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# Criticality in the Brain: Evidence and Implications for Neuromorphic Computing

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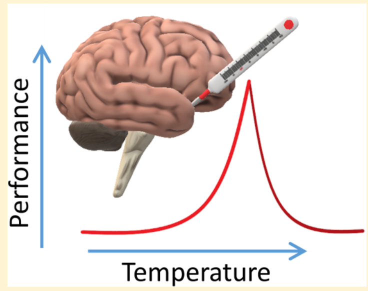
**ABSTRACT:** We have discovered an unexpected correlation between the operational temperature of the brain and cognitive abilities across a wide variety of animal species. This correlation is extracted from available data in the literature of the temperature range $\Delta T$ at which an animal's brain can operate and its encephalization quotient EQ, which can be used as a proxy for cognitive ability. In particular, we found a power-law dependence between $\Delta T$ and EQ. These data support the theory that the brain behaves as a critical system where temperature is one of the critical parameters, tuning the performance of the neural network.




**KEYWORDS:** *Criticality, brain, encephalization quotient, temperature, power law*



One of the biggest challenges for the 21st century is the development of a theory of the way the brain works. A longstanding issue has been the determination of the responsible factors for the brain's cognitive capacity. Neuroscientists often resort to the study of animal brains for their simpler structure. However, despite several decades of research, even a simple cognitive capacity theory for animals remains elusive.[1] Efforts dedicated to quantitatively estimate an animal's cognitive ability have been mostly directed toward problem-solving exercises[2−4] along with the extension of cognitive constructs like the general factor *g*.[5]

Another route explored for quantifying cognitive capacity are physiological proportions. Brain size alone does not correlate well with a higher cognitive capacity, given the examples of elephants and whales. Also, absolute and relative cerebral cortex volume suffer from the same disproportion in elephants and large cetaceans.[1] Recently, it was found that brain size corrected for body mass is a good predictor of cognitive abilities in carnivores.[4] Another physiological proportion, the encephalization quotient EQ, is thought to correlate with intelligence[1,6] and has been used in studies of cognitive capacity.[7,8] Initially advanced in 1973 by Jerison,[9] the encephalization quotient determines the deviation of an animal's brain weight from what would be expected for an animal of its mass. It uses an allometric relation between brain and body weight to account for the empirical fact that a bigger body size does not produce a linearly proportional bigger brain. This has been thoroughly applied to mammals,[9,10] with extensive efforts to apply it to other taxa such as fish,[11] birds,[12] and insects.[13] The ready availability of extensive literature data on animal brain and body weights makes the encephalization quotient a useful, albeit not perfect, tool for comparison of the cognitive capacity across species.

From the computational point of view, the brain is considered the ultimate parallel-computing paradigm. Its capacity stems from a massive interconnected network of neurons and synapses capable of information processing and learning. Information in the brain travels from neuron to neuron in the form of action potentials. These provoke a transient reversal in the polarity of the neuron's electrical membrane potential. Each neuron receives inputs from multiple neurons and delivers its output to multiple others. When the accumulation of inputs in a neuron reaches a certain threshold, action potentials are generated as the result of the voltage-gated opening of $Na^+$ channels.[14] Synapses play a key role in brain computation and memory, and are also affected by action potentials. Upon the arrival of an action potential to the synapse, a $Ca^{2+}$-mediated release of neurotransmitters occurs that triggers a postsynaptic action potential.[15] If the postsynaptic neuron is active at the same time, there will be a high concentration of calcium ions in the postsynaptic side. This concurrence leads to a strengthening of the neural pathway ("long term potentiation"), a fundamental process responsible for learning and memory.[16]

All of these complex physicochemical mechanisms need to be delicately controlled for a correct operation of the brain. One of the factors that heavily influences these mechanisms is temperature. Changes in extraneuronal temperature lead to a change in membrane resting potential. This, in turn, provokes a change in the action potential amplitude and duration, and neurons firing rate. Furthermore, temperature can modify the ion channel diffusion rate and the biochemical reactions rate.[17] It is clear then that the relation between the brain's temperature and its overall cognitive capability becomes an important and intriguing issue to be elucidated.

