Adaptation to Sensory Input Tunes Visual Cortex to Criticality

Woodrow L. Shew, Wesley P. Clawson, Jeff Pobst, Yahya Karimipanah, Nathaniel C. Wright, and Ralf Wessel

Tim Miller, August Miller, Viviana Nguyen, and Mayisha Nakib

University of Illinois PHYS 596 Team 8

Shew, Woodrow L., Clawson, Wesley P., Pobst, Jeff, Karimipanah, Yahya, Wright, Nathaniel C., Wessel, Ralf. Adaptation to sensory input tunes visual cortex to criticality. Nature Physics. 11, 659-663 (2015)

December 9, 2016

Nerves self-organize to critical point

- Nature Physics 22 June 2015
- Hypothesis: Nerves self-organize to critical point to optimize information processing
- Experimentally and computationally test if strong sensory input causes visual cortex to tune to signal
- Confirm predicted scaling laws theoretically expected at criticality

Red-eared turtle brains harvested for experiment

[0] Image taken from Korzeniec, Monika "Trachemys scripta elegans" Wikimedia Commons (2006)

Critical behavior occurs at phase transitions

- **Critical point** marks transition between two distinct phases/types of behavior
- Phase transitions often break symmetries of system
- Consequently, critical point often marks transition between a more ordered and a less ordered state $\Rightarrow$ "edge of chaos"
- Example: sandpile model[1]

[1] Bak et al., 1987; image from Hesse & Gross, 2014

Hallmarks of criticality

- Branching parameter $\sigma \approx 1$
- Critical slowing down
- Avalanche size S and duration T follow power-law distributions: $D(S) \sim S^{-\tau}$, $D(T) \sim T^{-\alpha}$
- Scale-invariance (self-similarity)

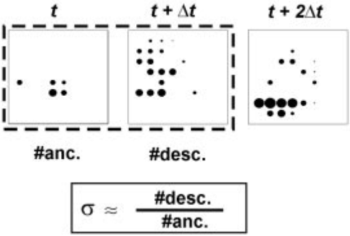


Figure: Branching parameter σ is defined as the # of peaks in activity at time $t + \Delta t$ (descendants) divided by the # of peaks at time t (ancestors).[1]

[1] Image from Beggs & Plenz, 2003

Hallmarks of criticality

- Branching parameter $\sigma \approx 1$
- Critical slowing down
- Avalanche size S and duration T follow power-law distributions: $D(S) \sim S^{-\tau}$, $D(T) \sim T^{-\alpha}$
- Scale-invariance (self-similarity)

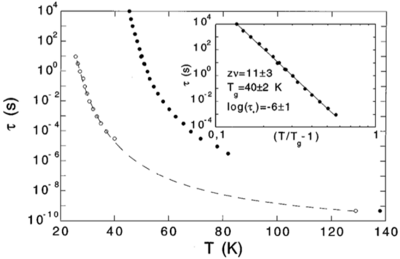


Figure: Relaxation time τ as a function of temperature T for a magnetic nanoparticle system. Inset: τ vs. $(T/T_g - 1)$, where T_g is the transition temperature.[1]

[1] Image from Djurberg et al., 1997

Hallmarks of criticality

- Branching parameter $\sigma \approx 1$
- Critical slowing down
- Avalanche size S and duration T follow power-law distributions: $D(S) \sim S^{-\tau}$, $D(T) \sim T^{-\alpha}$
- Scale-invariance (self-similarity)

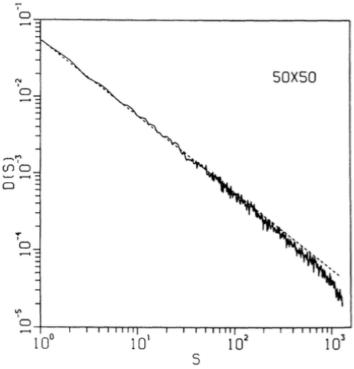


Figure: Distribution of avalanche sizes for sandpile model. Linear relationship on log-log scale indicates a power law.[1]

[1] Image from Bak et al., 1988

Hallmarks of criticality

- Branching parameter $\sigma \approx 1$
- Critical slowing down
- Avalanche size S and duration T follow power-law distributions: $D(S) \sim S^{-\tau}$, $D(T) \sim T^{-\alpha}$
- Scale-invariance (self-similarity)

