Artificial astrocyte networks

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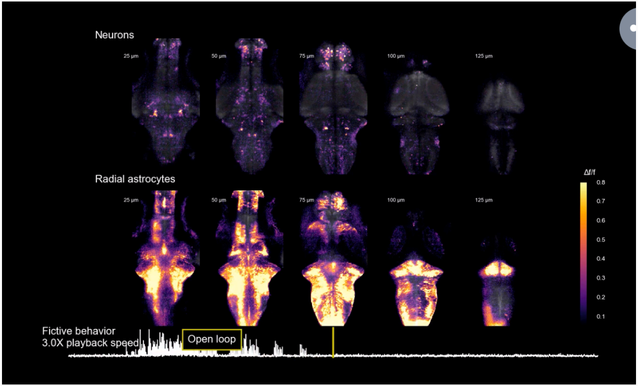
Astrocytes and cognition.



Neural (*top*) and astrocyte $[Ca^{2+}]$ dynamics (bottom) during frustrated movement. (Mu et al, *Cell* 2019; Taken from Video S2.)

Astrocytes and cognition.

- Can astrocyte $[Ca^{2+}]$ dynamics do distributed computation?

A theory for astrocytes?

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Artificial Astrocytes Improve Neural Network Performance

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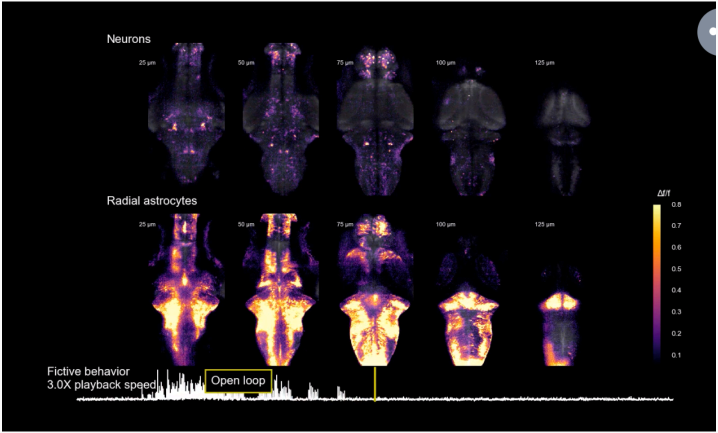
Abstract

Compelling evidence indicates the existence of bidirectional communication between astrocytes and neurons. Astrocytes, a type of glial cells classically considered to be passive supportive cells, have been recently demonstrated to be actively involved in the processing and regulation of synaptic information, suggesting that brain function arises from the activity of neuron-glia networks. However, the actual impact of astrocytes in neural network function is largely unknown and its application in artificial intelligence remains untested. We have investigated the consequences of including artificial astrocytes, which present the biologically defined properties involved in astrocyte-neuron communication, on artificial neural network performance. Using connectionist systems and evolutionary algorithms, we have compared the performance of artificial neural networks (NN) and artificial neuron-glia networks (NGN) to solve classification problems. We show that the degree of success of NGN is superior to NN. Analysis of performances of NN with different number of neurons or different architectures indicate that the effects of NGN cannot be accounted for an increased number of network elements, but rather they are specifically due to astrocytes. Furthermore, the relative efficacy of NGN vs. NN increases as the complexity of the network increases. These results indicate that artificial astrocytes improve neural network performance, and established the concept of Artificial Neuron-Glia Networks, which represents a novel concept in Artificial Intelligence with implications in computational science as well as in the understanding of brain function.

- Very little theoretical study of astrocyte computation.
- Focus is on neuron-glia interactions.

Astrocytes and cognition?



How to explain this result? We need a new theoretical account?

Goal of this talk.

- Prove two new results for distributed astrocyte computation.

Artificial neural networks.

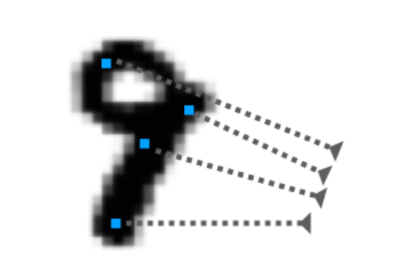
Visual digit recognition.

= 1,2,3,4,5,6,...