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Another reason why this issue is relevant is the fact that a lot of attention has been directed toward a new form of computation, which resembles the processes occurring in the brain: neuromorphic computing. From the condensed matter perspective, this has led to the search of solid-state devices that mimic the functionalities of neurons and synapses. It is not clear, however, how all these devices should work together in an optimal way to learn and process information, and this is the main motivation of this work.

In this paper, we use the encephalization quotient EQ of several animal species as a proxy for cognitive ability, and we study its relation to the temperature range $\Delta T$ in which each brain can operate. As we discuss below, our results show that $\Delta T$ behaves as a critical parameter in the brain, which suggests it could indeed be a factor influencing cognitive capacity. This may indicate that the development of a highly functioning brain requires operation in a narrow temperature range, supporting the theory of criticality in the brain.

We have compiled a comprehensive list of brain and body masses from the literature for several species belonging to different taxonomic groups and calculated the associated EQ. The EQ relates an animal's brain and body masses in an allometric fashion: $EQ = M_{brain}/M_{brain}^{exp}$, where the expected brain mass $M_{brain}^{exp} = A(M_{body})^B$. $B$ is the allometric exponent, and $A$ is a normalization constant. In general, for a wide variety of taxa, the allometric exponent $B$ lies between 0.5 and 0.8.[11,13,18] In this paper, we have used $B = 0.66$ as the allometric exponent.[9] We have also searched the literature for the temperature range $\Delta T$ at which each animal's brain (or in the absence of brain data, its body) can operate. In some cases, $\Delta T$ is underestimated due to the fact that no experiments were found where body temperature is pushed to the limit.

Table 1 shows the values obtained for each species as well as the associated literature references. An asterisk indicates the cases in which brain temperature data was not found.

In Figure 1, we have plotted the temperature range $\Delta T$ as a function of the encephalization quotient EQ on a broad parameter range of more than 2 orders of magnitude for both parameters. The result is astonishing. In a log–log scale, a straight line is obtained, which implies a power-law relation between $\Delta T$ and the encephalization quotient. A linear fit of the data (red line) to the equation $\log(\Delta T) = a + b\log(EQ)$ gives an adjusted $r^2$ of 0.9 and a slope $b = -0.54 \pm 0.05$.

**Table 1. Values for brain mass ($M_{brain}$), body mass ($M_{body}$), encephalization quotient (EQ), temperature range ($\Delta T$) and the references from where the values where extracted**

| Animal | $M_{brain}$ (g) | $M_{body}$ (g) | EQ | $\Delta T$ (°C) | mass/temp ref |
|---|---|---|---|---|---|
| Human | 1350 | 70 000 | 8.562 | 2.1 | 18/19 |
| Elephant* | 5220 | 321 600 | 2.648 | 2.7 | 20/21 |
| Penguin* | 17.3 | 3300 | 0.824 | 3 | 22/23 |
| Seal | 297 | 102 414 | 1.465 | 3.5 | 24/25 |
| Raven | 15.4 | 1200 | 1.430 | 5 | 26/27 |
| Wildebeest | 363 | 158 489 | 1.342 | 5.2 | 28/29 |
| Parrot* | 5.7 | 330 | 1.241 | 5.8 | 30/23 |
| Manta ray | 58.8 | 61 760 | 0.405 | 6 | 31/32–34 |
| Rat | 2 | 300 | 0.464 | 7 | 1/35 |
| Dogfish shark | 3.87 | 4200 | 0.157 | 11 | 31/32 |
| Lizard | 0.07 | 8 | 0.177 | 17 | 36/37 |
| Crocodile* | 7.886 | 70 000 | 0.050 | 17 | 38/39 |
| Frog* | 0.1 | 53 | 0.073 | 29 | 40/41 |
| Octopus* | 1.15 | 3292 | 0.055 | 31.8 | 42/43 |
| Wolf spider | 0.000237 | 0.0152 | 0.038 | 38 | 44/45 |

