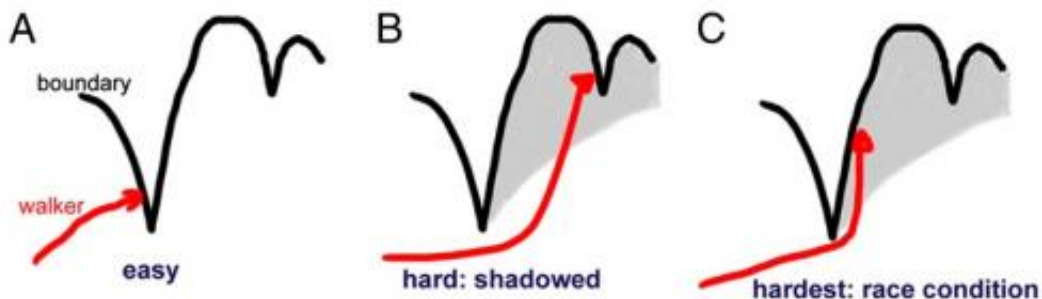


Phase transition may explain how brain neurons encode information

April 2 2013, by Lisa Zyga



A fluctuating quantity, or random walker, can hit a moving boundary in different ways: (A) Most likely, the walker will hit the left flank at a minimum. (B) Less likely, the walker will miss the minimum but quickly rise high enough to hit a second feature from the left. (C) Least likely, the walker will hit the right flank, which requires narrowly missing the minimum followed by quickly rising in a “race” with the moving boundary. In the case of neural coding, the fluctuating quantity is a neuron’s membrane voltage and the moving boundary is the threshold voltage required for the neuron to fire. Credit: Taillefumier and Magnasco. ©2013 PNAS

(Phys.org) —While scientists know that information is represented in the brain by the electrical activity of neurons, the details of this representation, called "neural coding," remain mysterious. How exactly do pulses of electricity get translated into thoughts and ideas?

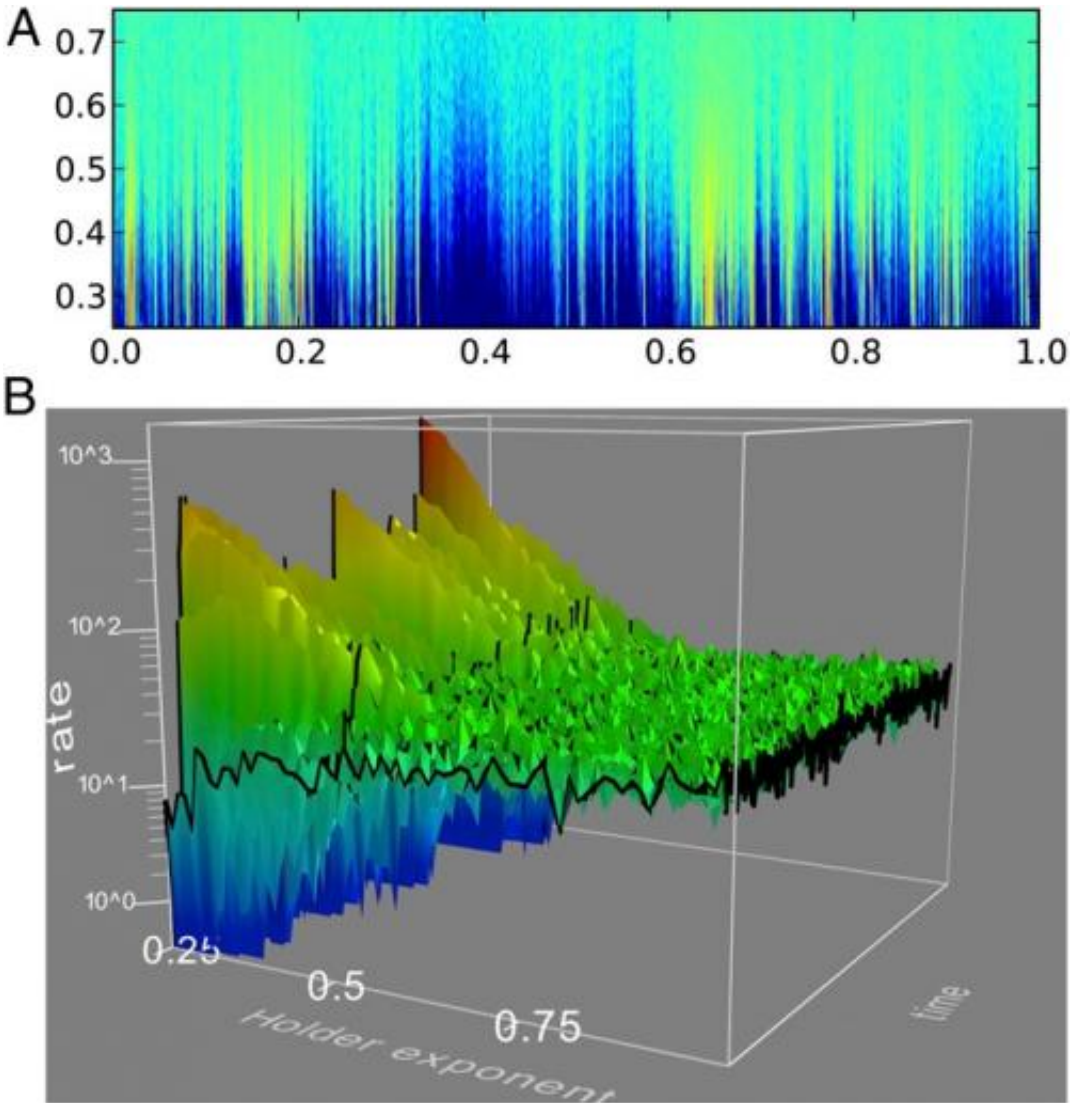
In the [standard model](#) of neuronal firing, neurons can use two kinds of

