Between order and chaos

A radical theory says the cognitive power of the human brain can be explained by its proximity to disorder. **David Robson** reports

Think back through your day and consider all the amazing tasks your brain has helped you perform. From brushing your teeth to eating your lunch and reading the words on this page, your thoughts, feelings and actions may appear to be the product of a finely tuned machine. Simply telling someone your name is a small miracle for electrical signals zapping across a 1.3-kilogram lump of jelly.

"You're pulling off one of the most complicated and exquisite acts of computation in the universe," says Keith Hengen, a biologist at Washington University in St Louis. Exactly how we achieve this complexity has puzzled philosophers and neuroscientists for centuries, and now it seems precision isn't the answer. Instead it could all come down to the brain's inherent messiness.

Researchers like Hengen refer to this idea as the critical brain hypothesis. According to them, our grey matter lies near a tipping point between order and disorder that they call the "critical zone", or – more poetically – the "edge of chaos". We can see the same kind of instability in avalanches and the spread of forest fires, where seemingly small events can have large knock-on consequences.

Systems teetering on this precipice are governed by precise mathematical principles, and it now seems that the same dynamics may also explain our minds' extraordinary efficiency and flexibility.

The idea that the brain's electrical signalling could somehow follow the same rules as natural disasters may sound absurd – but many neuroscientists besides Hengen are coming to the same conclusion. "Criticality offers a powerful framework for understanding brain function and dysfunction," says Karim Jerbi, a neuroscientist at the University of Montreal.

The hypothesis can predict the effects of mind-altering drugs and might help us to diagnose illnesses like Alzheimer's with greater precision. It may aid us in understanding why some people are smarter than others, and perhaps it could even explain the purpose of sleep – and the origins of consciousness itself.

Most excitingly, certain meditative techniques may allow us to shift our brains towards or away from the tipping point – with the potential to enhance our mental flexibility.

Critical theory

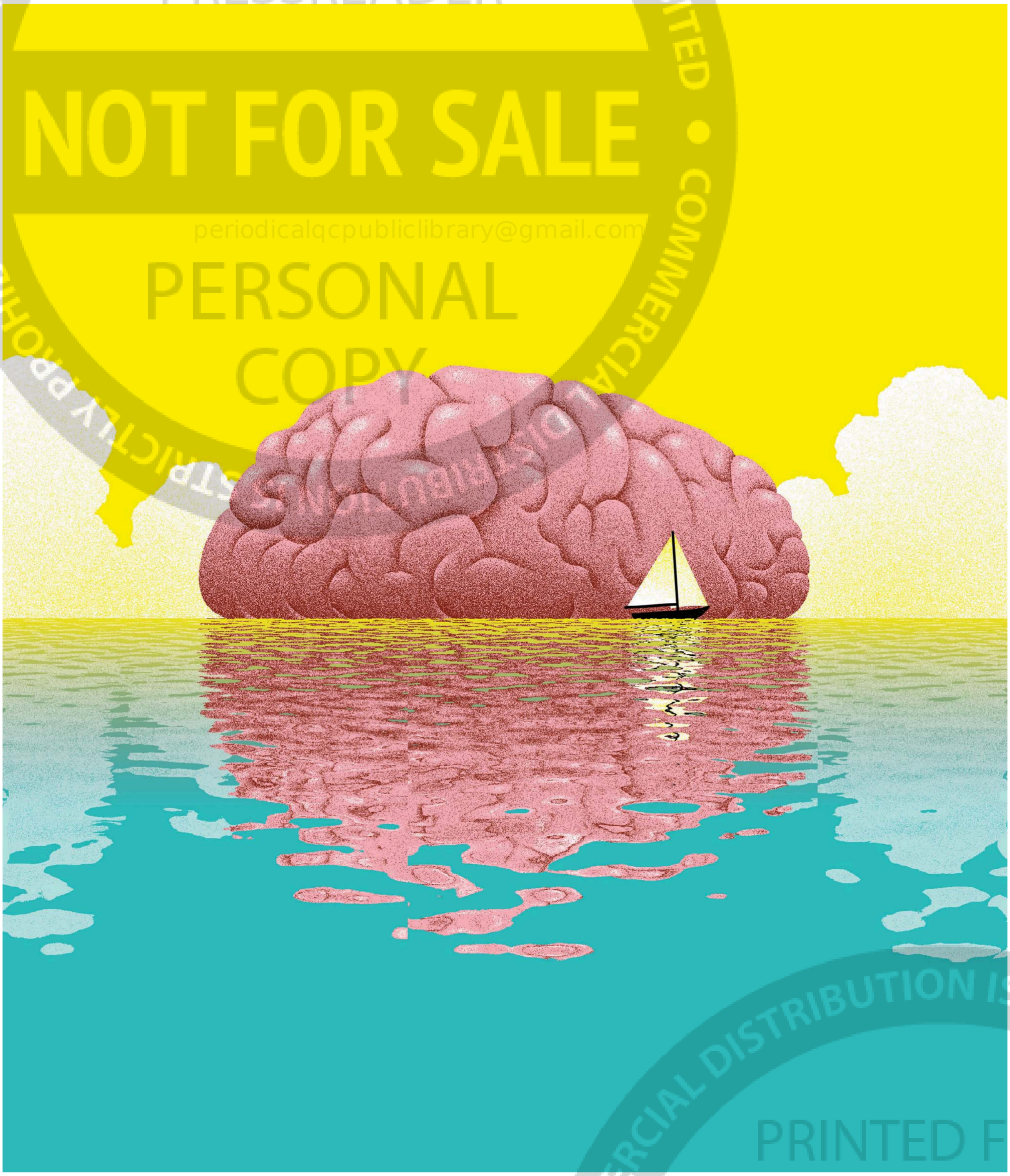
The seeds of the critical brain hypothesis can be traced back to Danish physicist Per Bak, who first outlined the laws governing critical systems in the 1980s and 90s. He found that the transmission of forest fires, for instance, lies on the cusp of a tipping point. Too far in one direction, and the whole ecosystem would quickly go up in flames, leaving no trees behind. Too far in the other, and each conflagration would die out rapidly, before any fire had a chance to spread.

