New Types of Experiments Reveal that a Neuron Functions as Multiple Independent Threshold

Presenter: Mehmet Ali Akyol
What is the basic computational unit of brain?
The cortical column?
The gene?

The neuron?

A neuron has 3 main elements:

- **Soma**: considered as a nonlinear computational unit
- **Dendrites**: collect the incoming signals to the soma
- **Axon**: transmits signal from the soma to the synapses
The dendritic trees are responsible for collecting the incoming electrical signals to the soma.
The number of dendrites can exceed thousands, while a single axon transmits the signal from the soma to the synapses of connected neurons.
The diameter of the soma is a few tens of micrometers and is negligible comparing to the length of the dendrites and the axon, which can exceed millimeters.

The soma is considered a crucial nonlinear computational element in the dynamics of the neuron.
Ion Pumps

- Neurons are covered with a semi-permeable membrane
- The membrane selectively absorb or reject ions in the intracellular fluid
- The membrane acts as an ion pump to maintain a different ion concentration between the internal and external fluids
- Sodium ions are removed from the internal fluid and potassium ions are absorbed from the external fluid to maintain an equilibrium condition
Resting Potential

- Due to the difference in the ion concentrations inside and outside, the cell membrane become polarized

- In the equilibrium, the interior of the cell is around -70 millivolts negative with respect to the outside. This potential difference is called resting potential
Action Potential

- Action potentials are electrical impulses that send signals through neuron, which are simply a temporary shift from negative to positive in the neuron’s membrane potential caused by ions suddenly flowing in and out of the neuron.
McCulloch and Pitts Model

- In 1943, neurophysiologist Warren McCulloch and mathematician Walter Pitts wrote a paper on how neurons might work.
- In order to describe how neurons in the brain might work, they modeled a simple neural network using electrical circuits.
McCulloch and Pitts Model
Artificial Neuron Model

https://medium.com/technologymadeeasy/for-dummies-the-introduction-to-neural-networks-we-all-need-c50f6012d5eb
Neuron

- For decades, neurons are known for the computational elements that compose the brain and their fundamental principles of activity.

- According to the long-lasting computational scheme, each neuron sums the incoming electrical signals via its dendrites and when the membrane potential reaches a certain threshold the neuron typically generates a spike to its axon.
A Threshold unit

B Discontinuous transmission

\[ f(W) \Theta [W - Th] \]
Models for a Neuron Functioning as an Excitable Threshold Element

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<th>Neuronal model</th>
<th>Neuronal equation</th>
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| I | ![Neuronal Model Diagram](image) | \[ \Theta \left[ W_1(t) + W_2(t) + W_3(t) - Th \right] \\
|   |                | \[ W_i(t) = \sum_j W_{i,j}(t-t_{i,j}) \] |
Models for a Neuron Functioning as a Excitable
Threshold Element

\[
\Theta \left[ f_1(W_1(t))\Theta[W_1(t) - Th_1] + f_2(W_2(t))\Theta[W_2(t) - Th_2] + f_3(W_3(t))\Theta[W_3(t) - Th_3] - Th \right]
\]
Models for a Neuron Functioning as a Excitable Threshold Element

\[ \Theta[W_1(t)-Th_1] \]
\[ \text{OR} \]
\[ \Theta[W_2(t)-Th_2] \]
\[ \text{OR} \]
\[ \Theta[W_3(t)-Th_3] \]
The study presents 3 types of experiments, using neuronal cultures, indicating that each neuron functions as a collection of independent threshold units.

The neuron is anisotropically activated following the origin of the arriving signals to the membrane, via its dendritic trees.
Experiments

- These 3 experiments present the computation scheme of a neuron based on nonlinear and discontinuous responses by the dendrites and/or the neurons.
Experiments

- Variability in the Spike of Waveforms
- Absence of Anisotropic Spatial Summation
- Absence of Intra- and Extra- Summation and Subtraction
Variability in the Spike of Waveforms

Consists of alternating stimulations of a neuron by two extracellular electrodes.
Variability in the Spike of Waveforms

Two stimulating electrodes generate two distinguishable sets of waveforms.
Variability in the Spike of Waveforms

The waveforms are not identical under either translation or rescaling of the voltage of one of the sets.
Variability in the Spike of Waveforms

- Results show that for a given neuron the waveform of a spike is not independent of the origin of the stimulation and its relative direction.
Absence of Anisotropic Spatial Summation

- Spatial summation is crucial to control and maintain the activity of neural networks.
- Current assumption is that the neuron integrates the incoming signals in an isotropic manner, independent of their arriving routes to the soma.
Absence of Anisotropic Spatial Summation

The experiment consists of two extracellular electrodes which were detected to reliably generate evoked spikes recorded intracellularly.
Absence of Anisotropic Spatial Summation

NRL and the threshold amplitude was estimated for each one of the two electrodes.
Absence of Anisotropic Spatial Summation

Based on the NRLs of the two electrodes, the neuron was repeatedly stimulated
Absence of Anisotropic Spatial Summation

- Results indicate that the neuron does not generate spikes even the two stimulations arrive simultaneously to the soma from two different directions and their amplitude sum significantly exceed the threshold.
Absence of Intra- and Extra- Summation and Subtraction

- The second experiment indicated that spatial summation is most probably performed anisotropically.
- In this experiment, the neuron is stimulated by two sub-threshold stimulations, extracellular and intracellular, which their arithmetic sum is above-threshold.
Absence of Intra- and Extra- Summation and Subtraction

- Expectation is that if the neuron functions as a centralized excitable mechanism, an evoked spike will be generated.

- Experiment is repeated for different timings of stimulations (to make sure to have overlap between the two stimulations) but no evoked spikes was observed.
Absence of Intra- and Extra- Summation and Subtraction

- Subtraction is also experimented by stimulation with a negative amplitude for the intracellular electrode, resulting in a temporary drop in the membrane voltage.

- The neuron simultaneously stimulated by an extracellular stimulation which is slightly above the threshold and by an intracellular stimulation which is slightly above the minus threshold.
Absence of Intra- and Extra- Summation and Subtraction

- The two stimulations almost annihilate each other arithmetically, however, an evoked spike was observed even when they completely overlapped
Absence of Intra- and Extra- Summation and Subtraction
Experiments

- The first type of experiments demonstrates that a single neuron’s spike waveform typically varies as a function of the stimulation location.

- The second type reveals that spatial summation is absent for extracellular stimulations from different directions.

- The third type indicates that spatial summation and subtraction are not achieved when combining intra- and extracellular stimulations, as well as for nonlocal time interference, where the precise timings of the stimulations are irrelevant.
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Conclusion

- Common viewpoint: A neuron consists of a unique and centralized excitable element which sums all the incoming signals
Conclusion

- Proposed viewpoint: A neuron consists of several independent threshold units
- Each threshold unit within the neuron collects its own incoming signals and there is no direct spatial summation between incoming signals to different threshold units
Conclusion

- The proposed new computational scheme for a neuron is expected to affect the theoretical efforts to explore the computational capability of neural nets.

- Neuron has to be split into several independent traditional neurons, according to the number of threshold units composing the neuron.
Conclusion

‣ The presented new computational scheme requires to explore its computational capability on a network level in comparison to the current scheme

‣ Results call to re-examine neuronal functionalities beyond the traditional framework, and the advanced computational capabilities and dynamical properties of such complex systems
Thank you for listening. Questions?