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Analysis of neuronal avalanches reveals spatial temporal roadmap of humans higher cognitive function

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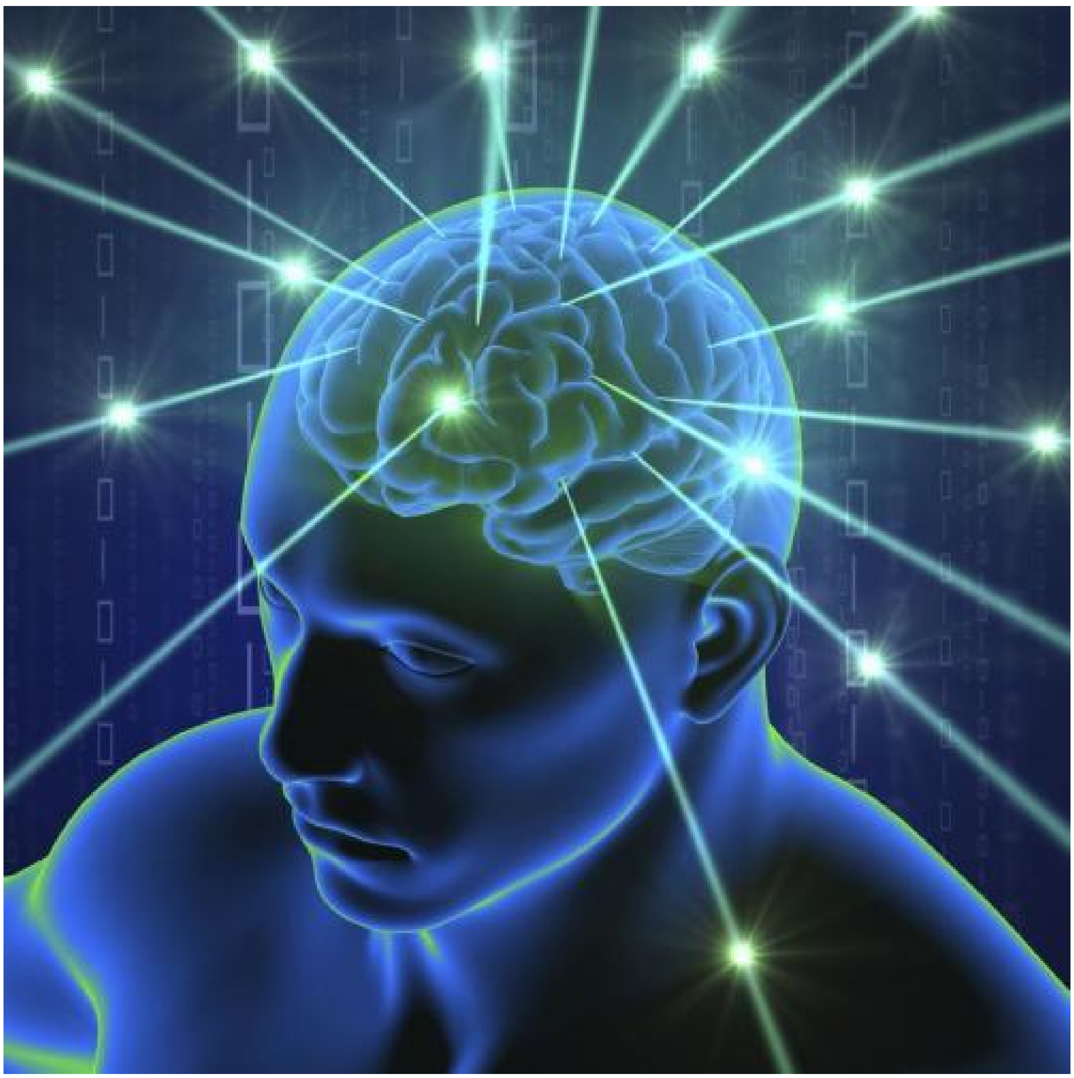

Credit: Rice University

The word 'avalanche' is generally associated with violent and unexpected events—such as rockslides, or the sudden collapse of unstable drifts of snow. But in brain research, avalanches—intermittent cascades of electrical activity—are everyday occurrences that are not only peaceful, but actually reflect stability.

For the first time ever in a study of the living human brain as it responds to outside stimuli, an Israeli doctoral candidate recently completed a quantitative analysis of how neuronal avalanches arise from the balance between two fundamental electrochemical forces mediated on the level of neural networks—the force that excites the propagation of electrical activity through the brain, and the force that inhibits it.

Using a non-invasive technique called magnetoencephalography (MEG), Ms. Oshrit Arviv compared the patterns of electromagnetic activity that occur in the resting brain, and those patterns generated by specific cognitive processes. Building on previous theoretical and experimental work on brain 'criticality'—the state at which brain activity hovers between attenuation and amplification of electric signals by maintaining excitation-inhibition balance—the new study is the first to demonstrate that neuronal avalanches can be triggered by high-level cognition. Arviv's novel computational approach also revealed that neuronal avalanche size and duration capture specific features of individual brain dynamics—demonstrating an analytic 'biometric' technique that links MEG-generated data to specific individuals.

