Time Factor in Neural Learning Processes

- **CIFMA – SEFM 2024**
- University of Aveiro

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Object

Neural plasticity, the brain's ability to adapt to new experiences, is one of the most important concepts in neuroscience.

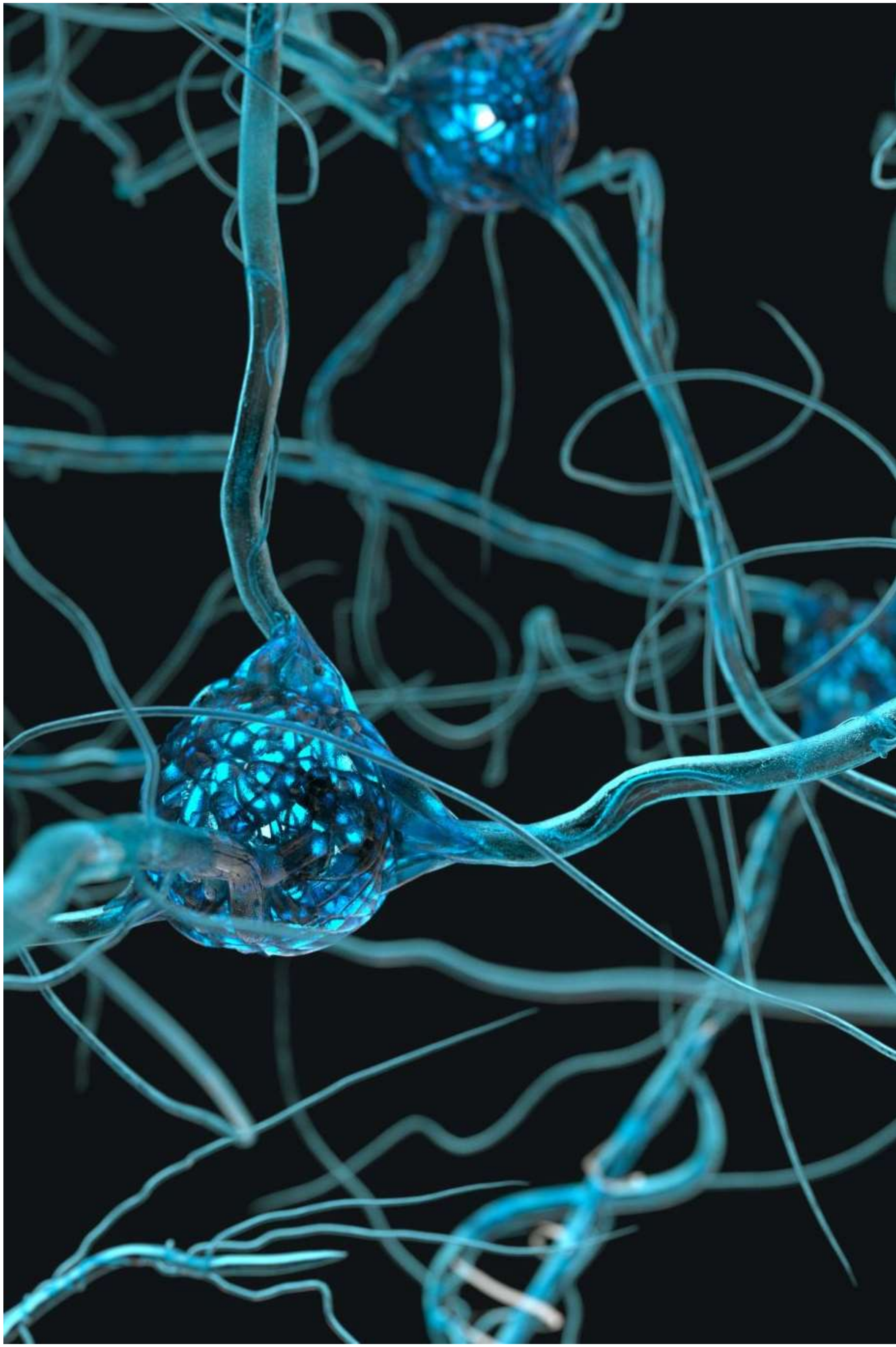
We aim to explore the role of timing and synchronization of external stimuli in shaping synaptic modifications. These factors play a crucial role in optimizing learning processes and cognitive rehabilitation.

Historical Context

Neural plasticity
Cajal,1894

Hebbian theory
Neurons that fire together wire together
Hebb, 1949

Early evidence of synaptic changes through repeated stimulation
Konorski, 1948



Summary

- Exploration of neural plasticity and **environmental interactions**
- Emphasis on **timing and synchronization** in shaping synaptic changes.
- Critical role of **temporal factors** in learning and cognitive development.
- **Applications** in cognitive rehabilitation and education.

Timing architecture

1 Environment, epigenetic

Stimuli architecture

2 Learning, synaptic changes

Neural architecture

We will try to propose a perspective focused on

Time Factor

Timing architecture

1

Impact of the environment on neural plasticity, from cellular influences during development of neural system to epigenetic ones with particular attention to changes of dendritic spines.

2

How the environment continues to affect neuronal changes through learning, emphasizing the importance of timing and the synchronization of external stimuli and synaptic modifications.

This study suggests that understanding the timing and coherence of synaptic activations is crucial for optimizing learning and improving cognitive rehabilitation strategies.