Instead, Bak showed that forest fires tend to be "scale-invariant", meaning that fires of any size are possible. The exact frequency, he showed, follows a "power law", which means smaller fires are more common than larger fires according to a ratio that depends on factors like the climate and terrain.

By the early 2000s, neuroscientists had begun to suspect that the brain's electrical activity demonstrates a similar pattern. Our neurons are connected in intricate networks of synaptic connections, and when any cell "fires", it can trigger other cells to fire in response. "Activity builds on itself much like an avalanche," says Jordan O'Byrne, Jerbi's PhD student at the University of Montreal, who recently published a paper reviewing the mounting evidence for the critical brain hypothesis.

This chain reaction sounds exactly like the kind of system that might straddle the tightrope between order and disorder. To test the idea, John Beggs, at Indiana University in Bloomington, and Dietmar Plenz at the US National Institute of Mental Health in Bethesda, Maryland, took slices from rats' brains and measured the electrical activity of neurons as they spontaneously fired within a Petri dish.

They found that, on average, each active neuron prompted just one other neuron to fire as a result of its signalling – a number that, according to the maths, represents the brain's tipping point. Much higher, and the ›



LUCA D'URBINO

avalanches could spread uncontrollably; much lower, and activity would fizzle out before it really got started. The rat brain slices were showing exactly the kind of scale-invariance and power law distribution that characterise other critical systems.

Multiple studies have since identified signs of criticality in other forms of neuronal behaviour, like the synchronisation of different brain regions. It has also been observed across many different species, including zebrafish, cats, monkeys and – of course – humans.

Along the way, there have been a few contradictory results, however, with some researchers failing to find the characteristics of criticality – such as power laws – in their measurements of brain activity. According to Hengen, these controversies pushed scientists in the field to use more sensitive recordings of neural activity and more sophisticated mathematical techniques to analyse the results. "The sceptical groups are, in my opinion, the best thing that ever happened for studying criticality in the brain," he says. "They forced the field to dig deeper."

Connectivity and creativity

Working with Woodrow Shew, a physicist at the University of Arkansas, Hengen examined data from 320 existing experiments and showed that the apparently contradictory results could be reconciled with the hypothesis if you use new statistical tests of criticality. Their paper was published in Neuron, one of the most influential neuroscience journals, in June.

Exactly how close someone's brain lies to a tipping point may depend on many different factors, such as the connectivity of the networks and the balance of neurotransmitters in our synapses. "There's a zone of healthy brain function around criticality," says Shew.

This helps us to adapt our thinking depending on circumstances. "It gives the brain some room to modulate its level of criticality dynamically in response to certain situations or tasks," says O'Byrne.

