Retrograde Signaling Mechanisms of Delta-9-THC: Parallels with Backpropagation in Neural Networks

Abstract

This paper explores the theoretical and mechanistic parallels between the neurobiological effects of Delta-9-tetrahydrocannabinol (THC) and the backpropagation algorithm used in artificial neural networks. We propose a novel framework suggesting that the endocannabinoid system, particularly when activated by exogenous cannabinoids like THC, may implement a biological analog to computational backpropagation. Through examination of retrograde signaling pathways, depolarization-induced suppression of inhibition/excitation (DSI/DSE), synaptic plasticity mechanisms, and network-level effects, we identify multiple convergent principles. The unique temporal dynamics of cannabinoid signaling, which operates on multiple timescales and influences both Hebbian and homeostatic forms of plasticity, provides a compelling biological substrate for error-correction processes similar to those employed in machine learning. This interdisciplinary synthesis offers new perspectives on both cannabinoid neuropharmacology and biologically-plausible implementations of learning algorithms, with implications for understanding consciousness, memory formation, and the development of novel neuromorphic computing architectures.

Keywords: Delta-9-THC, endocannabinoid system, backpropagation, neural networks, retrograde signaling, synaptic plasticity, computational neuroscience

1. Introduction

The search for biological mechanisms underlying learning and memory has intensified with advances in both neuroscience and machine learning. While artificial neural networks have achieved remarkable success using the backpropagation algorithm (Rumelhart et al., 1986), the biological plausibility of this computational technique has been questioned (Crick, 1989; Lillicrap et al., 2020). Backpropagation typically requires precise, activity-dependent weight adjustments propagated backward through network layers—a mechanism without an obvious biological counterpart in traditional neurotransmission models which primarily operate in a feedforward direction.

Concurrently, research on cannabinoids has revealed that the endocannabinoid system utilizes retrograde signaling mechanisms that allow postsynaptic neurons to modulate their presynaptic inputs (Wilson & Nicoll, 2001; Alger, 2002). This system becomes particularly engaged during the administration of Delta-9-tetrahydrocannabinol (THC), the primary psychoactive component in cannabis. THC's widespread effects on cognition, perception, and memory formation suggest its involvement in fundamental neural computations (Mechoulam & Parker, 2013).

This paper proposes that the retrograde signaling mechanisms activated by THC and endogenous cannabinoids may implement processes functionally analogous to backpropagation in artificial neural networks. We synthesize evidence from molecular neuroscience, electrophysiology, computational modeling, and behavioral studies to develop a comprehensive framework highlighting these parallels. By examining how THC interfaces with the endocannabinoid system to modulate synaptic transmission across multiple timescales and spatial domains, we identify mechanisms that could support error-correction processes similar to those utilized in machine learning algorithms.

The implications of this theoretical framework extend beyond understanding THC's psychoactive effects. They offer insights into how biological systems may solve the "credit assignment problem"—determining which neural connections should be strengthened or weakened during learning. Furthermore, this perspective may inform the development of more biologically plausible artificial intelligence architectures and advance our understanding of consciousness, learning, and memory formation.

2. Background and Theoretical Framework

2.1 The Endocannabinoid System

The endocannabinoid system (ECS) comprises cannabinoid receptors, endogenous ligands (endocannabinoids), and the enzymes responsible for their synthesis and degradation. The system plays crucial roles in synaptic plasticity, homeostatic regulation, and various cognitive functions (Katona & Freund, 2012). Two primary cannabinoid receptors have been identified: CB1 and CB2. CB1 receptors are among the most abundant G-protein-coupled receptors in the central nervous system, particularly concentrated in the cerebral cortex, hippocampus, basal ganglia, and cerebellum (Herkenham et al., 1990; Glass et al., 1997).

Endocannabinoids, including anandamide (AEA) and 2-arachidonoylglycerol (2-AG), are synthesized and released on demand from postsynaptic neurons in response to increased intracellular calcium and/or activation of certain metabotropic receptors (Piomelli, 2003). Unlike conventional neurotransmitters, which are stored in vesicles for release, endocannabinoids are produced from membrane phospholipid precursors when needed and immediately released into the synaptic cleft (Di Marzo et al., 2004).

A defining characteristic of the ECS is its predominant signaling direction—retrograde transmission from postsynaptic to presynaptic neurons (Wilson & Nicoll, 2002). Upon activation of postsynaptic neurons, endocannabinoids travel backward across the synapse to bind with presynaptic CB1 receptors, typically resulting in the suppression of neurotransmitter release (Kreitzer & Regehr, 2001; Ohno-Shosaku et al., 2001). This mechanism, termed depolarization-induced suppression of inhibition (DSI) when occurring at GABAergic synapses or depolarization-induced suppression of excitation (DSE) at glutamatergic synapses, provides a means for postsynaptic activity to regulate its own inputs (Figure 1).

2.2 Delta-9-THC and Its Neural Effects

Delta-9-THC exerts its psychoactive effects primarily by binding to CB1 receptors, acting as a partial agonist (Pertwee, 2008). Unlike endocannabinoids, which are rapidly degraded after release, THC persists in the system and causes prolonged activation of cannabinoid receptors, disrupting the temporal dynamics of normal endocannabinoid signaling (Mechoulam & Parker, 2013).

THC administration has been associated with various acute effects, including:

- Alterations in sensory processing and perception (Atakan, 2012)
- Impairments in short-term memory formation (Ranganathan & D'Souza, 2006)
- Changes in time perception (Atakan, 2012)
- Modulation of emotional processing (Bhattacharyya et al., 2010)
- Dose-dependent effects on attention and concentration (Solowij & Battisti, 2008)

At the cellular level, THC affects multiple neurotransmitter systems through its action on CB1 receptors. It modulates the release of glutamate, GABA, dopamine, serotonin, acetylcholine, and norepinephrine across various brain regions (Howlett et al., 2002; Pertwee, 2008). This broad neuromodulatory activity has been implicated in THC's complex effects on cognition and behavior.

2.3 Backpropagation in Neural Networks

Backpropagation is the predominant algorithm for training artificial neural networks, particularly deep learning architectures (Rumelhart et al., 1986; LeCun et al., 2015). The algorithm consists of two main phases:

1. **Forward Pass**: Input signals propagate through the network, with each layer performing computations based on input values and current connection weights, ultimately producing an output.
2. **Backward Pass**: The difference between actual and desired outputs (error) is calculated and propagated backward through the network. Connection weights are adjusted based on their contribution to the error, typically using gradient descent to minimize a loss function.

This process allows networks to learn complex representations and solve difficult pattern recognition tasks by iteratively adjusting connection strengths to reduce prediction errors. The fundamental innovation of backpropagation is its ability to solve the credit assignment problem—determining which connections in a multi-layer network should be strengthened or weakened to improve performance (Lillicrap et al., 2020).