Timing architecture

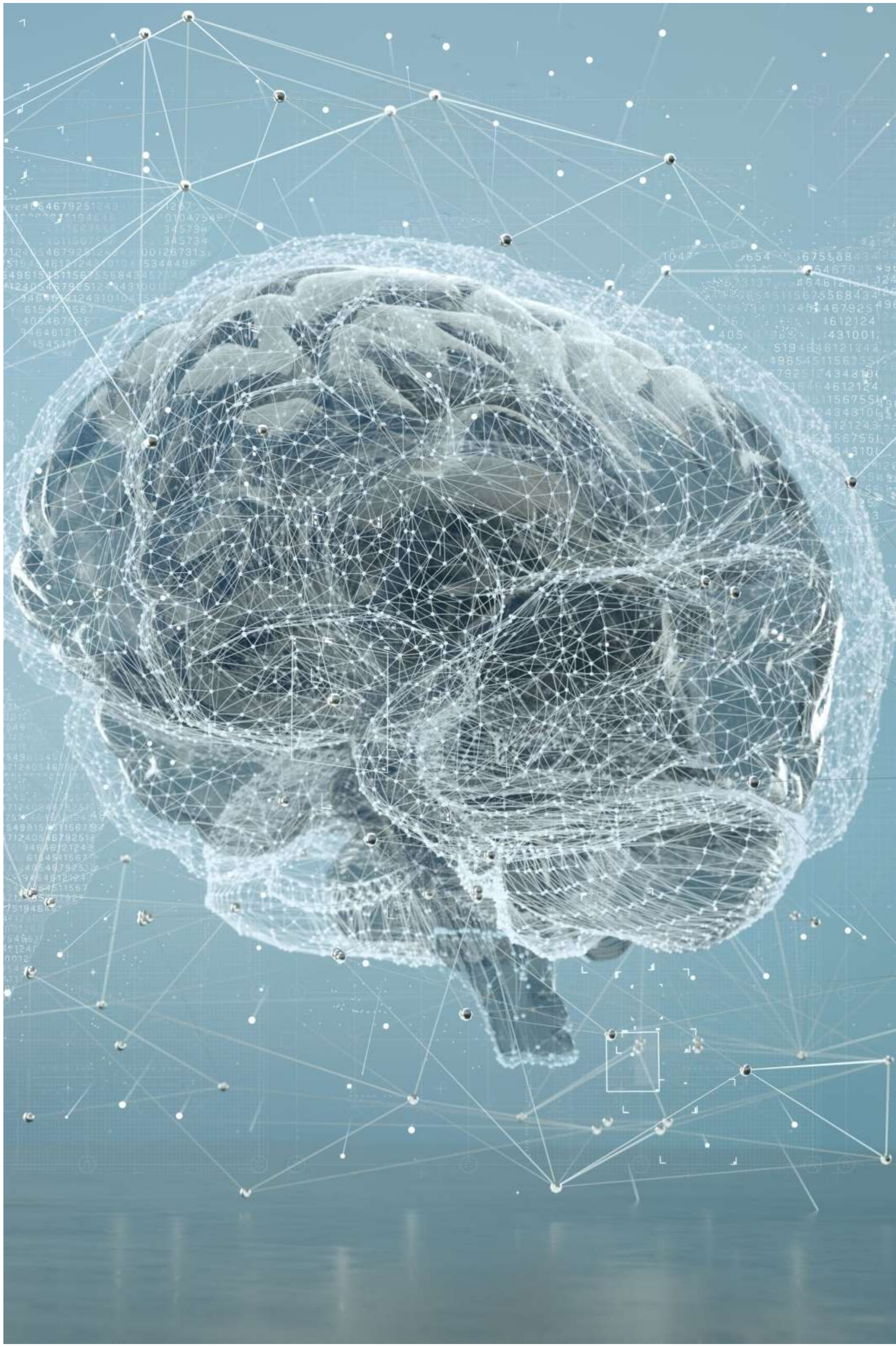
1

Impact of the environment on neural plasticity from cellular influences to epigenetic ones

Changes in dendritic spines

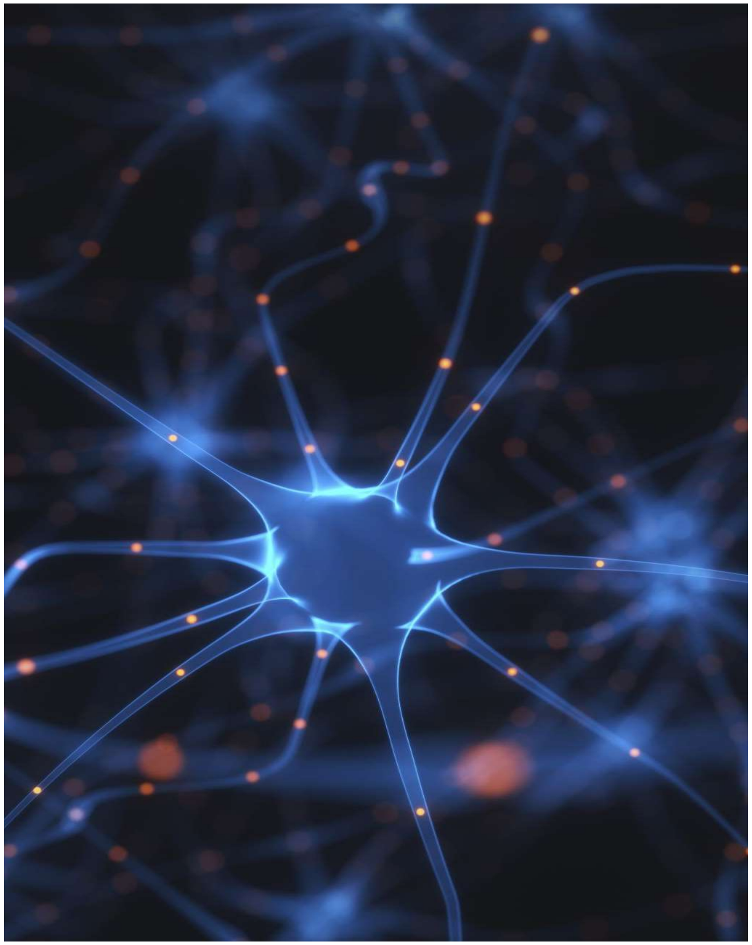
1 The Role of the Environment in Brain Development

- Neural development is influenced by both genetic factors and environmental stimuli.
- The environment helps to shape neural architecture through processes such as synaptic pruning.
- Pruning eliminates redundant connections, improving the brain's efficiency.