In a separate finding, the study demonstrates that stimulus-evoked avalanches—the neural patterns evoked when various subjects perform a specific perceptual task—share a high degree of similarity in terms of temporal and spatial distribution. This approach, which links specific cognitive tasks to the underlying neural network dynamics, represents an entirely new way to observe the human brain at work.

These findings were published on Oct. 14, 2015 in the *Journal of Neuroscience*. The article was co-authored with the joint supervisors of Arviv's doctoral studies: Dr. Oren Shriki, Head of the Computational Psychiatry Lab at Ben-Gurion University of the Negev, and Prof. Avi Goldstein of Bar-Ilan University's's Department of Psychology and Head of the Electromagnetic Brain Imaging Unit at the University's Gonda (Goldschmied) Multidisciplinary Brain Research Center.

Criticality—the Optimal State for Brain Function

"The billions of nerve cells in our brains are affected by opposing network-based forces, which either promote nerve-to-nerve communication, or inhibit it," says Arviv. "The dynamic balance between these two functionalities is expressed, in part, by avalanches—naturally-occurring phenomena that re-set electrical activity and reflect stability in the brain. Somewhere in the space between 'too much' and 'too little' neural activity is criticality: the state in which brain function is most efficient."

According to Arviv, criticality is the state at which one synchronized group of neurons will activate, on average, only one other synchronized group—a limitation that optimizes the electrochemical activity that serves as 'fuel' for brain function. "Scientists have long believed that the critical state optimizes the brain's ability to represent information," she says. "Ours was the first experimental research to quantify the spatio-temporal organization of the critical branching process that produces neural avalanches, and compare this organization as it occurs in stimulus-evoked cognition, and in the resting state."

Face Processing—a Visual Key to Unlocking Excitation-Inhibition Secrets

Arviv's experimental set-up used a visual task—the processing of faces—as a model system. Subjects were presented with 45 randomized pictures of mostly male faces, and were instructed to press a button when a female face appeared on the screen. While conducting the task, the subjects' brain activity was recorded with a whole-head magnetometer array—a MEG helmet.

"MEG is a technique based on direct reading of electromagnetic fields which allows the measurement of ongoing brain activity on a millisecond-by-millisecond basis, and can also show where in the brain such activity is produced," Arviv explains, adding that this ability to simultaneously gather a combination of excellent temporal data, together with good spatial data, gives MEG a distinct advantage over other methods. "We observed a fluctuation in the opposing forces of excitation and inhibition which appeared in response to a specific cognitive behavior—processing a face—and which triggered avalanches. Not only were we able to plot exactly where these avalanches occurred in the brain, we could also follow avalanche propagation over time. No one has ever been able to identify the moment when the excitation-inhibition balance changes, certainly in terms of high cognition. Here, we achieved a high-resolution, temporal-spatial portrait of the brain at work."

The 'Biometrics' of Avalanche Analysis

In another aspect of the same study, Arviv compared avalanches produced during face processing tasks to those avalanches produced when the brain is in a resting state—a state which was studied extensively by Dr. Oren Shriki at the National Institute of Mental Health, in Bethesda, Maryland. In her current research, Arviv identified a fascinating similarity between stimulus-evoked and resting-state avalanches as they occur within individual subjects—indicating that each human brain may be possessed of a 'fingerprint', or unique pattern of avalanche dynamics.

"Our study showed that, for individual subjects, cortical activity—at both the resting state, and during stimulus-evoked activity—shared similar avalanche characteristics in terms of size and distribution, as well as temporal dynamics," she says. "This means that you can potentially identify an individual mathematically, via the brain dynamics represented in the progression of their neural avalanches. This is interesting in terms of fundamental neuroscience, but also points toward the possibility that, sometime in the future, doctors might be able to identify changes in typical excitation-inhibition dynamics, and use it to diagnose neurological abnormalities or disease onset."

Mapping the Shape of Human Thought

According to Arviv, computational avalanche analysis is a new and sophisticated way to characterize the high-level cognition that takes place within the human brain.

"There have been many EEG and fMRI studies that give indirect accounting of neural activity, and localize it to specific areas of the brain. But by using MEG technology, and by focusing on excitation-inhibition dynamics, our analyses reveal new information about how the human brain maintains its electrochemical stability, and processes perceptual stimuli," Arviv says, adding that in her current research, she is applying avalanche analysis to a study of epilepsy. "This approach may shed light on mechanisms involved in maintaining healthy brain balance—and help explain how neural criticality affects cognitive function in both healthy and pathological populations."

Provided by Bar-Ilan University

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