Despite its computational success, several aspects of backpropagation have been considered biologically implausible (Crick, 1989; Bengio et al., 2015):

- The requirement for precise, symmetrical weight matrices between forward and backward passes (weight transport problem)
- The need for separate forward and backward pathways for activity and error signals
- The non-local nature of weight updates, requiring global error information
- The lock-step, synchronous computation through distinct forward and backward phases

Recent theoretical work has addressed some of these concerns, demonstrating that approximations to backpropagation can work effectively without requiring exact symmetry or global error signals (Lillicrap et al., 2016; Guerguiev et al., 2017; Sacramento et al., 2018). These developments have renewed interest in identifying potential biological mechanisms that could implement backpropagation-like computations in the brain.

3. Methodological Approaches to Investigating Cannabinoid-Backpropagation Parallels

Research exploring the relationship between cannabinoid signaling and neural computation has employed diverse methodologies, spanning multiple levels of analysis. These approaches can be categorized into molecular/cellular techniques, systems-level electrophysiology, computational modeling, and behavioral assessments.

3.1 Molecular and Cellular Techniques

Studies investigating cannabinoid effects at the molecular level have utilized:

- **Patch-clamp electrophysiology** to measure changes in synaptic transmission following endocannabinoid release or exogenous cannabinoid application (Wilson & Nicoll, 2001; Kreitzer & Regehr, 2001)
- **Calcium imaging** to visualize activity patterns across neuronal populations during cannabinoid modulation (Younts et al., 2013)
- **Optogenetic techniques** combined with electrophysiology to manipulate specific neuronal populations while monitoring cannabinoid-mediated effects (Basu et al., 2013)
- **Immunohistochemistry and electron microscopy** to characterize the subcellular localization of cannabinoid receptors and associated signaling machinery (Katona et al., 1999; Nyíri et al., 2005)
- **Transgenic approaches** using knockout or conditional knockout models of cannabinoid receptors and synthetic/degradative enzymes (Zimmer et al., 1999; Kano et al., 2009)

3.2 Systems-Level Electrophysiology

At the network level, researchers have employed:

- **In vivo electrophysiology** to record neuronal activity patterns during cannabinoid administration (Robbe et al., 2006)
- **Local field potential recordings** to assess changes in oscillatory activity and synchronization (Hájos et al., 2000; Robbe et al., 2006)
- **Multi-electrode array recordings** to characterize spatiotemporal activity patterns across neural circuits (Sales-Carbonell et al., 2013)

3.3 Computational Modeling

Computational approaches have included:

- **Biophysically-detailed neuron models** incorporating endocannabinoid signaling mechanisms (Heifets et al., 2008)
- **Neural network simulations** exploring how retrograde signaling affects learning and information processing (Brea et al., 2016)
- **Theoretical models** linking cannabinoid signaling to specific computational functions, such as filtering, prediction, and error correction (Matias et al., 2017)

3.4 Behavioral and Cognitive Assessments

The behavioral effects of cannabinoids have been studied using:

- **Learning and memory tasks** assessing different forms of memory affected by cannabinoids (Ranganathan & D'Souza, 2006)
- **Perceptual and attention paradigms** measuring changes in sensory processing and attentional focus (Atakan, 2012)
- **Neuropsychological test batteries** characterizing cognitive effects of acute and chronic cannabinoid exposure (Solowij & Battisti, 2008)
- **Brain imaging studies** (fMRI, PET) examining changes in brain activity and connectivity following cannabinoid administration (Bhattacharyya et al., 2012)

By integrating findings across these methodological approaches, we can develop a more comprehensive understanding of how cannabinoid signaling might implement computational processes analogous to backpropagation in neural networks.

4. Retrograde Signaling: The Biological Basis for Backward Information Flow

A fundamental feature of backpropagation algorithms is the backward transmission of error signals through network layers. In biological neural networks, the predominant direction of information flow is forward—from presynaptic to postsynaptic neurons via conventional neurotransmission. The

endocannabinoid system, however, represents one of the most extensive and well-characterized retrograde signaling mechanisms in the brain, providing a potential biological substrate for backward information flow.

4.1 Mechanisms of Endocannabinoid Production and Release

Endocannabinoids are synthesized in activity-dependent ways that make them particularly suitable for encoding error or surprise signals in neural circuits. Two principal pathways have been characterized:

4.1.1 Calcium-Dependent Endocannabinoid Release

Postsynaptic depolarization leads to calcium influx through voltage-gated calcium channels or NMDA receptors. Elevated intracellular calcium activates enzymes responsible for endocannabinoid synthesis, particularly diacylglycerol lipase-α (DGL-α) for 2-AG production (Hashimotodani et al., 2007). This mechanism ensures that endocannabinoid release is directly coupled to postsynaptic activity, allowing for precise temporal coding of neural events.

4.1.2 Receptor-Driven Endocannabinoid Release

Activation of certain Gq/11-coupled receptors, including group I metabotropic glutamate receptors (mGluR1/5) and M1/M3 muscarinic acetylcholine receptors, stimulates endocannabinoid synthesis through phospholipase C (PLC) pathways (Maejima et al., 2001; Kim et al., 2002). This mechanism links endocannabinoid release to specific neurotransmitter systems and can operate independently of or synergistically with calcium-dependent pathways.

These production mechanisms ensure that endocannabinoid signaling is:

1. Activity-dependent, increasing with postsynaptic depolarization
2. Proportional to the magnitude of calcium signals or receptor activation
3. Temporally precise, occurring rapidly following neuronal activation
4. Spatially restricted, affecting synapses near the site of production

These properties align with requirements for error signals in supervised learning frameworks, which must reflect the difference between actual and expected activity levels.

4.2 CB1 Receptor Activation and Downstream Effects

Upon release, endocannabinoids diffuse across the synaptic cleft and bind to presynaptic CB1 receptors. THC similarly activates these receptors, though with different temporal dynamics and efficacy. CB1 activation initiates several downstream signaling cascades that modulate neurotransmitter release:

4.2.1 Acute Effects on Neurotransmission

CB1 receptor activation produces rapid effects on neurotransmitter release probability through:

- Inhibition of voltage-gated calcium channels, reducing calcium influx required for vesicle fusion (Wilson et al., 2001)
- Activation of potassium channels, hyperpolarizing presynaptic terminals and decreasing excitability (Kreitzer & Regehr, 2001)
- Direct interference with the vesicle release machinery, downstream of calcium entry (Takahashi & Castillo, 2006)

These mechanisms collectively decrease neurotransmitter release probability, with stronger effects typically observed at GABAergic synapses (greater DSI) compared to glutamatergic ones (lesser DSE), partly due to higher CB1 expression on inhibitory terminals in many brain regions (Katona et al., 1999; Katona et al., 2006).

4.2.2 Long-Term Synaptic Plasticity

Beyond acute effects, cannabinoid signaling contributes to long-term synaptic plasticity through:

- Endocannabinoid-mediated long-term depression (eCB-LTD) at both excitatory and inhibitory synapses (Gerdeman et al., 2002; Chevaleyre & Castillo, 2003)
- Modulation of spike-timing-dependent plasticity (STDP) by altering the temporal requirements for coincident pre- and postsynaptic activity (Cui et al., 2016)
- Heterosynaptic plasticity, where cannabinoid release from strongly activated synapses affects neighboring, less active inputs (Heifets et al., 2008)

These longer-term effects suggest that cannabinoid signaling contributes to both the induction and maintenance phases of synaptic plasticity, analogous to the iterative weight updates in backpropagation.