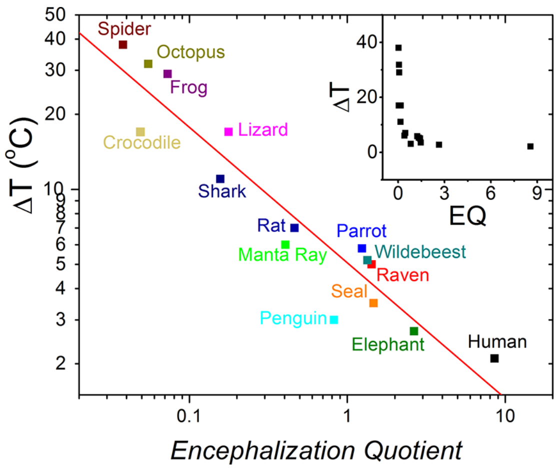


**Figure 1.** Temperature range $\Delta T$ as a function of the encephalization quotient EQ for several species. The red line represents the linear fit to the equation $\log(\Delta T) = a + b\log(EQ)$. Inset: same data represented in linear scale to highlight the criticality.

The large adjusted $r^2$ implies a high degree of correlation between the encephalization quotient and the temperature range at which the brain operates. However, as imperfect a measurement of cognitive capacity the EQ is, it seems that $\Delta T$ and cognitive ability are strongly correlated. Intuitively, we can understand this power-law dependence from the inset in Figure 1, where the same data is represented in a linear scale. Here we can see that $\Delta T$ is behaving as a critical parameter, i.e., EQ seems to diverge at $\Delta T = 0$. In other words, a small deviation from the optimal value $\Delta T = 0$ provokes a sharp degradation in EQ. This is the hallmark of a parameter that can critically tune the performance of a system.

It has been proposed that neuronal networks are critical systems,[46−49] in which there is a balance between excitation and inhibition of neuron spiking rates. Criticality is a characteristic found in numerous solid state critical systems.[50−53] In these systems, there is a parameter (usually temperature) or set of parameters that has a critical point in which a property of the system changes radically. For example, water has a liquid–vapor critical point where liquid water suddenly becomes compressible, a poor dielectric and a bad solvent.[54] Systems at the critical point also show power-law behaviors, fractality and avalanches.

All of these critical characteristics have been observed in the brain. Several studies of the brain have measured spike avalanches and found their sizes to follow power laws.[55−58] Moreover, there is evidence showing a disappearance of these power laws when synaptic transmissions are dampened, i.e., the system is tuned out of the critical point.[55] Several neuronal computation models have also shown that at the critical point network characteristics such as communication,[59] information storage,[60] computational power[61] and dynamic range[47] are optimally enhanced. Crucially, these works show that a neuronal network would be less capable when operating away from its critical point. This seems to be the same behavior observed in our data.

Temperature greatly influences neuronal-function characteristics including the activation of ion channels, neuronal membranes resting potential, pre- and postsynaptic transmitter release and conduction velocity of action potentials.[62−64] In this


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sense, temperature could be considered a parameter of the neuronal network determining its criticality. Therefore, at temperatures far from the critical temperature, the brain's operational capacity would be decreased. This hypothesis would explain the critical behavior of $\Delta T$ seen in Figure 1.

There are other biological variables that show a critical behavior in the brain. For instance, tight regulation of glucose metabolism is critical for brain physiology.[65] Since the mammalian brain depends upon glucose as its main source of energy, it is not inconceivable that thermoregulation (i.e., $\Delta T$) could be related to this.[65,66] An alternate explanation based on the parallel but independent evolutionary improvement of the cognitive capacity and temperature regulation for unknown reasons at this stage, may lead to a similar behavior. However, it is not clear how that would result in the critical behavior observed for $\Delta T$. A straightforward way to verify our hypothesis of temperature being a critical parameter would be to undertake experiments where animals are required to solve cognitive tasks while controlling the temperature of the brain. A lower performance in the cognitive tasks should be observed for bigger brain temperature deviations. Also, we could think of ways to impair the thermal regulatory system through drugs or DNA editing and study the impact on the performance on cognitive tasks.