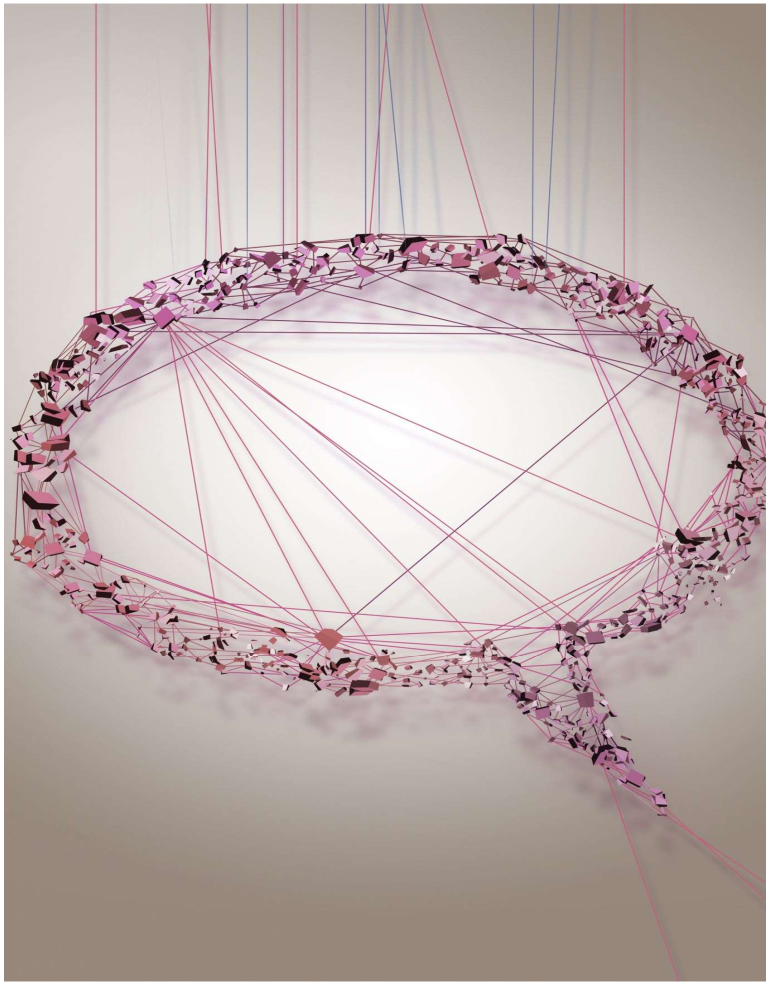
1.1 Glial Cells and Environmental Influence

- Glial cells, once considered mere support structures, play an active role in guiding neuron migration.
- Environmental stimuli can modulate their activity through epigenetic mechanisms, highlighting the deep connection between external conditions and neural development



1.2 Neural Darwinism

- Neural Darwinism (Edelman, 1987): Neurons are selected based on their utility.
- Useful neural circuits are reinforced, while others are pruned.
- The brain refines its synaptic architecture through experience and environmental interaction.

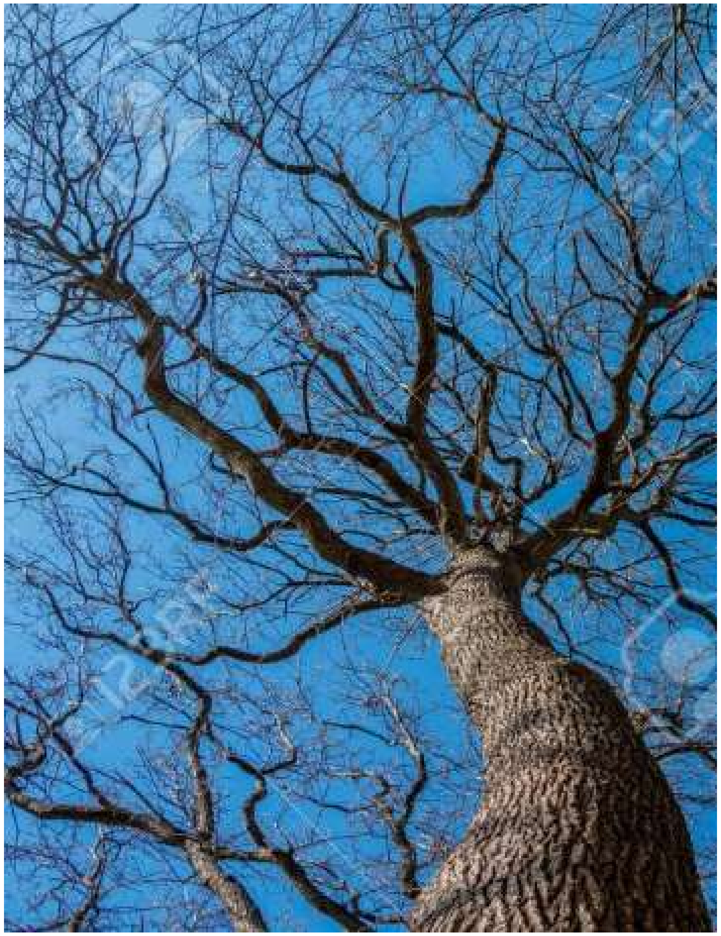


1.3 Epigenetics and Long-Term Brain Development

- Epigenetics modifies gene expression without changing DNA sequences.
- Environmental factors, such as maternal stress, can leave lasting imprints on brain development.
- Epigenetic “marks” influence how neurons connect, affecting learning and memory.

1.4 Plasticity in Mental Health and Learning

- Synaptic pruning plays a key role in mental health.
- Over-pruning is linked to schizophrenia, while under-pruning is connected to autism.
- Plasticity supports both cognitive and motor learning by adjusting neural connections.
- Chronic stress negatively impacts the hippocampus, reducing synaptic plasticity and impairing learning. Increased cortisol levels decrease hippocampal function, leading to weakened memory formation and cognitive performance.



1.5 Ongoing Plasticity Throughout Life

- Neural plasticity continues throughout adulthood.
- Experiences strengthen some synapses while weakening others.

Learning and memory rely on synaptic modifications

Spike-Timing-Dependent Plasticity STDP

Long term potentiation - LTP

Long term Depression - LTD.

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Timing architecture

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How the environment continues to affect neuronal changes through learning

The importance of timing and the synchronization of stimuli and synaptic modifications