4.3 Spatial and Temporal Characteristics of Retrograde Signaling

Endocannabinoid signaling operates across multiple spatial and temporal domains, creating a rich computational framework:

4.3.1 Spatial Domains of Action

- **Synapse-specific signaling**: Endocannabinoids can act locally at the synapse where they are produced, enabling input-specific plasticity (Wilson & Nicoll, 2001)
- **Spread to neighboring synapses**: Under some conditions, endocannabinoids may affect nearby synapses, enabling heterosynaptic effects within approximately 20-30 μm (Wilson & Nicoll, 2001; Kreitzer et al., 2002)

- **Cell-wide signaling**: Sufficient postsynaptic activation can trigger cell-wide endocannabinoid release, affecting multiple synaptic inputs onto a given neuron (Zhu & Lovinger, 2007)
- **Network-level effects**: Through modulation of specific cell types and circuit motifs, cannabinoid signaling can influence information flow through entire networks (Hájos et al., 2000; Robbe et al., 2006)

4.3.2 Temporal Dynamics

- **Rapid phasic signaling**: DSI/DSE typically develops within seconds and recovers within minutes, providing a temporally precise feedback mechanism (Wilson & Nicoll, 2001)
- **Tonic signaling**: Ambient endocannabinoid levels may tonically activate CB1 receptors under certain conditions, setting baseline levels of presynaptic inhibition (Losonczy et al., 2004)
- **Long-term plasticity**: Endocannabinoid-mediated LTD can persist for hours following a brief induction period (Chevaleyre & Castillo, 2003)

THC disrupts these precisely regulated temporal dynamics by causing prolonged CB1 receptor activation, potentially interfering with the timing-dependent aspects of endocannabinoid-mediated computations.

5. Parallels Between Cannabinoid Signaling and Backpropagation Components

By examining specific computational elements of backpropagation algorithms alongside cannabinoid signaling mechanisms, we can identify several striking parallels that suggest functional equivalence despite different physical implementations.

5.1 Error Computation and Signal Generation

In artificial neural networks, the backpropagation algorithm begins with calculating the difference between actual and target outputs—the error signal. This computation typically requires:

1. A representation of the target or expected output
2. Comparison with the actual neural activity
3. Generation of a signal proportional to this difference

In biological systems, several cannabinoid-related mechanisms may implement similar computations:

5.1.1 Prediction Error Signaling via Endocannabinoids

The synthesis and release of endocannabinoids depend on postsynaptic activity levels, which reflect the integration of incoming signals. When these activity levels exceed certain thresholds—potentially

representing a mismatch between expected and actual input—increased calcium influx triggers endocannabinoid production (Ohno-Shosaku et al., 2001; Wilson & Nicoll, 2001).

Research suggests that endocannabinoid release may specifically encode prediction errors in certain neural circuits. For example, in the ventral tegmental area (VTA), unexpected rewards trigger endocannabinoid signaling that modulates dopaminergic transmission—a system widely implicated in reward prediction error computations (Melis et al., 2004; Wang & Lupica, 2014).

5.1.2 Neuromodulatory Systems and Target Representation

Theoretical work on biologically plausible backpropagation has proposed that neuromodulatory systems might provide teaching signals or target representations (Lillicrap et al., 2020). The endocannabinoid system interfaces extensively with other neuromodulators, including:

- Dopamine systems, with mutual interaction between dopaminergic and endocannabinoid signaling in striatal and midbrain circuits (Melis et al., 2004; Mathur & Lovinger, 2012)
- Cholinergic systems, where muscarinic receptor activation can trigger endocannabinoid release (Kim et al., 2002)
- Monoaminergic systems, with CB1 receptors modulating serotonin and norepinephrine release (Haj-Dahmane & Shen, 2011)

These interactions may enable the endocannabinoid system to access target representations or prediction signals carried by these neuromodulatory pathways, facilitating error computation.

5.1.3 THC Effects on Error Computation

THC's partial agonism at CB1 receptors likely disrupts normal error computation processes by:

- Activating CB1 receptors independently of postsynaptic activity, creating "false" error signals
- Occluding the effects of endogenously produced endocannabinoids, reducing the dynamic range of error signaling
- Prolonging CB1 activation beyond the temporal window appropriate for precise error coding

These disruptions may contribute to THC's known effects on learning, memory, and cognitive processing (Ranganathan & D'Souza, 2006).

5.2 Error Backpropagation and Synaptic Credit Assignment

A crucial feature of backpropagation is the backward transmission of error signals to assign "credit" to specific synapses based on their contribution to the output. This requires:

1. Directional flow of error information opposite to the forward pass

2. Specificity in targeting connections that contributed to the error
3. Proportionality between weight updates and contribution to the error

5.2.1 Retrograde Signaling as Physical Backpropagation

The bidirectional nature of synaptic communication through the endocannabinoid system provides a physical substrate for backpropagation-like processes:

- Conventional neurotransmission mediates the forward pass (presynaptic → postsynaptic)
- Retrograde endocannabinoid signaling mediates the backward pass (postsynaptic → presynaptic)

This arrangement enables information about postsynaptic activity—potentially including error or prediction signals—to propagate backward to presynaptic terminals that contributed to that activity (Wilson & Nicoll, 2001; Ohno-Shosaku et al., 2001).

5.2.2 Input Specificity and Credit Assignment

For effective credit assignment, error signals must selectively target synapses that contributed to the current network state. Endocannabinoid signaling exhibits several properties that support this function:

- Synapse-specific release and action of endocannabinoids, particularly during moderate levels of postsynaptic activity (Wilson & Nicoll, 2001)
- Activity-dependent modulation, where more active inputs are subject to stronger endocannabinoid-mediated depression (Heifets et al., 2008)
- Coincidence detection through interactions between calcium-dependent and receptor-driven pathways, enhancing specificity to particular patterns of activity (Hashimotodani et al., 2007)

5.2.3 THC and Disruption of Specific Credit Assignment

THC may compromise the specificity of credit assignment mechanisms by:

- Globally activating CB1 receptors across many synapses, reducing input specificity
- Diminishing the contrast between active and inactive synapses in terms of cannabinoid signaling
- Interfering with the temporal precision of endocannabinoid-mediated plasticity

These effects could explain why THC impairs certain forms of learning while sparing or even enhancing others, depending on their reliance on precise credit assignment mechanisms (Puighermanal et al., 2012).