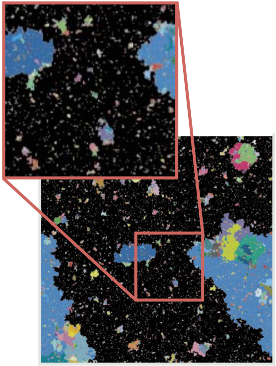


Figure: Cross-section of avalanches from simulation of crackling noise in magnets. Avalanches appear similar across spatial scales.[1]

[1] Image from Sethna et al., 2001

Neuronal networks self-organize to operate at criticality

- Systems at criticality are believed to optimize aspects of memory and information processing
- Verified in models of cellular automata,[1] cellular protein interactions,[2] and neuronal networks[3]
- Led to **criticality hypothesis**: neuronal networks self-organize to the critical point of a phase transition

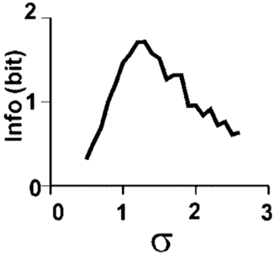


Figure: In a neuronal network model, transmitted information peaks at σ slightly greater than 1, which is indicative of critical behavior.[4]

[1] Langton, 1990

[2] Kauffman & Johnsen, 1991; Kauffman, 1993

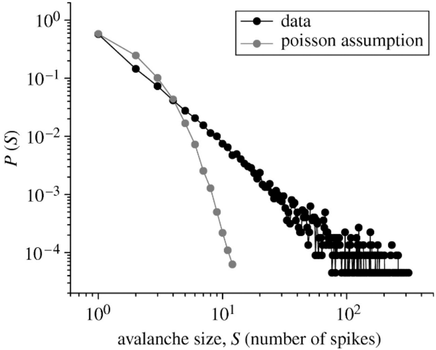
[3] E.g., Chialvo & Bak, 1999

[4] Image from Beggs & Plenz, 2003

History of Criticality and Previous Rat Brain Experiment

- Idea that neural networks adapt to criticality around since 1998[1]
- Previous experiments focus on cerebral cortex in rats[2]
- Several simulations imply critical adaptation exists [3]

Power Law in Rat Cerebral Cortex



Straight line on log plot indicates power law.

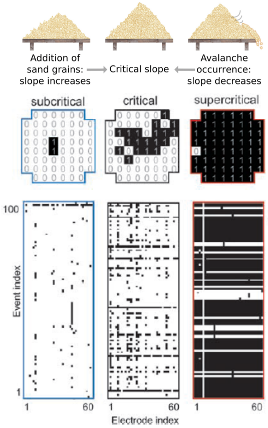
[1] Packard, 1988

[2] Beggs 2008, Image also from Beggs

[3] Rybarsch 2014

2013 Sand Pile Simulation but for Neurons

- Authors follow up there own theoretical studies from 2013
  - higher capacity to carry signals
  - less signal distortion
- Applications in understanding neurological disease: seizures, possibly autism [4]
- New Paper: Unlike prior experiments, this deals directly with incoming signals from external source - vision

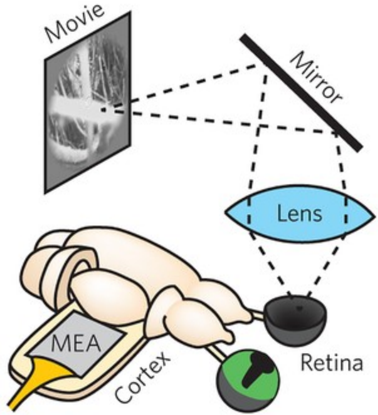


[4] Beggs 2008

[5] Image from Shew, 2013

Experimental Methods: Preparing the Turtle Brain

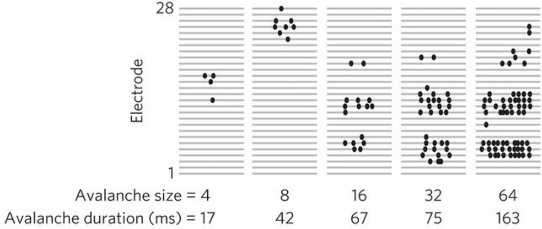
- Brain, optic nerves, and eyes surgically removed from 9 red eared turtles
- One eye cut in half and drained to expose retina
- Microelectrodes array inserted into the eye
- Videos projected onto retina using a projector and lenses to stimulate brain
- Microelectrodes used to measure signals through visual cortex.