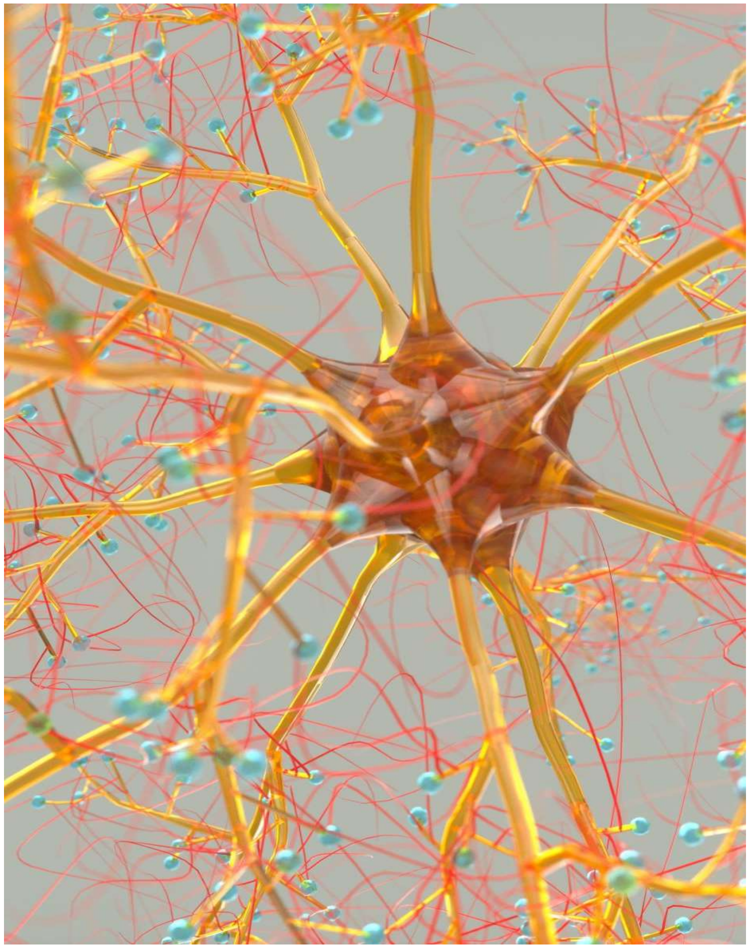
2 The Role of Synchronicity in Learning

- When external stimuli are presented in close sequence, the brain strengthens the association between them.

- This temporal coherence not only strengthens neural connections but also helps the brain predict future events based on past experiences.

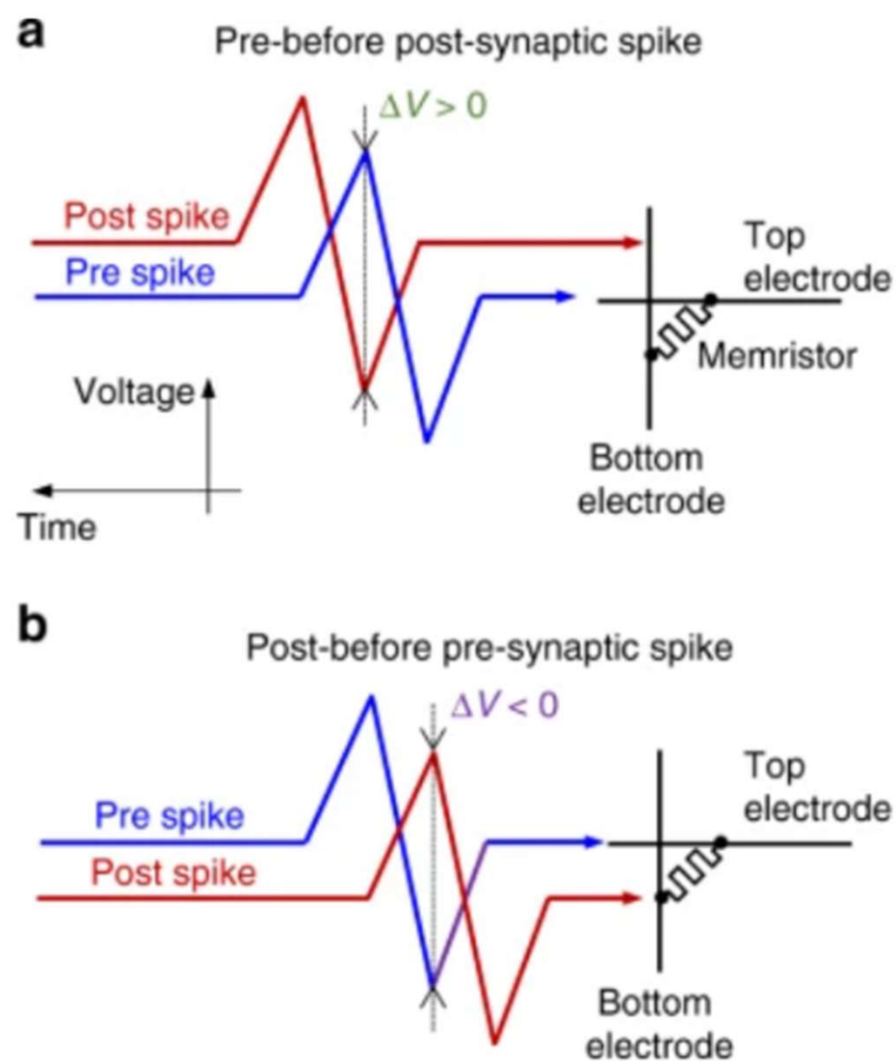
2.1 Hebbian Learning and Synaptic Strength

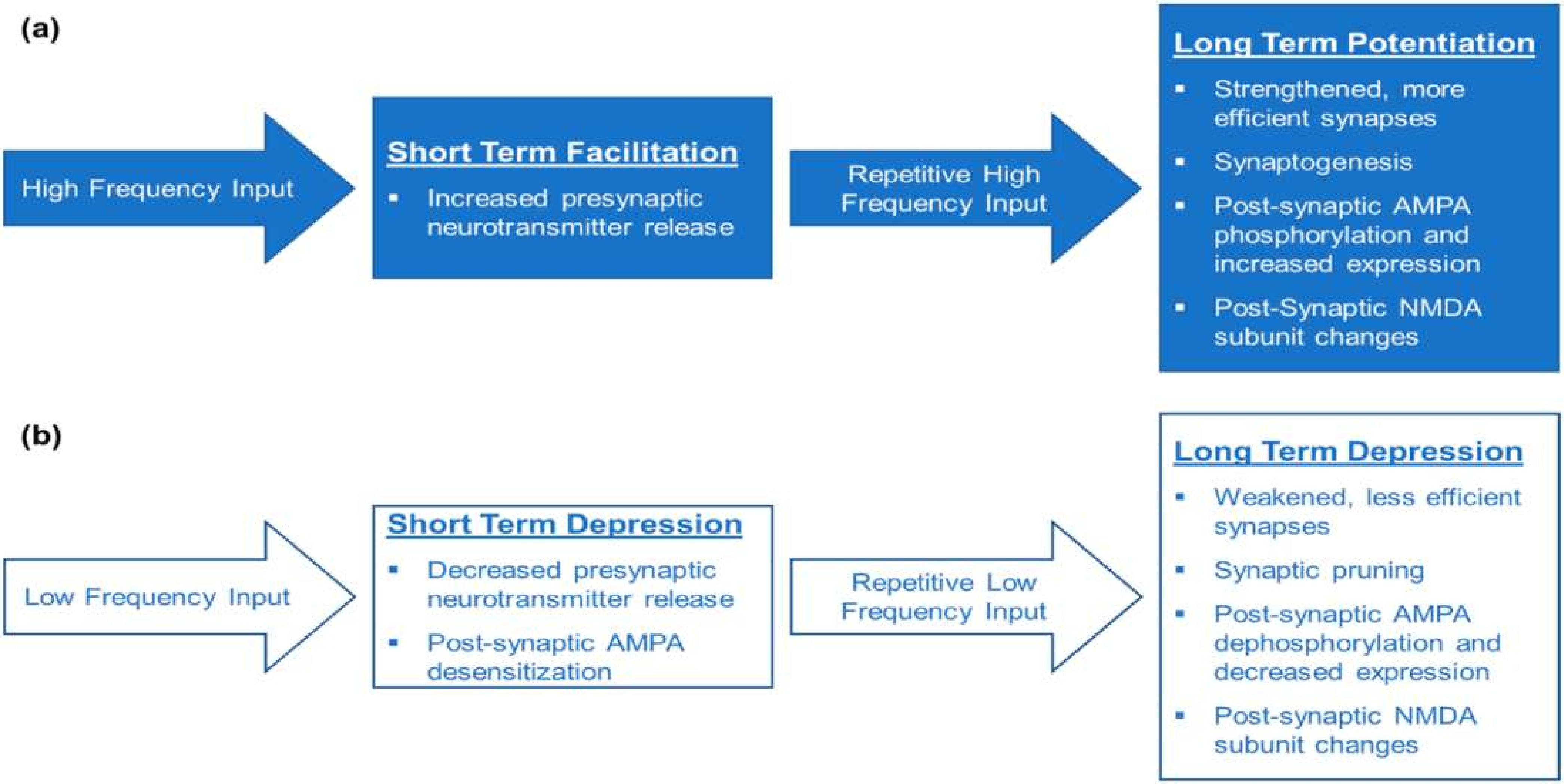
- Hebbian theory explains how neurons that fire together form stronger connections, making synaptic transmission more efficient. Repeated synchronized activation strengthens the neural pathways involved, enhancing learning and memory.