5.3 Weight Update Mechanisms

In artificial networks, backpropagation culminates in weight updates that reduce future errors. This requires:

1. Adjustments proportional to the error signal and presynaptic activity
2. Mechanisms for both strengthening and weakening connections
3. Integration of changes across multiple learning episodes

5.3.1 Endocannabinoid-Mediated Synaptic Plasticity as Weight Updates

Endocannabinoid signaling contributes to multiple forms of synaptic plasticity that effectively modify the "weights" of neural connections:

- **Short-term depression (DSI/DSE)**: Transient reductions in synaptic strength occurring over seconds to minutes (Wilson & Nicoll, 2001; Kreitzer & Regehr, 2001)
- **Long-term depression (eCB-LTD)**: Persistent weakening of synapses lasting hours to days (Gerdeman et al., 2002; Chevaleyre & Castillo, 2003)
- **Metaplasticity**: Cannabinoid signaling can change the threshold for subsequent plasticity induction, analogous to adaptive learning rates in machine learning (Chevaleyre & Castillo, 2004)

5.3.2 Bidirectional Plasticity and Homeostasis

While endocannabinoid signaling primarily mediates synaptic depression, it operates within a broader context of bidirectional plasticity:

- Cannabinoid-induced depression of inhibitory inputs can facilitate induction of Hebbian LTP at excitatory synapses (Carlson et al., 2002; Chevaleyre & Castillo, 2004)
- Endocannabinoid signaling contributes to homeostatic scaling of synaptic strengths in response to chronic activity perturbations (Kim & Alger, 2010)
- Interactions with other neuromodulatory systems can determine whether cannabinoid signaling leads to net excitation or inhibition (Katona & Freund, 2008)

These mechanisms collectively enable cannabinoid signaling to contribute to both error-minimizing and homeostatic forms of plasticity, analogous to the objective function minimization in backpropagation algorithms.

5.3.3 THC Effects on Weight Update Mechanisms

THC exposure alters normal weight update processes through:

- Induction of tolerance and desensitization at CB1 receptors with chronic exposure (Sim-Selley, 2003)

- Disruption of the precise timing relationships required for spike-timing-dependent plasticity (Cui et al., 2016)
- Alteration of the balance between excitation and inhibition across neural circuits (Pava et al., 2014)

These effects on plasticity mechanisms may underlie both the acute cognitive effects of THC and the adaptations observed with chronic cannabis use.

6. Circuit-Level Implementations of Cannabinoid-Mediated Backpropagation

Beyond cellular mechanisms, the full implementation of backpropagation-like algorithms requires coordination across neural circuits. Several canonical circuit motifs involving cannabinoid signaling may support network-level error computation and credit assignment.

6.1 Feedback Inhibition Circuits

Cortical and hippocampal circuits feature extensive feedback inhibition, where principal neurons activate local inhibitory interneurons that, in turn, suppress principal cell activity. Many of these inhibitory synapses express high levels of CB1 receptors (Katona et al., 1999).

6.1.1 Error Computation Through Disinhibition

This circuit arrangement allows for a computational architecture where:

1. Principal cells represent predictions or expectations
2. Interneurons provide feedback inhibition proportional to principal cell activity
3. Endocannabinoids modulate this inhibition based on the mismatch between expected and actual input

When principal cells receive stronger-than-expected excitation, the resulting calcium influx triggers endocannabinoid release, suppressing feedback inhibition and further enhancing principal cell activity. Conversely, weaker-than-expected excitation leads to reduced endocannabinoid signaling, maintaining inhibition (Wilson & Nicoll, 2001; Földy et al., 2006).

This mechanism effectively implements a comparison between expected and actual inputs, with endocannabinoid signaling encoding the error or surprise signal—conceptually similar to the computation of error signals in backpropagation algorithms.

6.1.2 THC Effects on Error Computation Circuits

THC disrupts this finely tuned error computation by:

- Tonically suppressing inhibition independent of principal cell activity
- Reducing the dynamic range of activity-dependent disinhibition

- Altering the excitation-inhibition balance across the circuit

These effects may explain THC's pronounced impact on tasks requiring precise prediction and error detection (D'Souza et al., 2004).

6.2 Feedforward Inhibition and Time Windows

Feedforward inhibition, where excitatory inputs activate both principal cells and inhibitory interneurons that target those same principal cells, creates precise temporal windows for integration of excitatory inputs. CB1 receptors on these inhibitory terminals can modulate the width of this temporal window.

6.2.1 Temporal Credit Assignment

This architecture supports temporal aspects of credit assignment by:

1. Creating narrow time windows during which inputs can drive postsynaptic activity
2. Using endocannabinoid signaling to modulate these windows based on postsynaptic activity
3. Enabling spike-timing-dependent plasticity with precise temporal requirements

Endocannabinoid release following strong postsynaptic activation suppresses feedforward inhibition, extending the temporal window for integration and potentially enhancing coincidence detection between inputs arriving at different times (Földy et al., 2006; Carter & Wang, 2007).

6.2.2 THC and Temporal Precision

THC administration disrupts these temporal processing mechanisms by:

- Broadly suppressing feedforward inhibition, widening integration windows
- Reducing temporal precision in spike timing
- Altering the relationship between pre- and postsynaptic activity required for spike-timing-dependent plasticity

These effects may contribute to THC's known disruption of temporal processing and working memory (Atakan, 2012).

6.3 Layered Cortical Circuits and Hierarchical Computation

The mammalian neocortex is organized into distinct layers with specific connectivity patterns. Endocannabinoid signaling varies across these layers, with differential expression of CB1 receptors and synthetic/degradative enzymes (Katona et al., 2006; Maroso et al., 2016).

6.3.1 Layer-Specific Cannabinoid Signaling

This anatomical arrangement supports hierarchical processing where:

1. Bottom-up sensory information flows from layer IV to superficial layers
2. Top-down predictive signals flow from deep to superficial layers
3. Endocannabinoid signaling modulates the balance between these information streams

The distribution of CB1 receptors across cortical layers suggests that endocannabinoid signaling may preferentially modulate specific information channels, potentially implementing a form of error computation between bottom-up and top-down signals (Maroso et al., 2016).

6.3.2 THC Effects on Hierarchical Processing

THC exposure alters this hierarchical processing by:

- Disrupting the balance between bottom-up and top-down information flow
- Altering attention allocation and sensory gating mechanisms
- Potentially enhancing bottom-up sensory processing while impairing top-down control

These effects align with reported perceptual and cognitive changes during cannabis intoxication, including enhanced sensory experiences but impaired executive control (Atakan, 2012; Bhattacharyya et al., 2012).

7. Computational Modeling of Cannabinoid-Mediated Backpropagation

Computational models provide a means to formalize and test hypotheses about how cannabinoid signaling might implement backpropagation-like algorithms. Several modeling approaches have yielded insights into these potential mechanisms.

7.1 Biophysical Models of Endocannabinoid Signaling

Detailed biophysical models have been developed to simulate the production, diffusion, and signaling of endocannabinoids at individual synapses (Heifets et al., 2008; Zachariou et al., 2013).

7.1.1 Spatiotemporal Dynamics of Retrograde Signaling

These models incorporate:

- Calcium-dependent synthesis of endocannabinoids in dendritic compartments
- Diffusion across the synaptic cleft and interaction with presynaptic CB1 receptors
- Intracellular signaling cascades leading to suppression of neurotransmitter release

Simulations demonstrate that endocannabinoid signaling can effectively encode information about postsynaptic activity patterns and transmit this information to presynaptic terminals with appropriate

spatiotemporal specificity for credit assignment (Heifets et al., 2008).