Such verification would have deep implications for areas like neuroscience or psychology. The data seem to support the theory of criticality as an explanation of how the brain works. The brain's level of cognitive capacity would be directly linked to the body's ability to maintain the neural network near the critical point, may it be through temperature, supply of ions for action potential transmission, a correct regulation of the excitatory and inhibitory chemical agents or all of these parameters together. A brain incapable of achieving this equilibrium would be a pathological one. In fact, it has been observed that characteristics of criticality disappear on patients suffering epileptic episodes recorded using invasive encephalography.[67] Therefore, the perturbation of the critical state in the brain could be indicative of a disease, which would imply the need for new therapies that address said imbalance.

In the same way, these results are relevant for the development of neuromorphic computing. In order to achieve maximum processing power and efficiency, the network has to be tuned to stay as close as possible to the critical point. It is no longer enough to just consume higher power. The choice of materials, density, distribution and interconnection of components (e.g., oscillators, memristors), their nonlinear $I-V$ characteristics, operational temperature, and so forth will be of critical importance.

In summary, we have discovered a correlation between the temperature range $\Delta T$ at which an animal's brain can operate and its encephalization quotient EQ. We find a clear power-law dependence between $\Delta T$ and the EQ across many animal species. The exact physical mechanism driving this is not clear at present time. Insofar the EQ is a proxy for cognitive ability, this implies that a narrow $\Delta T$ is favorable for high cognitive ability. These results seem to weigh in support of the theory of criticality in the brain and have important implications for the neuroscience and psychology community, in particular the potential development of new neurological disorder treatments.

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### Notes

The authors declare no competing financial interest.

## REFERENCES

(1) Roth, G., and Dicke, U. (2005) Evolution of the brain and intelligence. *Trends Cognit. Sci. 9*, 250−257.

(2) Macphail, E. M. (1982) *Brain and Intelligence in Vertebrates*, Clarendon Press, Oxford, England.

(3) Plowright, C. M. S., Reid, S., and Kilian, T. (1998) Finding hidden food: Behavior on visible displacement tasks by mynahs (Gracula religiosa) and pigeons (Columba livia). *J. Comp. Psychol. 112*, 13−25.

(4) Benson-Amram, S., Dantzer, B., Stricker, G., Swanson, E. M., and Holekamp, K. E. (2016) Brain size predicts problem-solving ability in mammalian carnivores. *Proc. Natl. Acad. Sci. U. S. A. 113*, 2532−2537.

(5) Deary, I. J., Lawn, M., and Bartholomew, D. J. (2008) A conversation between Charles Spearman, Godfrey Thomson, and Edward L. Thorndike: The International Examinations Inquiry Meetings 1931−1938. *Hist. Psychol. 11*, 122−142.

(6) Jerison, H. J., and Barlow, H. B. (1985) Animal Intelligence as Encephalization [and Discussion]. *Philos. Trans. R. Soc., B 308*, 21−35.

(7) Williams, M. F. (2002) Primate encephalization and intelligence. *Med. Hypotheses 58*, 284−290.

(8) Herzing, D. L. (2014) Profiling nonhuman intelligence: An exercise in developing unbiased tools for describing other "types" of intelligence on earth. *Acta Astronaut. 94*, 676−680.

(9) Jerison, H. J. (1976) Evolution of the Brain and Intelligence: Comment on Radinsky's Review. *Evolution 30*, 186−187.

(10) Boddy, A. M., Mcgowen, M. R., Sherwood, C. C., Grossman, L. I., Goodman, M., and Wildman, D. E. (2012) Comparative analysis of encephalization in mammals reveals relaxed constraints on anthropoid primate and cetacean brain scaling. *J. Evol. Biol. 25*, 981−994.

(11) Isler, K. (2013) Brain size evolution: How fish pay for being smart. *Curr. Biol. 23*, R63−R65.