2.2 Timing and Synaptic Plasticity

- The synchronization of neural activations is essential for learning and memory formation. Spike-Timing-Dependent Plasticity (STDP) demonstrates that precise timing between stimuli and synaptic responses strengthens neural connections (LTP), while poor timing weakens them (LTD).





(a)
High Frequency Input
Short Term Facilitation
Increased presynaptic neurotransmitter release
Repetitive High Frequency Input
Long Term Potentiation
Strengthened, more efficient synapses
Synaptogenesis
Post-synaptic AMPA phosphorylation and increased expression
Post-Synaptic NMDA subunit changes
(b)
Low Frequency Input
Short Term Depression
Decreased presynaptic neurotransmitter release
Post-synaptic AMPA desensitization
Repetitive Low Frequency Input
Long Term Depression
Weakened, less efficient synapses
Synaptic pruning
Post-synaptic AMPA dephosphorylation and decreased expression
Post-synaptic NMDA subunit changes

2.2 Basic principles of LTP

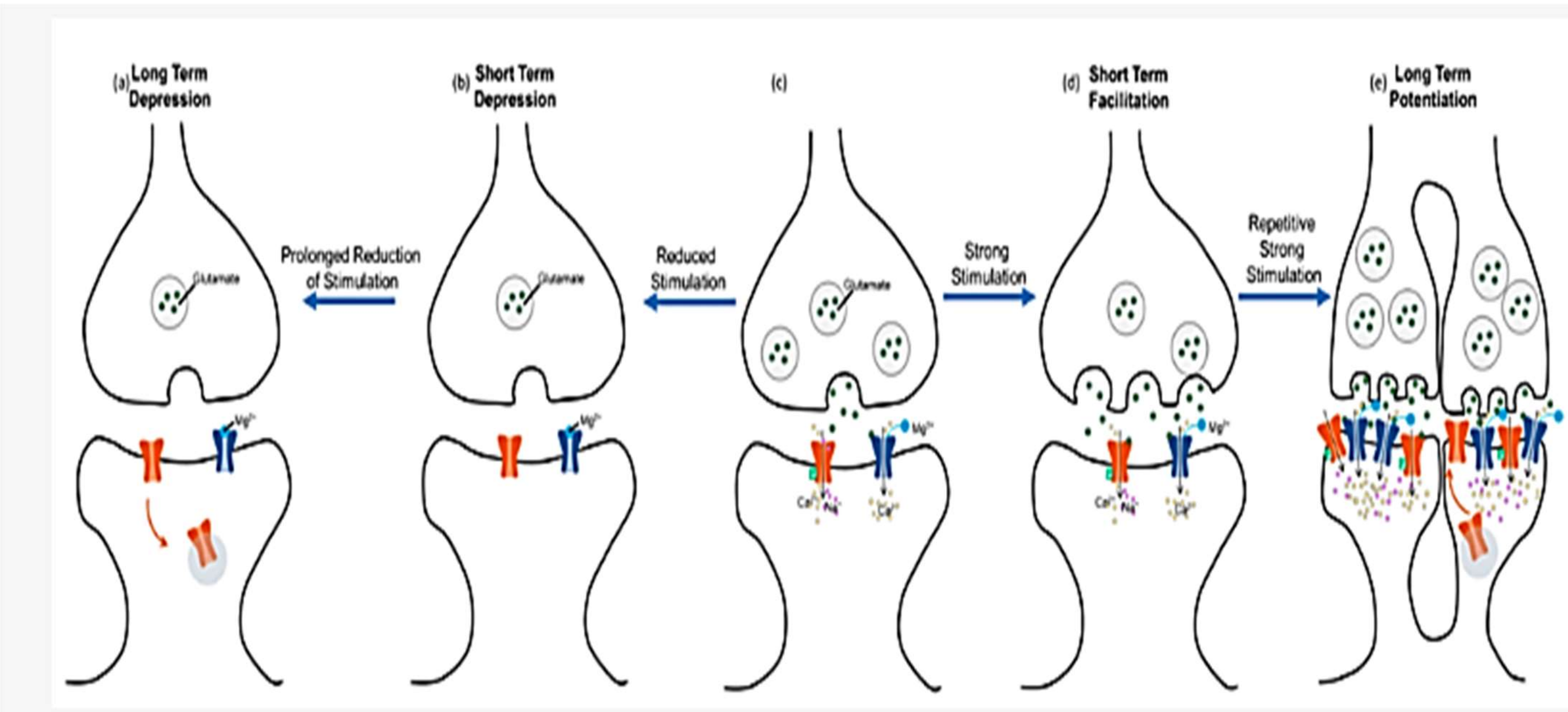
- LTP is a process by which synaptic strength between two neurons increases in response to repetitive, high-frequency neuronal activity.
- LTP is activated when a pre-synaptic neuron stimulates a post-synaptic neuron with a high rate of activity. This stimulation increases the influx of calcium within the post-synaptic neuron, activating a series of chemical reactions (such as protein phosphorylation and the production of new receptors), which strengthen the synapse.