[1] Image from Shew, 2015

Experimental Methods: Analyzing the Turtle Brain

- Scaling laws of neuronal avalanches were studied to determine whether or not the network was operating in the critical regime
- Specifically, avalanche size and duration were considered

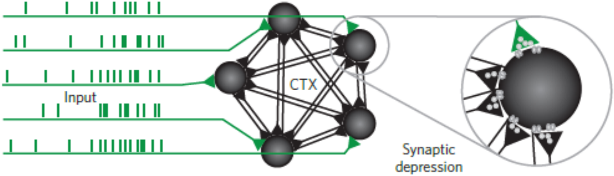


[1] Image from Shew, 2015

Methods: Integrate-and-Fire Dynamics

Computational Component

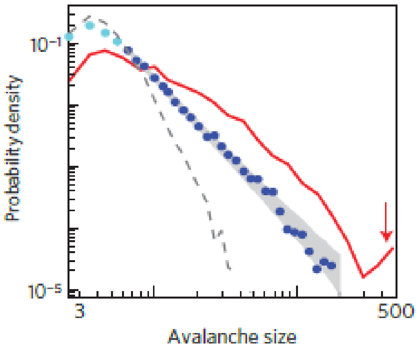
- 1000 Neurons with all-to-all connectivity each with external input
- Integrate-and-fire dynamics with differing synaptic weights leading to probabilistic firing in discrete time
- After firing, firing connections are depressed temporarily.

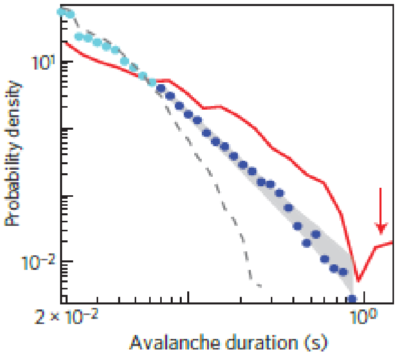


Above is a depiction of the connectivity of the system. All-to-all connectivity means every neuron influences every other neuron.

[1] Image from Shew, 2015

Results: Power-law Scaling in Experiment

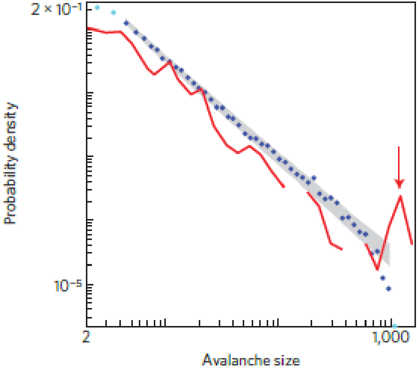


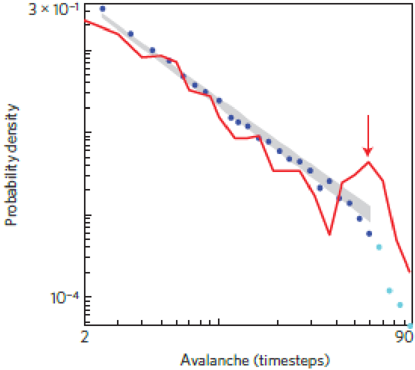


Avalanche size and duration follow power law ($P(D) \sim D^{-\tau}$, $P(s) \sim s^{-\alpha}$)