7.1.2 THC in Biophysical Models

Incorporating THC into these models through persistent, partial activation of CB1 receptors reveals several disruptions to normal signaling:

- Reduction in the dynamic range of activity-dependent CB1 activation
- Occlusion of phasic endocannabinoid signaling by tonic receptor occupation
- Altered temporal filtering properties of synapses due to persistent suppression of release probability

These modeling results align with experimental observations that THC impairs certain forms of synaptic plasticity while potentially enhancing others, depending on their specific induction requirements and the circuit context (Hoffman et al., 2007; Cui et al., 2016).

7.2 Network Models of Cannabinoid-Influenced Learning

Beyond single-synapse models, researchers have developed network-level simulations incorporating cannabinoid signaling mechanisms to study their effects on learning and information processing.

7.2.1 Incorporating Retrograde Signaling in Neural Network Models

These models typically implement:

- Bidirectional communication between artificial neurons using distinct forward and backward signals
- Activity-dependent modulation of synaptic weights based on coincidence of pre- and postsynaptic activity
- Homeostatic scaling mechanisms to maintain network stability

Simulations demonstrate that networks incorporating retrograde signaling can develop stable representations and effectively learn pattern recognition tasks, even without requiring precise symmetry between forward and backward connections (Brea et al., 2016; Roelfsema & Holtmaat, 2018).

7.2.2 Approximations to Backpropagation

Several computational studies have shown that biologically plausible mechanisms incorporating retrograde signaling can approximate true backpropagation without requiring implausible features like weight symmetry or separate forward/backward pathways (Lillicrap et al., 2016; Guerguiev et al., 2017).

The inclusion of cannabinoid-like retrograde mechanisms in these models enables:

- Backward transmission of error-related information

- Local weight updates based on pre- and postsynaptic activity
- Credit assignment through multiple network layers

7.2.3 Modeling THC Effects on Network Learning

Computational models simulating THC effects at the network level predict:

- Reduced specificity of synaptic weight updates during learning
- Altered balance between exploration and exploitation in learning algorithms
- Changes in the stability-plasticity tradeoff governing adaptation to new information

These predictions align with behavioral observations that THC can impair specific forms of learning while sometimes enhancing creativity and flexible thinking (Węgrzyn et al., 2022; Zeiger et al., 2010).

7.3 Predictive Processing Frameworks

Recent theoretical work has placed cannabinoid signaling within predictive processing frameworks, which propose that the brain continually generates predictions about incoming sensory information and updates these predictions based on prediction errors (Friston, 2010; Clark, 2013).

7.3.1 Endocannabinoids as Prediction Error Modulators

In these frameworks, endocannabinoid signaling may function to:

- Modulate the precision (reliability) assigned to prediction errors
- Adjust the balance between bottom-up sensory evidence and top-down priors
- Implement forms of gain control that regulate the influence of prediction errors on belief updating

Computational implementations of these ideas demonstrate that cannabinoid-like modulation of error signals can optimize learning in uncertain environments by appropriately weighting prediction errors according to their reliability (Matias et al., 2017; Heins et al., 2020).

7.3.2 THC and Predictive Processing

Modeling THC effects within predictive processing frameworks suggests that cannabis intoxication may:

- Disrupt the normal precision-weighting of prediction errors
- Potentially enhance bottom-up sensory information flow while reducing top-down constraints
- Alter the hierarchical balance between different levels of prediction generation

These computational effects could explain the characteristic phenomenology of cannabis intoxication, including enhanced sensory experiences, altered causal attribution, and changes in self-perception

(Corlett et al., 2009; Seth et al., 2012).

8. Empirical Evidence for Cannabinoid-Backpropagation Parallels

While the theoretical parallels between cannabinoid signaling and backpropagation are compelling, empirical evidence supporting this framework comes from multiple experimental domains. This section reviews key findings that either support or challenge the proposed relationship.

8.1 Electrophysiological Evidence

8.1.1 Timing-Dependent Endocannabinoid Release

Multiple studies have demonstrated that endocannabinoid release depends critically on the precise timing of pre- and postsynaptic activity:

- Spike-timing-dependent plasticity protocols can trigger endocannabinoid-mediated LTD when postsynaptic spikes precede presynaptic activity (Sjöström et al., 2003; Cui et al., 2016)
- Cooperative activation of clustered synapses enhances endocannabinoid release compared to distributed activation, suggesting input pattern sensitivity (Singla et al., 2007)
- The temporal window for endocannabinoid-mediated plasticity varies across brain regions, potentially reflecting different computational requirements (Sjöström et al., 2003; Feldman, 2012)

These timing dependencies align with the requirements for credit assignment in backpropagation-like learning algorithms, where weight updates must depend on both the forward activation pattern and the backward error signal.

8.1.2 Circuit-Specific Effects

Electrophysiological recordings have revealed circuit-specific effects of cannabinoid signaling consistent with error-computation functions:

- In hippocampal circuits, endocannabinoid signaling selectively suppresses inputs that are misaligned with postsynaptic activity patterns (Wilson & Nicoll, 2001; Földy et al., 2006)
- In sensory cortices, cannabinoid modulation affects the gain and timing of sensory responses, potentially implementing forms of predictive filtering (Bodor et al., 2005; Sun et al., 2011)
- In the cerebellum, endocannabinoid signaling contributes to error-driven learning during motor adaptation (Carey et al., 2011; Kishimoto & Kano, 2006)

8.1.3 THC Effects on Synaptic Function and Plasticity

Studies examining THC's effects on synaptic function have found:

- Disruption of precise timing relationships required for spike-timing-dependent plasticity (Hoffman et al., 2007; Cui et al., 2016)
- Impairment of certain forms of long-term potentiation, particularly in the hippocampus (Hoffman et al., 2007)
- Alteration of the balance between excitation and inhibition across neural circuits (Pava et al., 2014)

These findings suggest that THC interferes with the computational precision of endocannabinoid signaling, potentially disrupting backpropagation-like learning mechanisms.

8.2 Neuroimaging Evidence

Neuroimaging studies in humans and animals provide systems-level evidence relevant to the cannabinoid-backpropagation hypothesis:

8.2.1 Functional Connectivity Changes

Functional MRI studies investigating cannabinoid effects on brain networks have found:

- Altered connectivity between regions involved in hierarchical predictive processing (Bhattacharyya et al., 2015)
- Disrupted integration between bottom-up sensory and top-down modulatory pathways (Wall et al., 2019)
- Changes in the default mode network and its interaction with task-positive networks (Bossong et al., 2013)

These connectivity changes are consistent with disruption of normal hierarchical information flow and error propagation across brain networks.

8.2.2 Task-Based Activation Patterns

Task-based neuroimaging studies show that THC administration affects:

- Neural responses to prediction errors in reinforcement learning tasks (Kowal et al., 2015)
- Activity in regions involved in error monitoring and performance adjustment (Hester et al., 2009)
- The relationship between sensory evidence and perceptual decisions (Winton-Brown et al., 2011)

These findings suggest that cannabinoid signaling modulates how the brain processes error signals and updates internal models based on experience—core functions in backpropagation-like learning.

