Time scale-plasticity learning rule for dendritic neuron model to achieve online time-invariant sequence processing

Farbod Nosrat Nezami[1], **Viktoria Zemliak**[1], **Pascal Nieters**[1], **Gordon Pipa**[1],
1. Institute of Cognitive Science, University of Osnabrück, Osnabrück, Germany.

Summary. Time scale variability is a common phenomenon of naturally occurring time series. Sometimes events occur within the same sequence but with stochastically different timing between events, ex. the speed at which different syllables of a word are uttered. The exact timing of the occurrences of the event, and thus of the entire sequence, can also expand or shrink, a phenomenon known as time warping. The following abstract offers a model inspired by the dendritic trees of real neurons, which utilizes local homeostatic regulation of the length of the plateau potentials in dendritic compartments to adapt to changes in the time scales of the input sequence.

Neuromorphic computing is a rapidly developing field that seeks to design processors inspired by the human brain while improving energy efficiency and optimization, aiming to surpass theoretical limits on computational power with current architectures that arise from their processing power being constrained by physical properties such as size and heat dissipation behavior [2]. Pure analog or mixed analog and digital circuits have become the preferred choice for neuromorphic hardware design due to their superior energy consumption profile and ability to simulate complex dynamical systems, such as spiking neurons [7]. This presents a problem, however, since most real-world time series and sequences - the computation of which is an essential requirement of fields ranging from active sensing to spoken language [3] - occur on time scales far slower than the timescales of the dynamics of the analog electrical components proposed in many neuromorphic hardware designs [3]. Events within these time series can also occur on varying time scales, a phenomenon known as time warping (ex. the varying speed at which each syllable of a word like "com-pu-ter" is uttered). These varying time scales necessitate the development of a method to handle such sequences within neuromorphic systems. In this study, we propose a novel model of the neuron utilizing dendritic computation with local timescale plasticity as a potential solution to this problem of time variances in naturally occurring time series and sequences.

The biological brain and its neurons can handle processing time-varied sequences, but the precise mechanism of this process remains a mystery. However, it has been shown that by generating isolated plateau potentials, dendritic compartments can enable the neuron to possess a short-term memory allowing it to process the input sequence within the sum of its total plateau lengths [4]. There is also evidence from biology that neurons can modulate the length of the plateau potentials generated at each dendritic compartment based on the number of NMDA channels available and the concentration of glutamate at the excitation site [6]. Dendrites have demonstrated considerable computational power, even on the level of a single neuron, and recent research has shown that dendrites with plateau potentials can provide partial time-invariant sequence detection [4]. Nevertheless, most current models of neurons in artificial or spiking neural networks disregard the function of dendrites due to their complexity [5, 1], a trend our model rethinks in the search for a timescale variability adaptation mechanism.

We propose a self-regulating model of dendritic neurons to detect time-varied sequences, for instance detecting the word "com-pu-ter" despite the varied speed of utterance of its syllables. In our proposed model, the length of the plateau potentials in each dendritic compartment represents the local memory trace of that compartment. In other words, at each compartment, the plateau potentials enable the compartment to *remember* the symbols already detected in the previous compartments. In this model, if there is no feedback to a compartment, meaning there is no activity in the direct adjacent compartment earlier in the chain, the compartment assumes that no sequence could be detected due to its short plateau length. Therefore, the length of the plateau in the compartment will increase. This increase will allow for a more extended local memory and a longer look-ahead time. However, if there *is* an increase in the received feedback, the compartment assumes a higher rate of false positive activity and shortens its plateau length. The neuron will therefore self-regulate its dendritic compartments' timescales through this homeostatic and local time-plasticity mechanism in order to match the timescales of the input sequence, at which point it reaches an equilibrium state (see figure 1 for a visual overview).

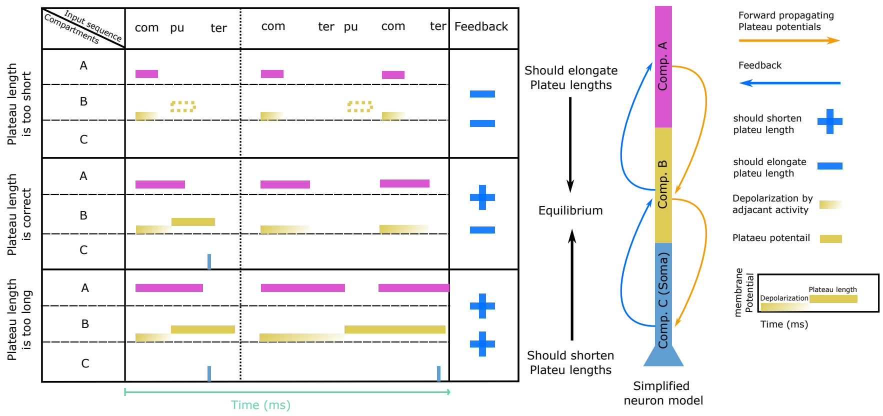

Figure 1: The proposed model of the local homeostatic timescale plasticity based on example input sequence $\{"com","pu","ter"\}$ showing the self-regulatory mechanism of the neuron and its dendritic compartments

Handling varying timescales in input sequence data is a key problem that computation systems must be able to address. The biological brain may handle this via dendritic plasticity. Our proposed neuromorphic model incorporates this plasticity with the goal of giving it the same robustness to timescale variance seen in the biological brain. Neurons using our described local timescale-plasticity mechanism would eventually learn the timescale statistics of input sequences, allowing our model to offer a simple self-regulating mechanism for handling timescales in sequence processing problems. And, since our model only utilizes the idea of self-regulation through local feedback, it can be easily implemented in various continuous-time systems, from software implementation to the electrical design of neuromorphic hardware, making it a possible solution to the timescale invariance problem in neuromorphic hardware at large.

References

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