(12) Isler, K., and van Schaik, C. (2006) Costs of encephalization: the energy trade-off hypothesis tested on birds. *J. Hum. Evol. 51*, 228−243.

(13) Wehner, R., Fukushi, T., and Isler, K. (2007) On being small: Brain allometry in ants. *Brain. Behav. Evol. 69*, 220−228.

(14) Barnett, M. W., and Larkman, P. M. (2007) The action potential. *Pract. Neurol. 7*, 192−197.

(15) Südhof, T. C. (2013) Neurotransmitter release: The last millisecond in the life of a synaptic vesicle. *Neuron 80*, 675−690.

(16) LYNCH, M. A. (2004) Long-Term Potentiation and Memory. *Physiol. Rev. 84*, 87−136.

(17) Buzatu, S. (2009) The temperature-induced changes in membrane potential. *Riv. Biol. 102*, 199−217.

(18) Jerison, H. J. (1977) the Theory of Encephalization. *Ann. N. Y. Acad. Sci. 299*, 146−160.

(19) Sund-Levander, M., Forsberg, C., and Wahren, L. K. (2002) Normal oral, rectal, tympanic and axillary body temperature in adult men and women: A systematic literature review. *Scand. J. Caring Sci. 16*, 122−128.



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ACS Chem. Neurosci. 2018, 9, 1254−1258