2.2 Basic principles of LTD

- LTD occurs when the synapse is stimulated repeatedly, but at a low frequency (usually between 1 and 5 Hz), or as a result of specific patterns of neuronal activity.
- This low-frequency stimulation leads to a reduction in the strength of the synapse and the likelihood that the postsynaptic neuron will respond to future stimuli from the presynaptic neuron.

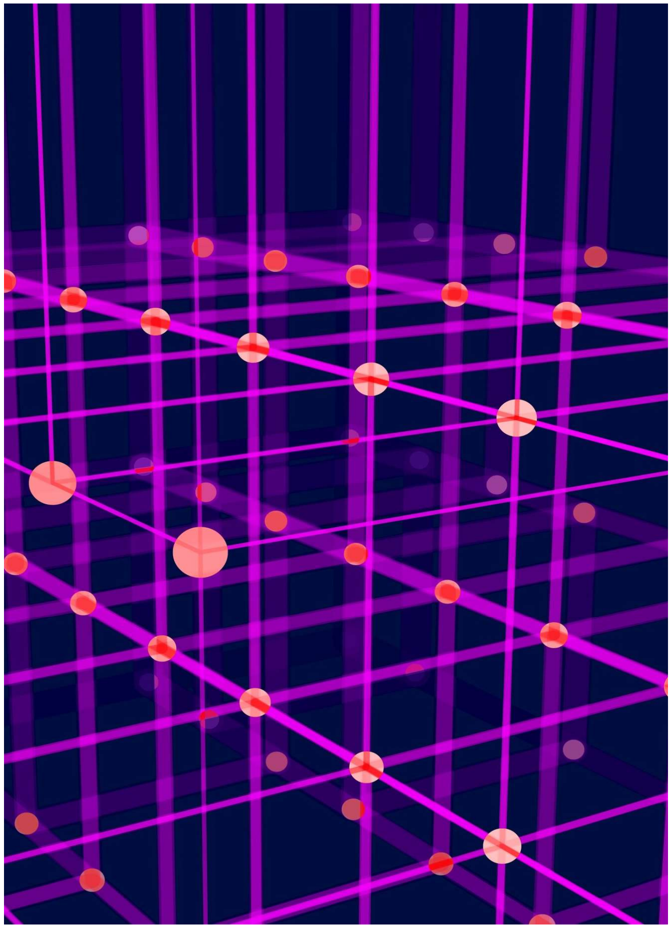
LTP e LTD

J. Walker and M. Detloff
Plasticity in Cervical Motor Circuits following Spinal Cord Injury and Rehabilitation, Biology 2021



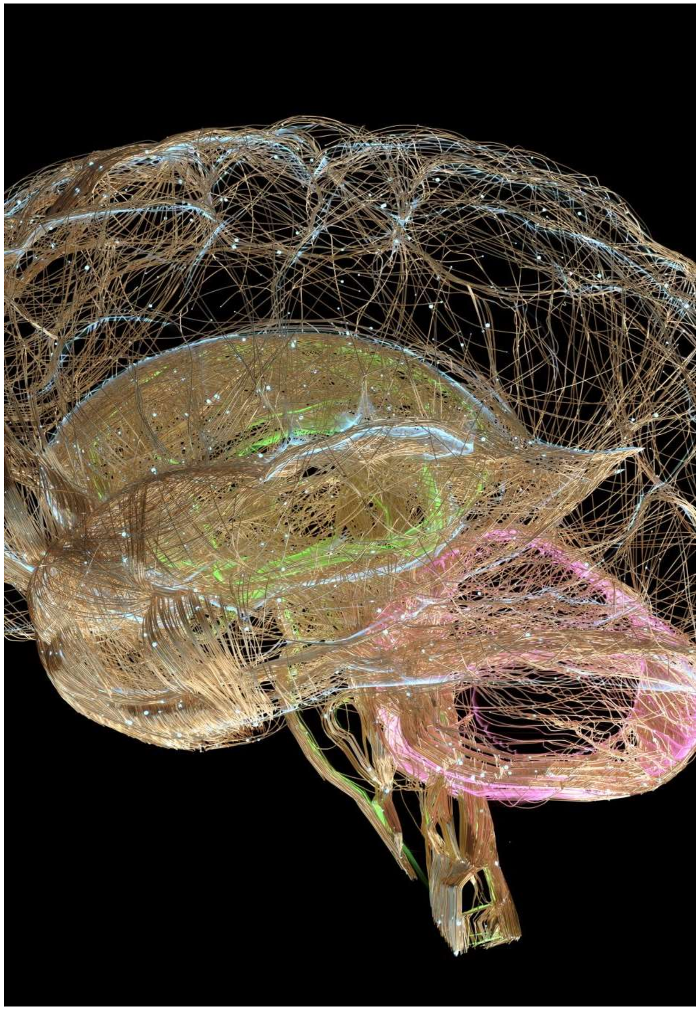
2.3 Timing Windows and Causality in Neural Responses

- Neural timing occurs within windows of milliseconds.
- When neurons activate within this window, their connection strengthens.
- Timing shapes the brain's perception of causality: repeated, closely timed activations suggest a causal link between events.



