

Article Addendum

Neural diversity creates a rich repertoire of brain activity

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Despite investigations dating back to the 19th century, the functional role of different cell types in the brain remains largely unknown. Using realistic computer simulations, we have recently shown that neural diversity can generate patterns of complex activity that were traditionally interpreted as irreducible noise. Such complex activity may directly contribute to both cognitive and behavioral outcomes, including motor control, perception and memory.

The mammalian brain has an impressive diversity of cells, connected together in complex circuits. There are at least twenty-one classes of interneurons in the CA1 region of hippocampus alone;¹ the retina has fifty-five neuronal types, and the function of less than half is known.²

An important consequence of neural diversity is that several aspects of the brain's activity that have traditionally been interpreted as irreducible randomness can now be explained in physiologically meaningful ways. For instance, neural populations of the hippocampus³ and cortex⁴ have a natural tendency to spontaneously synchronize their activity at nonperiodic, seemingly random times. Using computer simulations, we have recently shown that the unpredictable occurrence of spontaneous synchronization can emerge naturally from completely deterministic cellular interactions, without randomness—the key ingredient being neural diversity.⁵

In the model, neural diversity is generated by varying the intrinsic properties of different neurons (i.e., levels of excitability, refractory period, etc.). Each neuron's activity is influenced by other neurons that are sending information via synaptic connections. The electric pulses (spikes) received from these neurons tug the receiving cell's activity in different directions, producing fluctuations that appear completely random. When these intrinsic fluctuations in neural activity are combined with recurrent excitation, the result is a completely noiseless system that synchronizes its activity at seemingly random times (Fig. 1).

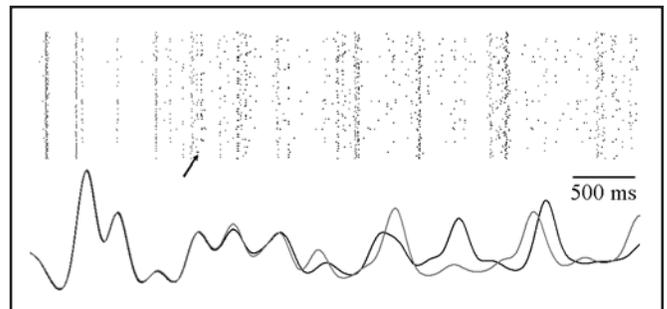


Figure 1. A noise-free model of spiking neurons, where different cells possess different intrinsic properties, produces complex and random-like activity. Top: spike raster of 100 cells (rows) over time. Bottom: population activity (convolved with a Gaussian kernel with 100 ms standard deviation). Gray: independent run of the model after shifting a single spike by 1 ms (shown by arrow).

These simulations suggest that the presumption of intrinsic randomness may be superfluous: apparently random patterns of nonperiodic behavior may arise spontaneously from within an entirely deterministic system, provided that different cells have different intrinsic properties.

Going further, it may be that even the most complex brain activity can be explained without resorting to random processes—a conjecture that departs radically from the assumption made by numerous contemporary models in neuroscience,⁶⁻⁸ wherein noise typically plays a central role in accounting for fluctuations in neural activity. For instance, models of retinal waves that arise during development assume that spontaneous firing of cells is determined randomly,⁶ and models that seek to capture the millisecond precision of spikes in the early visual system account for variability across different trials by the addition of noise.⁷

While noise may be essential for these models to behave in ways that appear realistic, an adequate account of the origin of the hypothesized randomness is lacking.⁸ It is not clear on evolutionary grounds what adaptive advantage such noise would convey. Would evolution drive the emergence of a large number of different cell types that only add noise and unreliability to brain activity?

It turns out that neural variability, emerging from the interactions of a diverse cell population, can play a number of important functional roles. At the level of individual neurons, neural diversity may allow information to be integrated over varying periods of time.⁹ At the population level, neural diversity is proposed to be involved in complex processes, including our representation and interpretation

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of the world, our capacity to form rich memories, and our capacity to produce appropriate, context-dependent behaviors.¹

Neural diversity may be pivotal to generating a rich repertoire of neural interactions, which can meet the complex computational and communicational demands of the brain. By preventing neural dynamics from getting “stuck” in so-called attractor states, neural diversity may facilitate quick responses to environmental demands in a wide variety of ways, and with less effort than a system where all cells are identical.

A characteristic aspect of our noise-free model is an extreme sensitivity to small changes in spike times.⁵ Such sensitivity is reported in the cerebral cortex, where differences in spike timing on the order of 3 ms between trials can influence the outcome of a decision process.¹¹ A noise-free model of spiking neurons clearly illustrates the importance of millisecond precision in spike timing: by shifting a single spike by 1 ms (the smallest change possible in the model), notable differences in spike dynamics emerge over time (Fig. 1).

While our work cannot entirely rule out the possibility of random noise, it suggests that such noise is genuinely parsimonious. Further, by linking the precise spike timing of neurons to population-level dynamics, computational simulations offer the promise of relating single-cell activity to their cognitive and behavioral outcomes, including high-level aspects of cognition such as language and reasoning.¹⁰

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