(20) Shoshani, J., Kupsky, W. J., and Marchant, G. H. (2006) Elephant brain. Part I: Gross morphology, functions, comparative anatomy, and evolution. *Brain Res. Bull. 70*, 124−157.
(21) Weissenböck, N. M., Arnold, W., and Ruf, T. (2012) Taking the heat: Thermoregulation in Asian elephants under different climatic conditions. *J. Comp. Physiol., B 182*, 311−319.
(22) Bee de Speroni, N., and Pirlot, P. (1987) Relative size of avian brain components of the magellanic penguin, the greater rhea and the tataupa tinamou. *Marine Ornithol. 15*, 7−22.
(23) Prinzinger, R., Preßmar, A., and Schleucher, E. (1991) Body temperature in birds. *Comp. Biochem. Physiol. Part A Physiol. 99*, 499−506.
(24) Kovacs, K. I. T. M., and Lavigne, D. M. (1985) Neonatal growth and organ allometry of Northwest Atlantic harp seals (Phoca groenlandica). *Can. J. Zool. 63*, 2793−2799.
(25) Blix, A. S., Walloe, L., Messelt, E. B., and Folkow, L. P. (2010) Selective brain cooling and its vascular basis in diving seals. *J. Exp. Biol. 213*, 2610−2616.
(26) Mlíkovský, J. (2003) Brain size and foramen magnum area in crows and allies (Aves: Corvidae). *Acta Soc. Zool. Bohem. 67*, 203−211.
(27) Marder, J. (1973) Body temperature regulation in the brown-necked raven (Corvus Corax ruficollis). I. Metabolic rate, evaporative water loss and body temperature of the raven exposed to heat stress. *Comp. Biochem. Physiol. A Mol. Integr. Physiol. 45*, 421−30.
(28) Shultz, S., and Dunbar, R. I. (2006) Both social and ecological factors predict ungulate brain size. *Proc. R. Soc. London, Ser. B 273*, 207−215.
(29) Jessen, C., Laburn, H. P., Knight, M. H., Kuhnen, G., Goelst, K., and Mitchell, D. (1994) Blood and brain temperatures of free-ranging black wildebeest in their natural environment. *Am. J. Physiol. - Regul. Integr. Comp. Physiol. 267*, R1528−R1536.
(30) Cairó, O. (2011) External measures of cognition. *Front. Hum. Neurosci. 5*, 108.
(31) Ari, C. (2011) Encephalization and Brain Organization of Mobulid Rays (Myliobatiformes, Elasmobranchii) with Ecological Perspectives. *Open Anat. J. 3*, 1−13.
(32) Block, B. A., and Carey, F. G. (1985) Warm brain and eye temperatures in sharks. *J. Comp. Physiol., B 156*, 229−236.
(33) Schweitzer, J., and Notarbartolo-Di-Sciara, G. (1986) The rete mirabile cranica in the genus Mobula: A comparative study. *J. Morphol. 188*, 167−178.
(34) Thorrold, S. R., Afonso, P., Fontes, J., Braun, C. D., Santos, R. S., Skomal, G. B., and Berumen, M. L. (2014) Extreme diving behaviour in devil rays links surface waters and the deep ocean. *Nat. Commun. 5*, 1−7.
(35) Bicher, H. I., Mitagvaria, N., Devdariani, M., Davlianidze, L., Nebieridze, M., and Momtselidze, N. (2013) Autoregulation of the Brain Temperature during Whole Body Hyperthermia. *Conf. Pap. Med. 2013*, 1−5.
(36) Nieuwenhuys, R., ten Donkelaar, H. J., and Nicholson, C. (1998) *The Central Nervous System of Vertebrates*, Springer: Berlin, Heidelberg.
(37) Trautwein, S. N., Gordon, C. J., and Heath, J. E. (1985) Changes in brain and body temperature of the lizard, Sceloporus undulatus hyacinthinus during rest and exercise. *Comp. Biochem. Physiol. Part A Physiol. 80*, 199−204.
(38) Ngwenya, A., Patzke, N., Spocter, M. A., Kruger, J. L., Dell, L. A., Chawana, R., Mazengenya, P., Billings, B. K., Olaleye, O., Herculano-Houzel, S., and Manger, P. R. (2013) The continuously growing central nervous system of the nile crocodile (Crocodylus niloticus). *Anat. Rec. 296*, 1489−1500.
(39) Seebacher, F., and Grigg, G. C. (1997) Patterns of body temperature in wild freshwater crocodiles, Crocodylus johnstoni: thermoregulation versus thermoconformity, seasonal acclimatization, and the effect of social interactions. *Copeia 1997*, 549−557.
(40) Linzey, D. (2003) *Vertebrate Biology*, McGraw Hill, Johns Hopkins University Press, Baltimore, MD.
(41) Reeves, R. B. (1972) An imidazole alphastat hypothesis for vertebrate acid-base regulation: Tissue carbon dioxide content and body temperature in bullfrogs. *Respir. Physiol. 14*, 219−236.
(42) Packard, a., and Albergoni, V. (1970) Relative growth, nucleic acid content and cell numbers of the brain in Octopus vulgaris (Lamarck). *J. Exp. Biol. 52*, 539−552.
(43) Garrett, S., and Rosenthal, J. J. C. (2012) RNA editing underlies temperature adaptation in K+ channels from polar octopuses. *Science 335*, 848−851.
