further," he says.

If there is any hint of success, Fisher has plenty of ideas lined up to test. There's the lithium question, and also whether related spin effects might explain mercury's influence on the brain – the phenomenon that became known as mad hatter disease, because hat-making traditionally involved prolonged exposure to mercury. Some commonly abundant isotopes of mercury have non-zero nuclear spin and might decohere phosphorus nuclear spins if caught inside a Posner molecule.

The questions keep coming. Does a bang on the head induce memory loss because it causes decoherence? Is nuclear spin the reason you can change brain states with transcranial magnetic stimulation, which fires a magnetic field across the brain? Fisher is working with neuroscientists and molecular biologists at Stanford University in California, where he is now on sabbatical, to address such questions. Most have taken a lot of convincing, he admits.

Johnjoe McFadden, a molecular biologist at the University of Surrey in Guildford, UK, is one researcher who remains to be persuaded. He once again invokes Occam's razor. "There are too many bits of it that need to hold together to make a coherent story," he says. "If any one aspect goes missing, it all falls apart."

Thagard, too, is waiting for the fall. "Do you need that extra level of explanation to account for interesting psychological phenomena? I don't think so," he says. But that's no reason not to seriously evaluate such proposals, he adds. "One of the great strengths of science is that people try different approaches and you get competing explanations. That's all good. I'm just putting my money on a different one."

Fisher meanwhile is putting his money where his mouth is: he has spent $20,000 of his own cash filing a patent on treating depression and similar mental conditions with compounds enriched in lithium-6. Perhaps appropriately, though, he remains in two minds about whether it will lead anywhere. "Could quantum cognition make sense of these things that are missing from our understanding of neuroscience?" he asks reflexively. "Maybe, yes." ■

Michael Brooks is a consultant for *New Scientist*