

Neurobiology

The turbulent brain

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ABSTRACT

Brain activity emerges from the coordinated dynamics of a huge network of neurons. Here, we explored what sorts of wave patterns can arise at the whole-brain scale, how these patterns change over time, and what mechanisms might underpin



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The human brain supports a rich repertoire of complex dynamics. This wide diversity of activity patterns underpins all our thoughts and behaviors. We also need some degree of flexibility so that our brains do not get stuck in one pattern for too long, but rather are able to jump between different patterns. But we're a long way from understanding how all these activity patterns emerge from the mass of neurons and wiring that makes up a brain. Nor do we know much about how the brain switches between different activity patterns. Sometimes, brain activity is so complex as to appear close to random. At other times, such as during sleep or in response to stimuli, there is substantial order among the chaos. Indeed behind the colloquial term "brain waves" there is a real phenomenon: brain electrical activity really can form ordered wave patterns, similar to water waves.

Brain waves have been observed at a wide range of spatial scales using numerous imaging technologies. We focused on waves at the large scales that we can feasibly measure in humans – of order millimeters to tens of centimeters. We asked two main questions: How might large-scale waves emerge from what we know about large-scale brain structure? And how can multiple different wave patterns emerge?

We used a mathematical model that describes the dynamics of a brain region – a "neural mass". The essential idea here is akin to how we can describe the air in a room using spatially-averaged quantities like temperature and pressure; we need not understand all the microscopic details of all the air molecules colliding randomly. To scale up from a small brain region to the whole brain, we coupled these neural

masses into a large-scale network via the "connectome" – an estimate, from magnetic resonance imaging, of how brain regions are wired together. By exploring the model using computer simulations, we can study the mechanisms that might generate the large-scale patterns of brain activity observed experimentally in humans.

We found that the modeled brain network can indeed generate a wide range of wave patterns. These include traveling waves, rotating waves, and patterns where waves emanate from a region or converge into a region – and combinations of all of the above. Intriguingly, we found that the dynamics lingered in each wave pattern for about 50 milliseconds then spontaneously and rapidly reconfigured into a different pattern. That is, flexible switching between patterns emerged naturally. The specific wave patterns are "metastable": stable enough to be observed but not so stable for the brain to be stuck there indefinitely. Moreover, the time scales of this switching are similar to those seen in brain activity recordings.

Digging deeper, we explored what was happening within and between consecutive wave patterns. We used methods from the study of turbulent fluids to explore the flows of activity across the brain. It turns out that the waves don't just wander randomly and uniformly over the brain, but rather seem to be organized heterogeneously around different brain regions. The switching between patterns occurs

when parts of the flow suddenly break down and reconfigure – similar to what happens in turbulent fluids. We also explored what's special about the human brain network that supports these waves. The crucial ingredient appears to be the brain's spatial properties, such that nearby regions are more strongly connected than more distant ones. Breaking these spatial relationships in the model abolishes waves.

Our model thus provides a mechanism for the emergence of large-scale wave patterns in the human brain. Moreover, the model unifies these wave phenomena with the flexible switching between brain activity patterns seen in experiments. The notion that activity flows around the brain makes it intriguing to speculate that this is a way for information to flow around the brain. A kind of higher-level propagation than the classical idea that information flows from network hop to network hop as in the internet, say. In the wave picture, information is carried by wave patterns that emerge from the combined influence of all the network routes in the connectome – think of this as the software running on the hardware. Our results point to a need to measure brain activity with both high spatial and high temporal resolution, going beyond the classic long-time averages that currently dominate brain imaging research. Only then can we glean more clues toward understanding the full richness of brain activity.