That the healthy brain, while awake, never seems to veer too far from criticality suggests it must carry some serious advantages. The first is the breadth of information transmission and processing. Thanks to the scale-invariance of critical systems, signals can be passed over both small and large distances, which enables communication both within and between many different brain regions. The result is vastly more computational power. "The brain can explore the entire space of solutions," explains Hengen.

> **"Lying between order and disorder may help the brain adapt"**

Lying between order and disorder may also help the brain to adapt to new situations. "It allows the brain to be both stable enough to make sense of the world and dynamic enough to optimally respond to it," says Jerbi. "We believe the brain operates near this edge of chaos because it's the ideal zone for complex thinking, learning, decision-making and adapting to new situations."

If this were the case, you would predict that small differences in the brain's proximity to the critical point would influence someone's overall cognitive function – and that is exactly what Naoki Masuda, now at the University of Michigan, and his colleagues found in 2020.

The team asked 138 adults to take tests to measure "fluid intelligence" – the ability to apply logic and reasoning to solving novel problems – which was then compared with measures of brain activity taken from fMRI scans. Sure enough, Masuda and his colleagues found that the brains of people with higher scores tended to lie closer to the boundary between order and chaos than those with lower scores – which is exactly what you would expect if criticality enhanced the brain's information processing and calculation.

The enhanced flexibility arising from the critical zone could be seen in an experiment by cognitive scientist Jaana Simola and her colleagues at the University of Helsinki in Finland. The participants had to play a computer game that constantly changed its rules, which required them to update their approach on the fly. The closer their brains were to the critical point, the better they performed.

Jerbi suspects the brain's proximity to the critical point may be especially important for creativity – a form of thinking that isn't measured in standard IQ tests. "Creativity emerges from the brain's ability to explore novel ideas while maintaining enough structure to make them meaningful," he says. "Criticality may provide the

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Certain types of meditation may edge the brain nearer or farther from criticality

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Brain activity closer to the tipping point between order and chaos is correlated with intelligence

optimal neural environment for this process, allowing the brain to shift fluidly between spontaneous, divergent thought and focused, goal-directed reasoning."

Large departures from the critical zone – either into order or disorder – may result in serious brain dysfunction. "While criticality gives the brain its edge, it also means that small shifts – due to illness, stress or injury – can sometimes push it into less optimal or even harmful states," says Jerbi.

Alzheimer's disease is a case in point. Studies have shown that Alzheimer's-affected brains often suffer some serious damage before the patients begin to demonstrate a rapid decline in their thinking. This may mark the moment when the brain struggles to remain within the critical zone, producing a serious dip in its computational abilities. "There comes a point where, if you take out enough nodes from a network, you now really start to see the richness of the network fall right off," says Vincent Zimmern, a PhD student at Paris-Saclay University who recently authored a paper on the clinical applications of criticality.

Why we sleep

The potential implications of brain criticality have started to attract widespread attention from other neuroscientists. "General interest has been growing at an accelerating pace in recent years," says O'Byrne. "The word is getting out." And that has led to ever more ambitious proposals for what the phenomenon might explain.

Hengen, for instance, wonders whether sleep may have evolved to return the brain to its critical point. His studies of rats already provide good evidence that fatigue is intimately linked to the brain's criticality. "The strongest predictor of whether or not an animal is going to be awake or asleep in the next hour is its proximity to criticality," he says. "The closer you get to the critical point, the more likely you are to be awake. And the further you are from the critical point, the more likely you are to be asleep."

It seems that the longer we work the brain, the further it moves from the tipping point, while sleep helps to tune it back into the critical zone. Without that rest period, the brain would fail to reach its optimum state, resulting in the reduction of cognitive performance that has long been known to accompany insomnia. The length and quality of sleep can even influence automatic processes like breath control, says Hengen. Such widespread effects suggest that sleep evolved to address a basic underlying factor that governs all its processing – and that, he argues, is its proximity to the critical point.

O'Byrne is of the same mind. "One of the functions of sleep – and perhaps its most important function – may be to allow the brain's connections to be recalibrated and to return whole-brain dynamics to the critical point."

Chemical crutches such as caffeine may reduce fatigue by pushing the brain towards criticality, but that comes at a price. Jerbi's University of Montreal colleague Philipp Thölke recently invited participants to sleep in a laboratory on two separate nights. On one occasion, they were given 100 mg doses of caffeine – the equivalent of a strong espresso – 3 hours and then 1 hour before their bedtime. On the other, they went cold turkey. The researchers then asked them to wear an electroencephalography (EEG) headcap with electrodes that could measure their brain's electrical activity as they slept.