2.3 Learning and the Synchronization of Neural Networks

Larger neural networks rely on synchronized firing to form "neural maps" that represent learned behaviors. Temporal coherence across these networks is key to learning, as the brain associates closely timed stimuli to form a cohesive memory +
(Tang et al., 1999)



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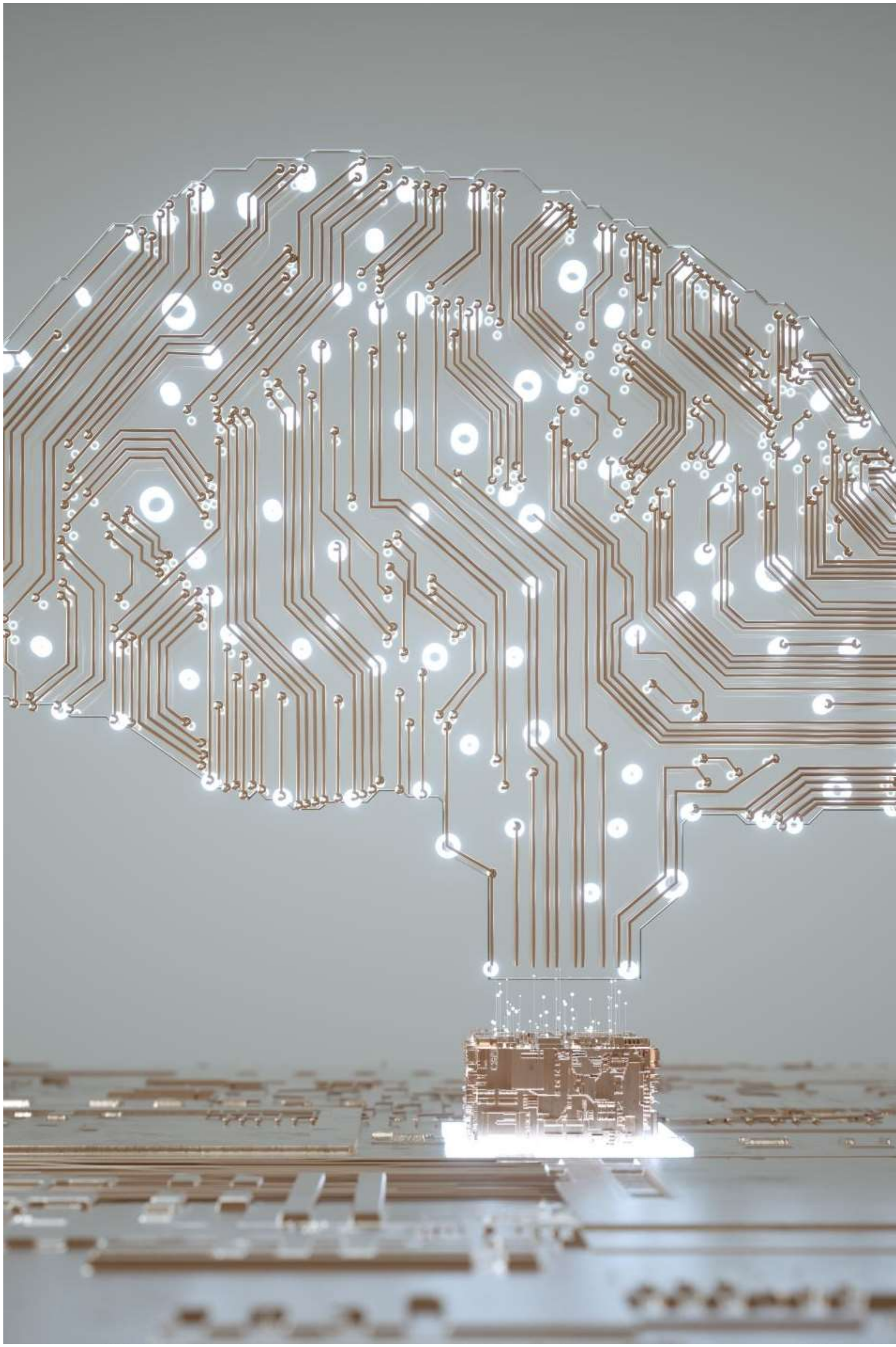
3 Voluntary Learning and Agency

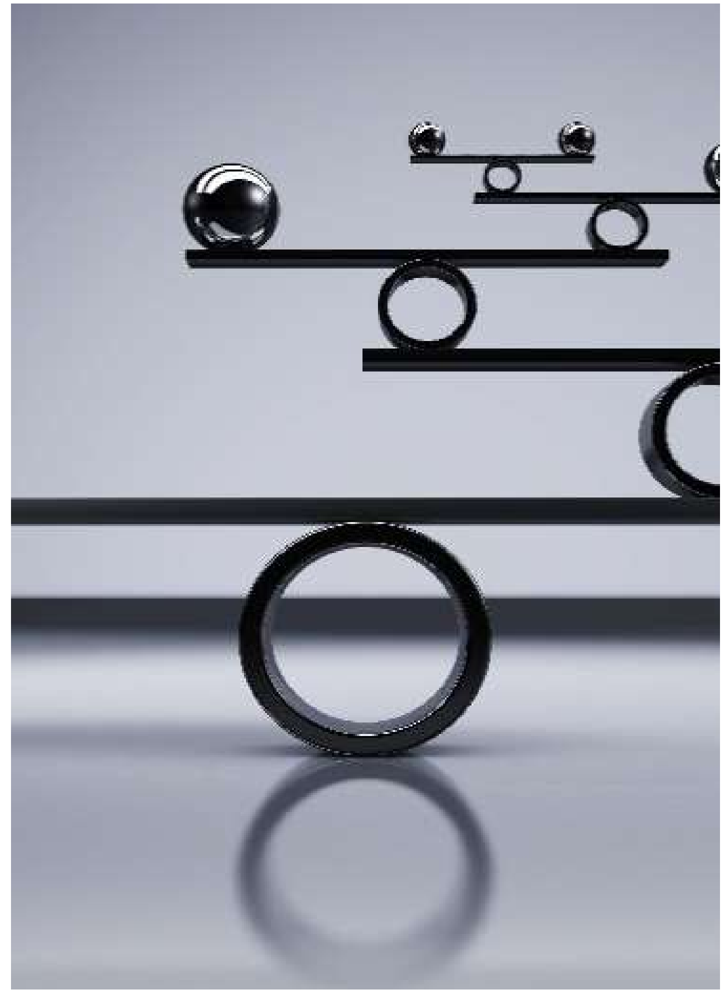
- Voluntary learning, where individuals exert control over their actions, leads to a strong sense of agency.

- This is linked to precise neural activations, where the brain recognizes the action as self-generated, strengthening the neural circuits involved.