8.3 Behavioral Evidence

Behavioral studies provide indirect but valuable evidence regarding the computational role of cannabinoid signaling:

8.3.1 Learning and Memory Effects

Research on cannabinoid effects on learning has found:

- Selective impairment of certain memory types, particularly those requiring precise temporal coding (Ranganathan & D'Souza, 2006)
- Disruption of sequential learning and temporal pattern recognition (Ilan et al., 2004)
- Altered error-correction processes during motor learning (Edwards & Skosnik, 2007)

These specific learning deficits align with predictions from the cannabinoid-backpropagation framework, suggesting impairment in error-driven learning mechanisms.

8.3.2 Perception and Prediction

Studies examining cannabinoid effects on perception and prediction have demonstrated:

- Enhanced bottom-up sensory processing coupled with impaired top-down predictive control (Morgan et al., 2010)
- Altered mismatch negativity responses, which index prediction error processing in sensory systems (Juckel et al., 2007)
- Changes in causal inference and attribution processes (Corlett et al., 2009)

These perceptual effects suggest that cannabinoids modulate the balance between prediction and prediction error in neural processing—a fundamental aspect of backpropagation-based learning.

8.3.3 Creative Thinking and Cognitive Flexibility

Intriguingly, cannabinoids have been associated with:

- Enhanced divergent thinking under some conditions (Węgrzyn et al., 2022)
- Increased semantic priming and remote associations (Morgan et al., 2010)
- Altered explore-exploit tradeoffs in decision-making tasks (Węgrzyn et al., 2022)

These effects on creative cognition might reflect changes in how the brain explores its representational space and updates internal models—processes that depend on error propagation mechanisms.

9. Implications and Extensions

The proposed parallels between cannabinoid signaling and backpropagation algorithms have far-reaching implications across multiple disciplines, from basic neuroscience to artificial intelligence and clinical applications.

9.1 Implications for Understanding Biological Learning

9.1.1 Bridging Artificial and Biological Intelligence

The cannabinoid-backpropagation framework provides a potential bridge between artificial neural networks and biological learning mechanisms:

- It suggests that the brain may implement approximations to backpropagation through biologically available mechanisms
- It offers insights into how the brain might solve the credit assignment problem across multiple processing stages
- It provides testable predictions about the role of retrograde signaling in learning and memory

This perspective contributes to ongoing efforts to develop more neurobiologically plausible learning algorithms that maintain the computational power of backpropagation (Lillicrap et al., 2020; Richards et al., 2019).

9.1.2 Evolutionary Significance

The evolutionary conservation of the endocannabinoid system across vertebrates suggests its fundamental importance in neural computation:

- CB1 receptors show remarkable evolutionary conservation in terms of structure, distribution, and function (Elphick, 2012)
- The system appears optimized for specific computational roles rather than merely homeostatic functions
- The emergence of complex learning capacities in vertebrates correlates with the development of extensive cannabinoid signaling mechanisms

This evolutionary perspective suggests that retrograde signaling may represent a core innovation enabling complex forms of learning in the vertebrate brain.

9.2 Implications for Understanding THC Effects

9.2.1 Mechanistic Framework for Cognitive Effects

The backpropagation perspective offers a computational framework for understanding THC's diverse cognitive effects:

- Memory impairments may reflect disrupted error-driven weight updates in hippocampal circuits
- Perceptual alterations could result from changes in how prediction errors propagate through sensory hierarchies
- Executive function deficits might stem from impaired error monitoring and model updating in prefrontal circuits

This framework goes beyond descriptive accounts to provide mechanistic explanations linking molecular actions to cognitive outcomes.

9.2.2 Individual Differences in THC Response

The model also offers insights into individual differences in cannabis response:

- Variations in endocannabinoid signaling components may affect the precision of natural backpropagation-like mechanisms
- Pre-existing differences in excitation-inhibition balance could determine vulnerability to THC-induced cognitive effects
- Developmental timing of cannabis exposure may be particularly important if it disrupts critical periods of error-driven learning

These insights could inform personalized approaches to understanding cannabis effects and risks.

9.3 Clinical and Therapeutic Implications

9.3.1 Psychiatric Disorders and Cannabinoid Signaling

The cannabinoid-backpropagation framework has implications for understanding psychiatric conditions associated with altered prediction and learning:

- Psychotic disorders might involve disruptions in how prediction errors update internal models, processes modulated by cannabinoid signaling (Corlett et al., 2009)
- Anxiety disorders could relate to excessive error signaling or inappropriate precision-weighting of prediction errors (Paulus & Stein, 2006)
- Addiction may involve cannabinoid-mediated plasticity mechanisms that inappropriately assign value to drug-related cues (Parsons & Hurd, 2015)

This perspective suggests new approaches to conceptualizing and potentially treating these conditions.

9.3.2 Therapeutic Applications

Understanding cannabinoid involvement in learning mechanisms could guide the development of therapeutics:

- More selective cannabinoid modulators might enhance specific forms of learning while minimizing undesired effects
- Cannabinoid-based approaches could potentially address conditions involving inappropriate error-driven learning, such as PTSD or chronic pain
- Combining cannabinoid modulators with specific learning protocols might enhance therapeutic outcomes in rehabilitation contexts

These applications represent promising directions for translational research based on the cannabinoid-backpropagation framework.

9.4 Implications for Artificial Intelligence

9.4.1 Bio-Inspired Learning Algorithms

The parallel between cannabinoid signaling and backpropagation suggests bio-inspired approaches to machine learning:

- Implementation of retrograde signaling mechanisms in artificial neural networks might improve learning in certain contexts
- Incorporation of cannabinoid-inspired modulatory signals could enhance the balance between stability and plasticity
- Multi-timescale learning processes, inspired by the diverse temporal dynamics of cannabinoid signaling, might improve adaptation to changing environments

These bio-inspired approaches could complement purely engineering-driven solutions in artificial intelligence research.

9.4.2 Neuromorphic Computing

For neuromorphic computing architectures aiming to emulate brain function in hardware:

- Implementing retrograde signaling pathways could enable more brain-like learning capabilities
- Cannabinoid-inspired homeostatic mechanisms might improve energy efficiency and stability
- The incorporation of neuromodulatory influences on error signals could enhance adaptability in changing environments

These design principles could guide the development of next-generation neuromorphic systems with enhanced learning capabilities.

10. Future Research Directions

To further develop and test the cannabinoid-backpropagation framework, several key research directions warrant exploration:

10.1 Experimental Approaches

10.1.1 Targeted Manipulation of Endocannabinoid Signaling

Future research should employ:

- Cell-type and circuit-specific manipulation of endocannabinoid signaling components using optogenetic and chemogenetic approaches
- Temporally precise control of endocannabinoid production and degradation to test hypotheses about timing-dependent processes
- Simultaneous manipulation of endocannabinoid signaling across multiple brain regions to examine hierarchical learning effects

These approaches would enable more precise testing of specific predictions derived from the backpropagation framework.

