



Theoretical models of synaptic short term plasticity

Matthias H. Hennig*

School of Informatics, Institute for Adaptive and Neural Computation, University of Edinburgh, Edinburgh, UK

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*Correspondence:

Matthias H. Hennig, School of Informatics, Institute for Adaptive and Neural Computation, University of Edinburgh, 10 Crichton Street, Edinburgh EH8 9AB, UK
e-mail: m.hennig@ed.ac.uk

Short term plasticity is a highly abundant form of rapid, activity-dependent modulation of synaptic efficacy. A shared set of mechanisms can cause both depression and enhancement of the postsynaptic response at different synapses, with important consequences for information processing. Mathematical models have been extensively used to study the mechanisms and roles of short term plasticity. This review provides an overview of existing models and their biological basis, and of their main properties. Special attention will be given to slow processes such as calcium channel inactivation and the effect of activation of presynaptic autoreceptors.

Keywords: short term plasticity, synaptic transmission, mathematical model, synaptic depression, synaptic facilitation

INTRODUCTION

Chemical synapses are highly specialized structures that enable neurons to exchange signals, or to send signals to non-neural cells such as muscle fibers. Even though there is a staggering diversity of synapse morphologies and types in the brain, the fundamental process of synaptic transmission is always the same. A presynaptic membrane potential depolarization, typically caused by the arrival of an action potential, triggers the release of neurotransmitter, which then binds to receptors that, in turn, generate a response in the postsynaptic neuron.

A key quantity in neural circuits is the synaptic efficacy or strength, which varies over time. Cellular processes such as long-term potentiation and depression contribute to the patterning of the nervous system during development, and are thought to constitute the basis of learning and memory (Morris, 2003). Slow and long-lasting homeostatic processes adjust synaptic strength to maintain circuit activity within functional regimes (Turrigiano and Nelson, 2004). In addition, a whole range of activity-dependent processes exist that modulate synaptic efficacy continuously on very short time scales ranging from milliseconds to minutes (for reviews, see Zucker and Regehr, 2002; Fioravante and Regehr, 2011). Unlike long-term and homeostatic plasticity, short term plasticity, the topic of this review, has a direct influence on the computation performed by neural circuits as these dynamics take place on the time scale of stimulus-driven activity, neural computations and behavior.

Broadly, short term plasticity can be classified as synaptic depression and facilitation. Depression refers to the progressive reduction of the postsynaptic response during repetitive presynaptic activity, while facilitation is an increase synaptic efficacy. Each of these may be caused by a range of different mechanisms with different time constants, and the two forms are not mutually exclusive. For instance, a particularly well-studied example of a strongly depressing synapse is the calyx of Held, a giant synaptic terminal in the mammalian auditory brainstem (Schneeggenburger and Forsythe, 2006). A closer

look at the underlying mechanisms, however, reveals that the response is also modulated by facilitation, which is however, partially masked by depression. In fact, most synapses express some combination of these two mechanisms, but with considerable variability between different neuron types (Wang et al., 2006).

The purpose of this review is to summarize models of short term plasticity, to discuss their biological background and plausibility, and to provide a guide for selecting an appropriate model and level of detail. The focus here is on the mechanistic aspects of these models, for a review of functional implications see Abbott and Regehr (2004). The review begins with a reminder of the main processes involved in synaptic transmission. Next, the vesicle depletion model and its variants will be introduced as a canonical model for short term plasticity. Finally, several additions to this class of models will be discussed that were required to explain more recent experimental findings.

PRINCIPLES OF SYNAPTIC TRANSMISSION

Almost all factors contributing to short term plasticity are located in the presynaptic terminal. To identify the relevant variables required in models, we begin with a brief review of the main events following the arrival of a presynaptic action potential at a synapse, as illustrated in Figure 1. The site where synaptic transmission of neural activity is initiated is called the active zone (AZ), a presynaptic morphological specialization where vesicles containing neurotransmitter and proteins required for the release process are clustered. The AZ is opposed by the postsynaptic density (PSD), an area that contains a large number of different proteins implicated in synapse maintenance and plasticity. In addition to a whole variety of structural and signaling complexes, the PSD contains the bulk of the neurotransmitter receptors mediating the postsynaptic response.