Results: Power-law Scaling in Simulation

Results 2: Electric Boogaloo

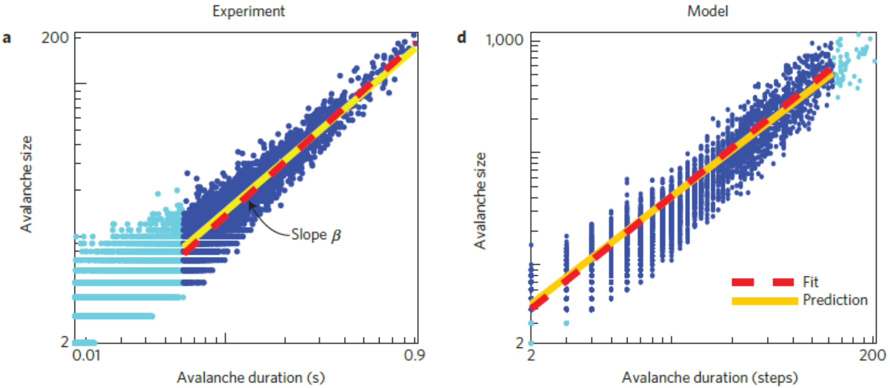




Avalanche size and duration follow power law $(P(D) \sim D^{-\tau}, P(s) \sim s^{-\alpha})$

[1] Image from Shew, 2015

Results: Power-law Avalanches



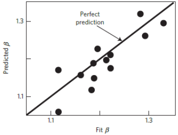
Relationship between avalanche size and duration given by $s \sim D^{-\beta}$, where $\beta = \frac{\alpha - 1}{\tau - 1}$

[1] Image from Shew, 2015

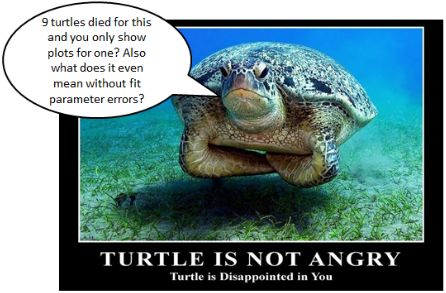
Things that made us mad!

- Paper only shows data for one turtle (others in supplementary), but it does have this:

  β parameters for all turtles



- q values are reported but errors on fit parameters are not
- Deviation between distributions only in supplementary information



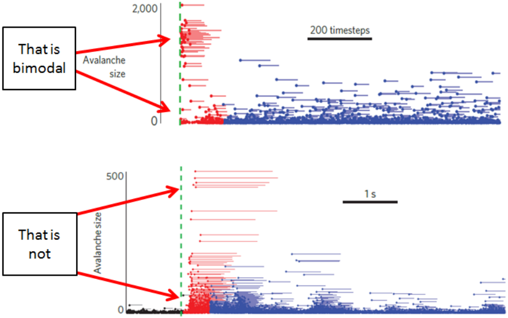
---

[1] Image Mandy Barton's Pintrest

[2] Image Shew, 2015

Things that made us mad!

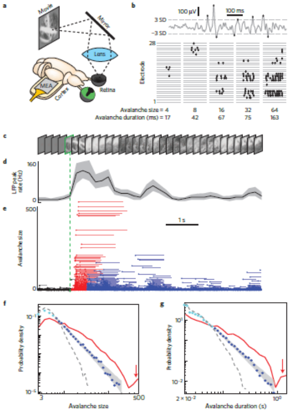
- Why all to all connections?
- Why every neuron receives signal from outside?
- Bi-modal distribution obvious during the transient period for simulation, but not in experiment



[1]Shew, 2015

Things that made us glad!

- Clear concise prose
- Figures organized neatly all in one spot per section
- Authors email you back very quickly



Here's the entire experiment in one snapshot

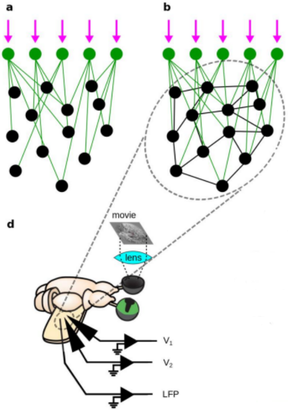
[1] Shew, 2015

Citation Evaluation

- Paper has been cited 13 times (according to the SCOPUS database)
  - Cited by 6 experimental papers
  - Cited by 7 theoretical papers
- Criticality has been found in other organisms including mice and humans

Critical Behavior Confirmed!

- Combines experimental and computational methods
- Avalanche size and duration follow power law, and other criterion characteristic of critical behavior after transient period.
- Would be nice if errors on fit parameters were reported
- Legacy: Ongoing



Newer work: different network and two nerves compared along with local area

[4] Nathaniel C. Wright, Mahmood S. Hoseini, Ralf Wessel, Biorxiv Nov 2016