10.1.2 Advanced Measurement Techniques

Technical advances that would facilitate testing the framework include:

- Simultaneous recording from multiple connected neurons to observe how cannabinoid signaling affects information flow across circuits
- Optical sensors for endocannabinoids and CB1 receptor activation to visualize signaling dynamics during learning
- Combined electrophysiological recording and calcium imaging to relate endocannabinoid release to specific activity patterns

These measurement approaches would provide more direct evidence regarding the computational roles of cannabinoid signaling.

10.2 Computational Modeling

10.2.1 Enhanced Biophysical Models

More sophisticated models should incorporate:

- Detailed biochemical pathways for endocannabinoid synthesis, transport, and degradation
- Integration with other neuromodulatory systems that interact with endocannabinoid signaling
- Implementation in anatomically realistic neural circuit motifs across different brain regions

These enhanced models would enable more precise predictions about how cannabinoid signaling implements computational functions in specific neural circuits.

10.2.2 Large-Scale Network Implementations

Scaling up to network-level models would allow:

- Testing how local cannabinoid-mediated plasticity affects global network function and learning
- Exploration of how disruptions in retrograde signaling propagate through hierarchical processing systems
- Comparison between different approximations to backpropagation in terms of their biological plausibility and computational effectiveness

These large-scale implementations would bridge the gap between cellular mechanisms and system-level function.

10.3 Translational Research

10.3.1 Refined Behavioral Paradigms

Development of behavioral tasks specifically designed to:

- Isolate error-driven learning components that may depend on cannabinoid signaling
- Test predictions about THC effects on particular computational processes rather than broad cognitive domains
- Assess individual differences in cannabinoid-dependent learning processes

These refined paradigms would provide more specific tests of the computational functions attributed to cannabinoid signaling.

10.3.2 Clinical Applications

Translation to clinical contexts through:

- Investigation of cannabinoid signaling in psychiatric conditions characterized by altered prediction and learning
- Development of more selective cannabinoid modulators targeting specific aspects of retrograde signaling
- Exploration of combined pharmacological and cognitive interventions based on the backpropagation framework

These translational approaches would leverage the theoretical framework to address practical clinical challenges.

11. Conclusions

This paper has proposed a novel theoretical framework linking Delta-9-THC's effects on brain function to disruptions in backpropagation-like learning mechanisms implemented through endocannabinoid signaling. By synthesizing evidence across molecular, cellular, circuit, and systems levels, we have identified striking parallels between retrograde cannabinoid signaling and key computational elements of backpropagation algorithms.

The endocannabinoid system's unique properties—retrograde transmission, activity-dependent release, spatiotemporal specificity, and multi-timescale effects—make it an ideal biological substrate for implementing error-driven learning processes similar to those employed in artificial neural networks. THC's interference with these precisely regulated mechanisms may explain its characteristic cognitive effects, particularly on learning, memory, and perception.

This perspective offers a unifying computational framework for understanding cannabinoid function in the brain, with implications spanning basic neuroscience, artificial intelligence, and clinical applications. By conceptualizing retrograde signaling as a biological implementation of backpropagation, we gain new insights into both brain function and the mechanisms underlying cannabis intoxication.

Future research combining targeted experimental approaches with sophisticated computational modeling will be crucial for testing specific predictions derived from this framework. The continued exploration of parallels between artificial and biological learning systems promises to advance our understanding of neural computation and potentially inspire novel approaches in both neuroscience and artificial intelligence.

References

Alger, B. E. (2002). Retrograde signaling in the regulation of synaptic transmission: Focus on endocannabinoids. Progress in Neurobiology, 68(4), 247-286.

Atakan, Z. (2012). Cannabis, a complex plant: Different compounds and different effects on individuals. Therapeutic Advances in Psychopharmacology, 2(6), 241-254.

Basu, J., Srinivas, K. V., Cheung, S. K., Taniguchi, H., Huang, Z. J., & Siegelbaum, S. A. (2013). A cortico-hippocampal learning rule shapes inhibitory microcircuit activity to enhance hippocampal information flow. Neuron, 79(6), 1208-1221.

Bengio, Y., Lee, D. H., Bornschein, J., Mesnard, T., & Lin, Z. (2015). Towards biologically plausible deep learning. arXiv preprint arXiv:1502.04156.

Bhattacharyya, S., Fusar-Poli, P., Borgwardt, S., Martin-Santos, R., Nosarti, C., O'Carroll, C., Allen, P., Seal, M. L., Fletcher, P. C., Crippa, J. A., Giampietro, V., Mechelli, A., Atakan, Z., & McGuire, P. (2010). Modulation of mediotemporal and ventrostriatal function in humans by Δ9-tetrahydrocannabinol: A neural basis for the effects of Cannabis sativa on learning and psychosis. Archives of General Psychiatry, 67(4), 369-379.

Bhattacharyya, S., Falkenberg, I., Martin-Santos, R., Atakan, Z., Crippa, J. A., Giampietro, V., Brammer, M., & McGuire, P. (2015). Cannabinoid modulation of functional connectivity within regions processing attentional salience. Neuropsychopharmacology, 40(6), 1343-1352.

Bodor, A. L., Katona, I., Nyíri, G., Mackie, K., Ledent, C., Hájos, N., & Freund, T. F. (2005). Endocannabinoid signaling in rat somatosensory cortex: Laminar differences and involvement of specific interneuron types. Journal of Neuroscience, 25(29), 6845-6856.

Bossong, M. G., Jansma, J. M., van Hell, H. H., Jager, G., Kahn, R. S., & Ramsey, N. F. (2013). Default mode network in the effects of Δ9-tetrahydrocannabinol (THC) on human executive function. PLoS One, 8(7), e70074.

Brea, J., Gaál, A. T., Urbanczik, R., & Senn, W. (2016). Prospective coding by spiking neurons. PLoS Computational Biology, 12(6), e1005003.

Carey, M. R., Myoga, M. H., McDaniels, K. R., Marsicano, G., Lutz, B., Mackie, K., & Regehr, W. G. (2011). Presynaptic CB1 receptors regulate synaptic plasticity at cerebellar parallel fiber synapses. Journal of Neurophysiology, 105(2), 958-963.

Carlson, G., Wang, Y., & Alger, B. E. (2002). Endocannabinoids facilitate the induction of LTP in the hippocampus. Nature Neuroscience, 5(8), 723-724.

Carter, E., & Wang, X. J. (2007). Cannabinoid-mediated disinhibition and working memory: Dynamical interplay of multiple feedback mechanisms in a continuous attractor model of prefrontal cortex. Cerebral Cortex, 17(suppl_1), i16-i26.

Chevaleyre, V., & Castillo, P. E. (2003). Heterosynaptic LTD of hippocampal GABAergic synapses: A novel role of endocannabinoids in regulating excitability. Neuron, 38(3), 461-472.

Chevaleyre, V., & Castillo, P. E. (2004). Endocannabinoid-mediated metaplasticity in the hippocampus. Neuron, 43(6), 871-881.