Neurotransmitter release from vesicles located at the AZ is initiated by an elevation of the intracellular calcium concentration $[Ca^{2+}]_i$ due to opening of voltage gated calcium channels

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Neural Information Processing with Dynamical Synapses Si Wu, Michael K Y Wong, Misha Tsodyks, 2015-01-08

Thalamic Function - Beyond a Simple Relay Vincenzo Crunelli, William Martin Connolly, W. Martin Usrey, 2016-05-20

The thalamus is often described as a relay. Typified by sensory pathways this concept leads to thalamic nuclei being viewed as areas that passively stream information from a single source to the cortex without affecting the nature of that information. However, diverse intrathalamic connections, the varying synaptic and membrane properties of thalamic neurons, and the large number of inputs from non-sensory sources make the idea that the thalamus is just a passive relay unlikely. Furthermore, a large number of thalamic nuclei are not primarily driven by sensory signals nor do they exclusively target the cortex, meaning the thalamus must do more than simply pass sensory signals to the cortex. Finally, there is a wealth of research demonstrating that the thalamus does indeed function in ways that are not captured by the concept of a simple relay. So why, given all of this, is the primary paradigm for describing the thalamus a relay? This Research Topic covers original research, reviews, and hypotheses on thalamic function that explore the concept that the thalamus performs computational tasks other than simply passively relaying information.

Neural Computation in Embodied Closed-Loop Systems for the Generation of Complex Behavior: From Biology to Technology Poramate Manoonpong, Christian Tetzlaff, 2018-10-11 How can neural and morphological computations be effectively combined and realized in embodied closed-loop systems, e.g., robots, such that they can become more like living creatures in their level of performance? Understanding this will lead to new technologies and a variety of applications. To tackle this research question, here we bring together experts from different fields, including Biology, Computational Neuroscience, Robotics, and Artificial Intelligence, to share their recent findings and ideas and to update our research community. This eBook collects 17 cutting-edge research articles covering neural and morphological computations as well as the transfer of results to real-world applications like prosthesis and orthosis control and neuromorphic hardware implementation.

Self-Organized Criticality, Three Decades Later Subhrangshu Sekhar Manna, Attilio L. Stella, Peter Grassberger, Ronald Dickman, 2022-01-28

The Plastic Brain Rommy von Bernhardi, Jaime Eugenin, Kenneth J. Muller, 2017-10-26 A comprehensive overview of the many factors that can influence brain plasticity throughout the lifespan. Addresses perinatal plasticity, functional state plasticity, injury-induced plasticity, and stressor-induced plasticity. Because it looks at so many aspects of the field, this volume will serve as a great resource for students as well as researchers interested in expanding their knowledge. The volume comes out as an integrated view based in the expertise of Ibero-American neuroscientists working in the field.

The Handbook of Brain Theory and Neural Networks Michael A. Arbib, 2003 This second edition presents the enormous progress made in recent years in the many subfields related to the two great questions: how does the brain work and how can we build intelligent machines. This second edition greatly increases the coverage of models of fundamental neurobiology, cognitive neuroscience, and neural network approaches to

language Midwest **Neural and Brain Modeling** Ronald J. MacGregor,1987 Network Dynamics in Computer Models of Neocortex with Synaptic Plasticity Arthur Rudolf Houweling,2003 *CSA Neurosciences Abstracts* ,1996 **Synaptic Plasticity, Learning and Cortical Dynamics** Yves Fregnac,1997 **Dissertation Abstracts International** ,2008

International Review of Neurobiology Carl Curt Pfeiffer,John Raymond Smythies,1959 **Synaptic Function** Neurosciences Institute (New York, N.Y.),1987 This book consists of five sections The first section details methods for analyzing both presynaptic and postsynaptic function and emphasizes the molecular aspects of synapses It describes ongoing studies of neurotransmitter release voltage sensitive ion channels and electronic transmission at gap junctions The second section focuses on the growing menagerie of neurotransmitters their categorization into chemical families their relation to ion channels their modulation by second messenger systems and their role in pharmacologic action The third section considers the important relationship of transmitter diversity and synaptic types to the behavior of actual cellular networks All of the studies described in these sections point to the necessity of considering interactions between anatomy chemistry physiology and pharmacology if synaptic function is to be understood at any one of these levels of analysis *Theoretical Systems in Biology* Gilbert Chauvet,1996 Philosophical Transactions of the Royal Society of London ,1999 *The Neural and Molecular Bases of Learning* J. P. Changeux,M. Konishi,1987-05-11 Presents the results of the Dahlem Workshop on the Neural and Molecular Bases of Learning held in Berlin December 1985 Contains an interdisciplinary collection of studies examining the ways in which all organisms learn to adapt to changes in their environments Chapters cover important recent research on the behavioral biophysical molecular and genetic bases of learning and the rapid progress occurring in these and allied fields The book aims to promote the international exchange of scientific information and to encourage new models based on the cellular and molecular rules common to all forms of learning **Proceedings of the 25th Annual International Conference of the IEEE Engineering in Medicine and Biology Society** IEEE Engineering in Medicine and Biology Society. Conference,2003 *Encyclopedia of Learning and Memory* Larry R. Squire,1992 Comprehensive guide to the psychology and biology of learning and memory Proceedings of the National Academy of Sciences of the United States of America National Academy of Sciences (U.S.),2002 Network ,2003

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