3.1 Agency and Spike-Timing-Dependent Plasticity

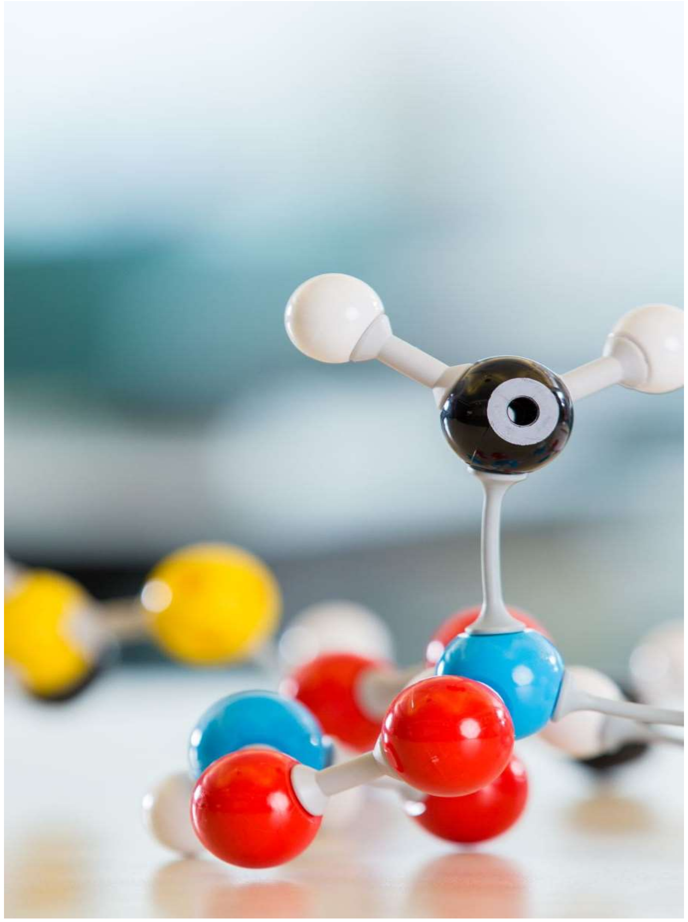
- Agency is the sense that I am the cause or author of a movement. Babies develop early this feeling by perceiving the contingency between afferent (sensor) and efferent (motor) information.
- The biological STDP that synchronizes the neural dynamics almost everywhere in the central nervous system, constitutes a good algorithm to detect contingency in sensorimotor networks.
- The coherence or the dissonance in the sensorimotor information flow imparts then the agency level.



3.1 Agency and Spike-Timing-Dependent Plasticity

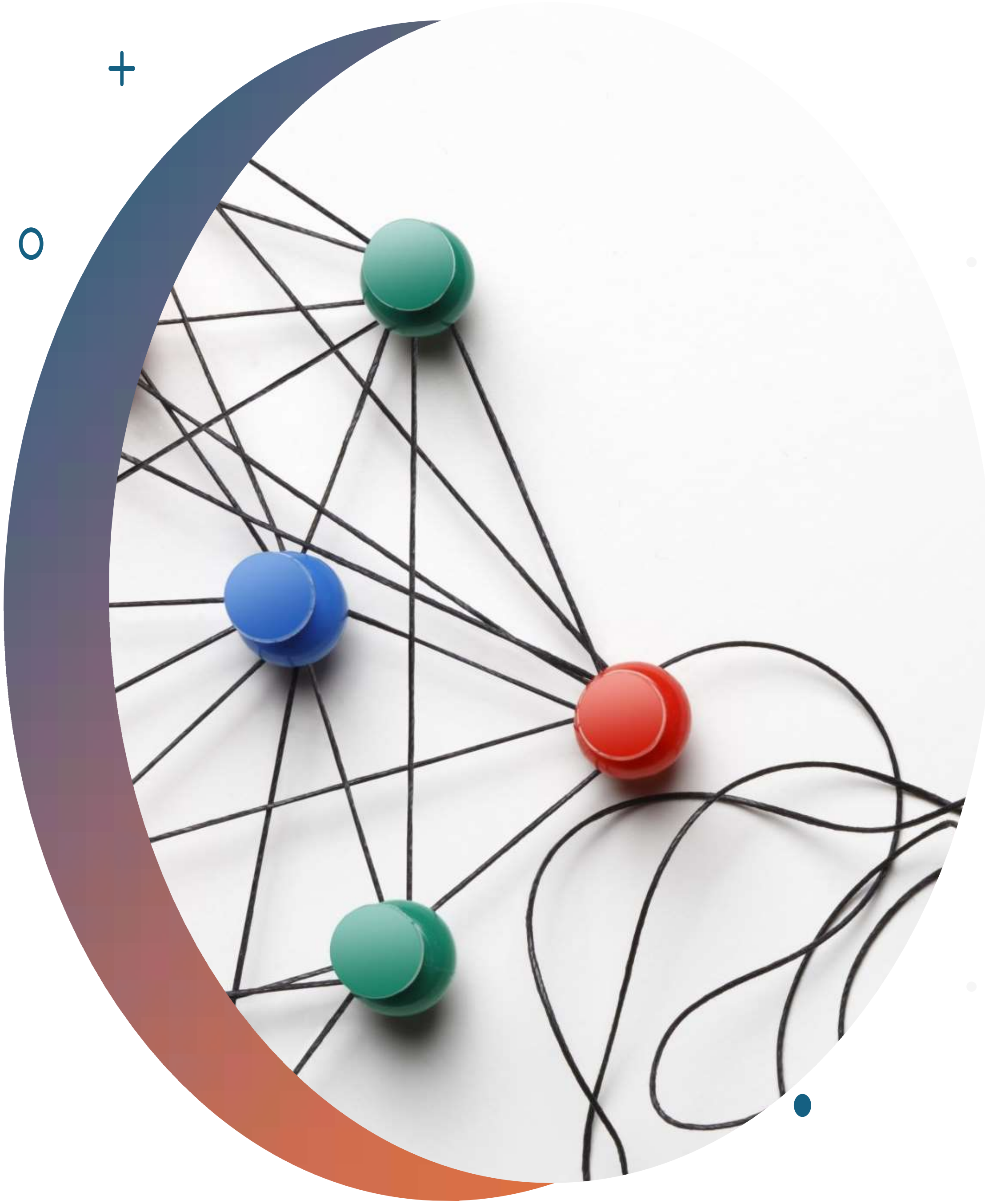
How the timing of neural activations creates a sense of agency?

- In voluntary actions, repeated precise timing reinforces the brain's perception of control.
- In conditioned learning, a lack of precise timing leads to a diminished sense of agency.



3.2 Practical Implications of a timing framework

- Applications in education: Enhancing learning by aligning teaching methods with neural timing.
- Applications in Cognitive rehabilitation: Adopting timing-based interventions can improve recovery from cognitive deficits.
- Stress management: Reducing stress preserves neural plasticity and learning abilities.



Conclusion

Neural plasticity is a dynamic process shaped by environmental and temporal factors.

Synchronization between external stimuli and neural activations optimizes learning and memory.

Understanding these processes can improve educational and rehabilitation strategies, enhancing cognitive health and performance.

Thank you

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