(44) Punzo, F., and Ludwig, L. (2002) Contact with maternal parent and siblings affects hunting behavior, learning, and central nervous system development in spiderlings of Hogna carolinensis (Araeneae: Lycosidae). *Anim. Cogn. 5*, 63−70.
(45) Humphreys, W. F. (1974) Behavioural thermoregulation in a wolf spider. *Nature 251*, 502−503.
(46) De Arcangelis, L., Perrone-Capano, C., and Herrmann, H. J. (2006) Self-organized criticality model for brain plasticity. *Phys. Rev. Lett. 96*, 28107.
(47) Kinouchi, O., and Copelli, M. (2006) Optimal dynamical range of excitable networks at criticality. *Nat. Phys. 2*, 348−352.
(48) Kitzbichler, M. G., Smith, M. L., Christensen, S. R., and Bullmore, E. (2009) Broadband criticality of human brain network synchronization. *PLoS Comput. Biol. 5*, e1000314.
(49) Beggs, J. M., and Timme, N. (2012) Being critical of criticality in the brain. *Front. Physiol. 3*, 1−14.
(50) Bak, P., Tang, C., and Wiesenfeld, K. (1987) Self-organized criticality: An explanation of the 1/f noise. *Phys. Rev. Lett. 59*, 381−384.
(51) Cote, P. J., and Meisel, L. V. (1991) Self-organized criticality and the Barkhausen effect. *Phys. Rev. Lett. 67*, 1334−1337.
(52) Vives, E., Ortín, J., Mañosa, L., Ràfols, I., Pérez-Magrané, R., and Planes, A. (1994) Distributions of avalanches in martensitic transformations. *Phys. Rev. Lett. 72*, 1694−1697.
(53) Sharoni, A., Ramirez, J. G., and Schuller, I. K. (2008) Multiple avalanches across the metal-insulator transition of vanadium oxide nanoscaled junctions. *Phys. Rev. Lett. 101*, 26404.
(54) Anisimov, M. A., Sengers, J. V., and Sengers, J. M. H. L. (2004) Near-critical behaviour of aqueous systems. In *Aqueous Systems at Elevated Temperatures and Pressures* (Palmer, D. A., Fernández-Prini, R., and Harvey, A. H., Eds.), pp 29−71, Elsevier.
(55) Mazzoni, A., Broccard, F. D., Garcia-Perez, E., Bonifazi, P., Ruaro, M. E., and Torre, V. (2007) On the dynamics of the spontaneous activity in neuronal networks. *PLoS One 2*, e439.
(56) Gireesh, E. D., and Plenz, D. (2008) Neuronal avalanches organize as nested theta- and beta/gamma-oscillations during development of cortical layer 2/3. *Proc. Natl. Acad. Sci. U. S. A. 105*, 7576−7581.
(57) Petermann, T., Thiagarajan, T. C., Lebedev, M. A., Nicolelis, M. A. L., Chialvo, D. R., and Plenz, D. (2009) Spontaneous cortical activity in awake monkeys composed of neuronal avalanches. *Proc. Natl. Acad. Sci. U. S. A. 106*, 15921−15926.
(58) Miller, K. J., Sorensen, L. B., Ojemann, J. G., and Den Nijs, M. (2009) Power-law scaling in the brain surface electric potential. *PLoS Comput. Biol. 5*, e1000609.
(59) Beggs, J. M., and Plenz, D. (2003) Neuronal Avalanches in Neocortical Circuits. *J. Neurosci. 23*, 11167−11177.
(60) Socolar, J. E. S., and Kauffman, S. A. (2003) Scaling in ordered and critical random Boolean networks. *Phys. Rev. Lett. 90*, 068702.
(61) Bertschinger, N., and Natschläger, T. (2004) Real-Time Computation at the Edge of Chaos in Recurrent Neural Networks. *Neural Comput. 16*, 1413−1436.
(62) Abrams, T. W., and Pearson, K. G. (1982) Effects of temperature on identified central neurons that control jumping in the grasshopper. *J. Neurosci. 2*, 1538−1553.
(63) Janssen, R. (1992) Thermal influences on nervous system function. *Neurosci. Biobehav. Rev. 16*, 399−413.
(64) Warzecha, A.-K., Horstmann, W., and Egelhaaf, M. (1999) Temperature-dependence of neuronal performance in the motion


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*ACS Chem. Neurosci.* 2018, 9, 1254−1258

pathway of the blowfly Calliphora erythrocephala. *J. Exp. Biol. 202*, 3161−3170.
(65) Mergenthaler, P., Lindauer, U., Dienel, G. A., and Meisel, A. (2013) Sugar for the brain: The role of glucose in physiological and pathological brain function. *Trends Neurosci. 36*, 587−597.
(66) Roh, E., Song, D. K., and Kim, M.-S. (2016) Emerging role of the brain in the homeostatic regulation of energy and glucose metabolism. *Exp. Mol. Med. 48*, e216.
(67) Meisel, C., Storch, A., Hallmeyer-Elgner, S., Bullmore, E., and Gross, T. (2012) Failure of adaptive self-organized criticality during epileptic seizure attacks. *PLoS Comput. Biol. 8*, e1002312.


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