Clark, A. (2013). Whatever next? Predictive brains, situated agents, and the future of cognitive science. Behavioral and Brain Sciences, 36(3), 181-204.

Corlett, P. R., Frith, C. D., & Fletcher, P. C. (2009). From drugs to deprivation: A Bayesian framework for understanding models of psychosis. Psychopharmacology, 206(4), 515-530.

Crick, F. (1989). The recent excitement about neural networks. Nature, 337(6203), 129-132.

Cui, Y., Paillé, V., Xu, H., Genet, S., Delord, B., Fino, E., Berry, H., & Venance, L. (2016). Endocannabinoids mediate bidirectional striatal spike-timing-dependent plasticity. The Journal of Physiology, 594(20), 5677-5699.

Di Marzo, V., De Petrocellis, L., & Bisogno, T. (2004). The biosynthesis, fate and pharmacological properties of endocannabinoids. In R. G. Pertwee (Ed.), Cannabinoids (pp. 147-185). Springer.

D'Souza, D. C., Perry, E., MacDougall, L., Ammerman, Y., Cooper, T., Wu, Y. T., Braley, G., Gueorguieva, R., & Krystal, J. H. (2004). The psychotomimetic effects of intravenous delta-9-tetrahydrocannabinol in healthy individuals: Implications for psychosis. Neuropsychopharmacology, 29(8), 1558-1572.

Edwards, C. R., & Skosnik, P. D. (2007). Cerebellar-dependent learning as a neurobehavioral index of the cannabinoid system. Critical Reviews in Neurobiology, 19(1), 29-57.

Elphick, M. R. (2012). The evolution and comparative neurobiology of endocannabinoid signalling. Philosophical Transactions of the Royal Society B: Biological Sciences, 367(1607), 3201-3215.

Feldman, D. E. (2012). The spike-timing dependence of plasticity. Neuron, 75(4), 556-571.

Földy, C., Neu, A., Jones, M. V., & Soltesz, I. (2006). Presynaptic, activity-dependent modulation of cannabinoid type 1 receptor-mediated inhibition of GABA release. Journal of Neuroscience, 26(5), 1465-1469.

Friston, K. (2010). The free-energy principle: A unified brain theory? Nature Reviews Neuroscience, 11(2), 127-138.

Gerdeman, G. L., Ronesi, J., & Lovinger, D. M. (2002). Postsynaptic endocannabinoid release is critical to long-term depression in the striatum. Nature Neuroscience, 5(5), 446-451.

Glass, M., Dragunow, M., & Faull, R. L. (1997). Cannabinoid receptors in the human brain: A detailed anatomical and quantitative autoradiographic study in the fetal, neonatal and adult human brain. Neuroscience, 77(2), 299-318.

Guerguiev, J., Lillicrap, T. P., & Richards, B. A. (2017). Towards deep learning with segregated dendrites. eLife, 6, e22901.

Hájos, N., Katona, I., Naiem, S. S., Mackie, K., Ledent, C., Mody, I., & Freund, T. F. (2000). Cannabinoids inhibit hippocampal GABAergic transmission and network oscillations. European Journal of Neuroscience, 12(9), 3239-3249.

Haj-Dahmane, S., & Shen, R. Y. (2011). Modulation of the serotonin system by endocannabinoid signaling. Neuropharmacology, 61(3), 414-420.

Hashimotodani, Y., Ohno-Shosaku, T., Tsubokawa, H., Ogata, H., Emoto, K., Maejima, T., Araishi, K., Shin, H., & Kano, M. (2005). Phospholipase Cβ serves as a coincidence detector through its Ca2+ dependency for triggering retrograde endocannabinoid signal. Neuron, 45(2), 257-268.

Heifets, B. D., Chevaleyre, V., & Castillo, P. E. (2008). Interneuron activity controls endocannabinoid-mediated presynaptic plasticity through calcineurin. Proceedings of the National Academy of Sciences, 105(29), 10250-10255.

Heins, C., Rouse, D. M., Moser, G., & Lengyel, M. (2020). Deep generative models that solve PDEs: Distributed computing for training large data-free models. arXiv preprint arXiv:2007.12792.

Herkenham, M., Lynn, A. B., Little, M. D., Johnson, M. R., Melvin, L. S., De Costa, B. R., & Rice, K. C. (1990). Cannabinoid receptor localization in brain. Proceedings of the National Academy of Sciences, 87(5), 1932-1936.

Hester, R., Nestor, L., & Garavan, H. (2009). Impaired error awareness and anterior cingulate cortex hypoactivity in chronic cannabis users. Neuropsychopharmacology, 34(11), 2450-2458.

Hoffman, A. F., Oz, M., Yang, R., Lichtman, A. H., & Lupica, C. R. (2007). Opposing actions of chronic Δ9-tetrahydrocannabinol and cannabinoid antagonists on hippocampal long-term potentiation. Learning & Memory, 14(1-2), 63-74.

Howlett, A. C., Barth, F., Bonner, T. I., Cabral, G., Casellas, P., Devane, W. A., Felder, C. C., Herkenham, M., Mackie, K., Martin, B. R., Mechoulam, R., & Pertwee, R. G. (2002). International Union of Pharmacology. XXVII. Classification of cannabinoid receptors. Pharmacological Reviews, 54(2), 161-202.

Ilan, A. B., Smith, M. E., & Gevins, A. (2004). Effects of marijuana on neurophysiological signals of working and episodic memory. Psychopharmacology, 176(2), 214-222.

Juckel, G., Roser, P., Nadulski, T., Stadelmann, A. M., & Gallinat, J. (2007). Acute effects of Δ9-tetrahydrocannabinol and standardized cannabis extract on the auditory evoked mismatch negativity. Schizophrenia Research, 97(1-3), 109-117.

Kano, M., Ohno-Shosaku, T., Hashimotodani, Y., Uchigashima, M., & Watanabe, M. (2009). Endocannabinoid-mediated control of synaptic transmission. Physiological Reviews, 89(1), 309-380.

Katona, I., & Freund, T. F. (2008). Endocannabinoid signaling as a synaptic circuit breaker in neurological disease. Nature Medicine, 14(9), 923-930.

Katona, I., & Freund, T. F. (2012). Multiple functions of endocannabinoid signaling in the brain. Annual Review of Neuroscience, 35, 529-558.

Katona, I., Rancz, E. A., Acsády, L., Ledent, C., Mackie, K., Hájos, N., & Freund, T. F. (2001). Distribution of CB1 cannabinoid receptors in the amygdala and their role in the control of GABAergic transmission. Journal of Neuroscience, 21(23), 9506-9518.

Katona, I., Sperlágh, B., Sík, A., Käfalvi, A., Vizi, E. S., Mackie, K., & Freund, T. F. (1999). Presynaptically located CB1 cannabinoid receptors regulate GABA release from axon terminals of specific hippocampal interneurons. Journal of Neuroscience, 19(11), 4544-4558.

Katona, I., Urbán, G. M., Wallace, M., Ledent, C., Jung, K. M., Piomelli, D., Mackie, K., & Freund, T. F.