What are ANNs?

$= 9?$

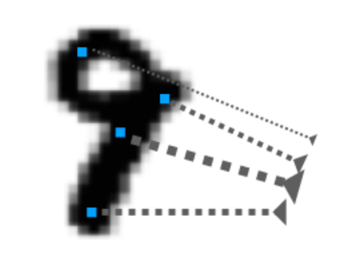
What are ANNs?



x

$\sum x_{ij} = 9$

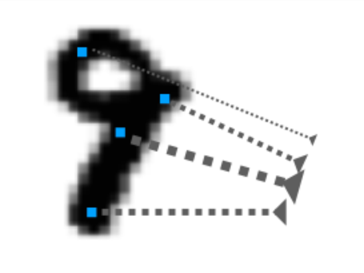
What are ANNs?



x

$$\sum w_{ij}x_{ij} + b_i = 9$$

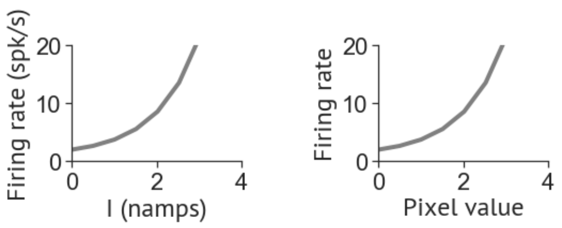
What are ANNs?



x

$$\phi(\sum w_{ij} x_{ij} + b_i) = 9$$

What are ANNs?



FI-curve (left) $\approx$ ϕ nonlinearity (right)

What are ANNs?

A deep ANN network. Each box is a *layer*: $\phi(\sum w_{ij}x_{ij} + b_i)$

AANs

Basic astrocyte limits.

- No synapses
- No axons
- No spikes

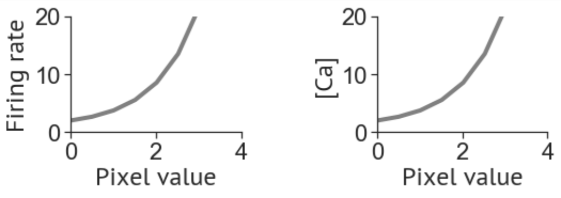
Basic astrocyte properties

- $[Ca^{2+}]$ dynamics
- $[Ca^{2+}]$ dependent gliotransmission

Recovering $\{\phi, w_i, \sum\}$?

- Let's make four assumptions that let us form a functional analogy between neurons and astrocytes.

Assumption 1 (ϕ).

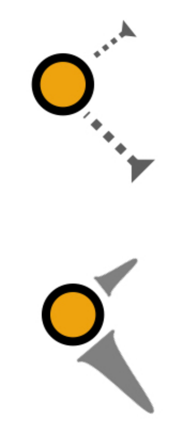


Firing rate (left) $\leftrightarrow$ [Ca^{2+}] dynamics (right)

-

Assumption 2 (w_i).

- Directional $[Ca^{2+}]$-dependent gliotransmission.



Assumption 3 ($\sum$).

- Directional $[Ca^{2+}]$ waves, driven by gliotransmission.
    - Axons send spikes across a spatial distances with fidelity.
    - A $[Ca^{2+}]$ wave can travel a spatial distance with fidelity.

Assumption 4 (locals only).

- Only nearest neighbor cells can communicate.

In theory.

Computational calcium waves.

- Let's treat neurons only as a source of input; glia do all the computation!
- Let's study a forward moving $[Ca^{2+}]$ wave (Assump. 1-4).
- Prove: our simple model of $[Ca^{2+}]$ waves is a universal function approximator.

A universal function approximator.

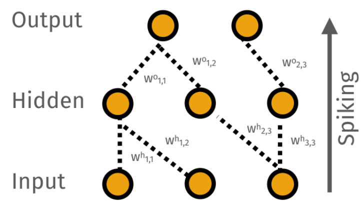
$|D - f(x)| < \epsilon$

D : visual recognition system in fly (*target*)

$f(x)$: an ANN (*approximator*)

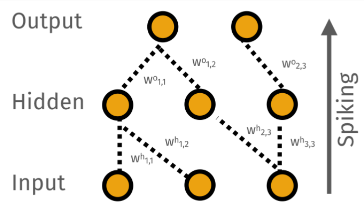
ϵ : the error (*a positive number*)

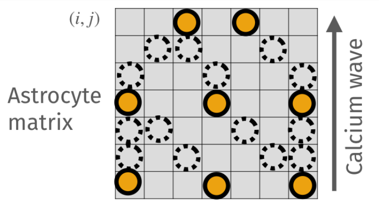
Proof sketch.