The team found that caffeine consistently moved the brain closer to the critical point during sleep. "It kept the brain in a semi-alert state," says Jerbi, a co-author of the paper, which was published earlier this year. The result may not be just a restless night; by reducing our time out, caffeine may prevent the brain from bouncing back to its full powers by morning. "It potentially interferes with the restorative functions of sleep."

Brain criticality could even help us unlock the enduring mystery of consciousness. It is a notoriously tricky concept to define precisely, but most neuroscientists and philosophers agree that, at its most basic, consciousness involves a "subjective perspective" – be that in real life or even a dream – that includes perceptions or mental images with distinct › qualities, such as colour and shape.

According to one leading hypothesis, called integrated information theory, this subjective perspective arises from the way data is processed and combined in the brain, so that the integrated total is more than the sum of its parts. Intriguingly, mathematical models suggest that measures of information integration peak when the brain approaches the critical point, which would mean that it is essential for the awareness of our thoughts, feelings and sense of self.

One way to test this theory has been to examine the effects of different anaesthetics. Xenon and propofol, for instance, appear to eliminate all conscious experience. Ketamine, by contrast, produces a state of dissociation that cuts the patient off from the outside world without removing awareness entirely. They can still experience vivid dreams that are filled with very strong sensations and a sense of self, for instance.

In a paper published last year, O'Byrne and his colleagues found that the brains of patients under ketamine remained near the critical zone, whereas the brains of those who had taken xenon or propofol moved away from the tipping point. "This seems to suggest that brain criticality is a necessary condition for consciousness, though more work will be needed before we can say this with more confidence," he concludes.

Fine-tuning our thinking

Given the role that criticality plays in our thinking, it is natural to wonder whether we can learn how to tune the brain's position within the critical zone. Wouldn't it be useful to edge the brain away from it before bed, for instance, or bring it closer to the tipping point when we need to process complex information or brainstorm new ideas?

Hengen is currently on the case. "Woody [Shew] and I are doing some cool stuff examining whether you can influence a brain's proximity [to] criticality in a way that promotes complex learning." He is coy about the details, though he says that it involves crafting sleep patterns – and that his experiments with animals are already revealing impressive results.

Another option is meditation, though we have to be careful about the specific kind

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Sleep may have evolved to bring the brain back to its critical point

"This suggests that brain criticality is a necessary condition for consciousness"

we use. Practices like Samatha meditation, which involves intense focus on a single sensation, such as your breath, would lead the brain to move away from the critical point. "This makes sense, since criticality is a state of maximum sensitivity and flexibility, but during focused-attention meditation, you're trying to tune out distractions and 'crystallise' your mind in order to bring out certain important details," says O'Byrne.

Vipassana, or open-monitoring meditation, on the other hand, encourages a non-judgemental awareness of all thoughts, feelings and sensations that pass through the mind. "Here, we would expect criticality to instead be increased, so as to become maximally sensitive to the environment," says O'Byrne. And a new study from Annalisa Pascarella at Italy's National Research Council provides tantalising evidence for this idea.

The participants were 12 Buddhist monks from the Santacittārāma monastery near Rome. Within the study, Pascarella asked the monks to engage in Samatha and Vipassana for 6 minutes each while she measured their brain activity with a magnetoencephalography (MEG) headcap – a technique that is similar to EEG but offers more data from across the whole cortex.

As hypothesised, the researchers found that the focused Samatha meditation moved the brain away from the tipping point, while the Vipassana open-monitoring meditation moved the brain towards it. "They were able to make their brains even more critical than during normal resting wakefulness," says O'Byrne, a co-author of the paper. The study is now available as a pre-print and is awaiting peer review. The results suggest that, with enough practice, it seems we can shift the brain's activity at will, allowing us to achieve the perfect state of mind for the task at hand.

It's worth noting that each monk had accumulated more than 2000 hours of meditation experience, but new technologies could eventually ease that process. Jerbi – who was also a co-author of the Buddhist meditation paper – points to something called neurofeedback. This presents users with a visual representation of the brain's activity, using portable EEG, as they practice, which is thought to speed up the training of certain meditative techniques.

In the meantime, we might simply learn to appreciate our slightly chaotic minds a little more. Those moments of mild scattiness may simply be a sign that we are sitting comfortably in the critical zone, with all the benefits that provides. ▮

David Robson is a science writer and author of *The Laws of Connection: 13 social strategies that will transform your life*

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