neural codes: rate codes, in which information is encoded only in the average rate of firing; and temporal codes, in which information is encoded not only in the average rate but also in the [precise timing](#) of each pulse, with sensitivity down to the submillisecond range. Temporal firing means that firing patterns with the same average rate can encode different messages—a key insight into understanding neural coding. While the distinction between the two neural codes has previously been considered one of degree, a new study has found that neurons change between the two coding regimes abruptly rather than smoothly due to a phase transition separating the two regimes.

The researchers, Thibaud Taillefumier and Marcelo Magnasco at The Rockefeller University in New York, have published their paper on their discovery of a neural phase transition in a recent issue of *PNAS*.

"Just like a phase transition between a [solid](#) and a liquid allows us to make a clear distinction between the two phases of matter, we discovered that there is also a phase transition between rate codes and temporal codes in neural coding, and this distinction remains even when you are not considering a theoretical model but actual [liquids/solids](#), with [imperfections](#) or [impurities](#)," Magnasco told *Phys.org*.

The researchers' discovery of the phase transition between the two neural regimes arises from a more general mathematical question called the "first passage problem." The question is, when is the first time that a fluctuating quantity (e.g., voltages in neurons, prices in a market, etc.) reaches a given boundary? The question becomes even more difficult when the boundary itself is fluctuating—as is often the case in real-life situations, including the neural coding scenario.



(A) 2D and (B) 3D renderings of the probability density of neuron firing as a function of time (horizontal) and the Holder exponent (vertical) in log scale. In (B), it can be seen that, toward the back of the figure, the rate goes to either zero or infinity everywhere due to a phase transition. Credit: Taillefumier and Magnasco. ©2013 PNAS

In neural coding, neurons generate electrical pulses, or action potentials, to encode information and communicate with each other. In order for a neuron to generate one of these pulses, its membrane voltage must exceed a threshold voltage, which then triggers a chain reaction of events

in the neuron that ultimately causes it to fire. The neuron's membrane voltage is constantly fluctuating in response to both electrical pulse inputs from other neurons as well as the neuron's own internal noise. The threshold voltage also fluctuates, so that at certain times the neuron's membrane must have more voltage to surpass the threshold than at other times.

In this study, the researchers investigated the probability that a neuron's fluctuating membrane voltage first exceeds the fluctuating threshold, and found that this probability undergoes a phase transition as a function of the roughness of the boundary, which refers to how much the threshold boundary fluctuates.

The researchers mathematically defined boundary roughness by the Holder exponent, H . The boundary is perfectly smooth at $H = 1$. The researchers identified the critical value at which the phase transition occurs at $H = 1/2$, the point at which the roughness of the fluctuating boundary equals the roughness of the fluctuating quantity. They found that, when $H > 1/2$ (smoother boundary), the probability density for finding the "first passage" of the fluctuating quantity through the fluctuating boundary is a continuous function. That is, the probability is never zero and never infinity, but always somewhere in between. When H

Although the finding of a phase transition at $H = 1/2$ is a general finding that can be applied to many areas, it is particularly relevant in the case of neural coding. Previous research in neural coding has shown that, when $H = 1/2$, a neuron's input voltage is uncorrelated yet precisely balanced; in other words, it is white noise.

"If you plot the fluctuating voltage of the neural membrane as a function of time, it has a value of $H = 1/2$," Magnasco said. "What our calculation shows is that, at least mathematically, the trajectory with the smallest H

always wins—when the walker has the lowest H , then it can always overtake the boundary, while when it is the boundary with the smallest H then when the walker starts from behind it has zero chances of catching up—until the boundary reverses on itself and turns back down."

This significance of $H = \frac{1}{2}$ in neural coding led the researchers to realize that the phase transition at this value defines a sharp boundary between rate codes (which occur with a smoother boundary, when $H > \frac{1}{2}$) and temporal codes (which occur with a rougher boundary, when H

Because the first passage problem appears in many situations, the discovery of the phase transition may have implications for diverse areas such as voltages in electrical circuits, prices of commodities in markets, the variables describing the severity of a disease, the time-to-failure of a device, game theory problems, and biological species extinction probabilities, among others.

In the future, the researchers want to further investigate the implications of boundary roughness.

"We want to understand if there is a single 'timing' regime or whether there are multiple regimes for different H

More information: Thibaud Taillefumier and Marcelo O. Magnasco. "A phase transition in the first passage of a Brownian process through a fluctuating boundary with implications for neural coding." *PNAS Early Edition*. DOI: [10.1073/pnas.1212479110](https://doi.org/10.1073/pnas.1212479110)
Also at [arXiv:1206.6129](https://arxiv.org/abs/1206.6129) [q-bio.NC]

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