- D can be approximated by f in $M << N$ connections.
- Bölcskei et al, *J. Math. of Data Science* 2019.
- Accept: $|D - f(x)| < \epsilon$

Proof sketch.

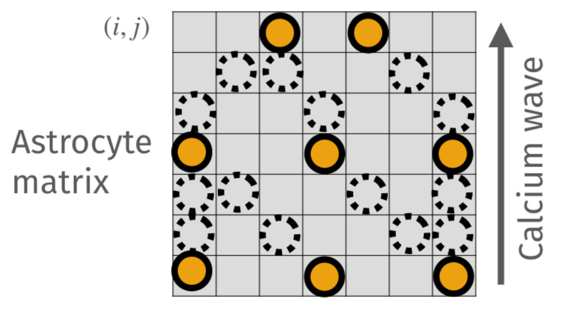




- *D* can be approximated by *f* in $M << N$ connections.
- Bölcskei et al, *J. Math. of Data Science* 2019.
- Accept: $|D - f(x)| < \epsilon$

- If summed "weight" of a Ca^{2+} wave is the same as an axon.
- Then the networks are equivalent.
- Also accept: $|D - g(x)| < \epsilon$

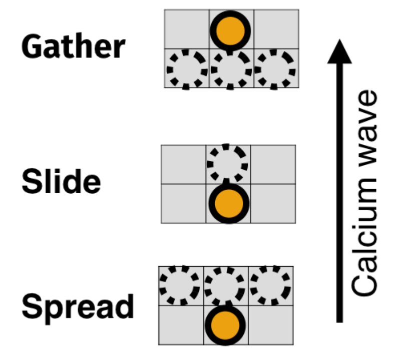
Proof sketch.



Astrocyte Sudoku.

In practice.

Three kinds of astrocyte layers.



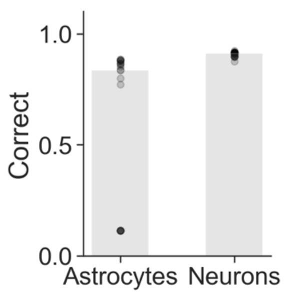
I explored three fundamental kinds of astrocyte Ca^{2+} waves [in PyTorch].

An astrocyte network.

- Two equivalent neural (*left*) and astrocyte networks (*right*).
- For astrocyte computation width requires depth.

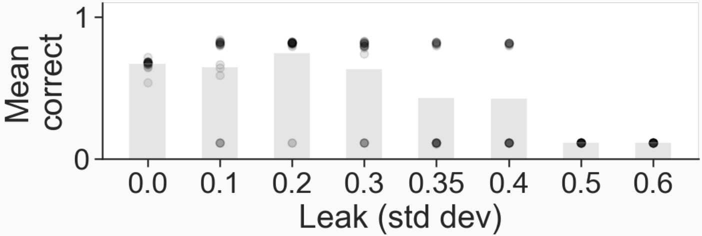
Methods.

- Task: MINST digits
- Use: $\{slide, spread, gather\}$ in pytorch
  1. VAE, $N = (784, 20)$
  2. Perceptron, $N = (20, 30, 10)$
- Loss: Cross-entropy
- Optimizer: ADAM (stochastic gradient descent).



Test set performance (N=20 epochs)

Results.



Effect of gliotransmitter diffusion on model performance

Conclusions.

Conclusions.

- Artifical astrocytes can compute any function, in theory.
- An upper bound for the performance of real astrocytes?
- Our simple model Ca^{2+} waves can solve hard vision problems, in practice.

Future work.

- Artificial upper bound $\rightarrow$ biological upper bound (help)
- Recurrent waves (in collaboration)
- Better motivated tasks (help)

Open science.

Code `github.com/CoAxLab/glia_playing_atari`

Talk `github.com/parenthetical-e/glia-talk-sfn-2019`

Thank you!