Salmasi et al. BMC Neuroscience 2015, 16(Suppl 1):P149
http://www.biomedcentral.com/1471-2202/16/S1/P149

BMC Neuroscience

POSTER PRESENTATION | Open Access

Information-theoretic analysis of a dynamic release site using a two-channel model of depression

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From 24th Annual Computational Neuroscience Meeting: CNS*2015
Prague, Czech Republic. 18-23 July 2015

Synapses are dynamic communication channels between neurons as their rates of information transfer depend on past history. While information theory has been used to study the information efficacy of synapses [1-3], the effect of synaptic dynamics, including short-term depression and facilitation, on the information rate is not yet fully understood.

To reduce the complexity of the problem, we confine ourselves here to a single release site of the synapse. This allows us to analytically calculate the information transfer at the release site for a simple model of synaptic depression which is based on binary channels. The input of the model is a spike train, modeled by an independent identically distributed process $X = \{X_i\}_{i=1}^{\infty}$, where each X_i has a Bernoulli distribution with $P(X_i = 0) = \alpha$. The model's output is a process $Y = \{Y_i\}_{i=1}^{\infty}$, such that if there is a release at time, then $Y_i = 1$ and otherwise $Y_i = 0$. We model the short term depression by two binary asymmetric channels that represent the possible states of the release site: the 'recovered' state, when no release occurred in the previous time step (Figure 1a), and the 'used' state, following vesicle release (Figure 1b). In particular, we

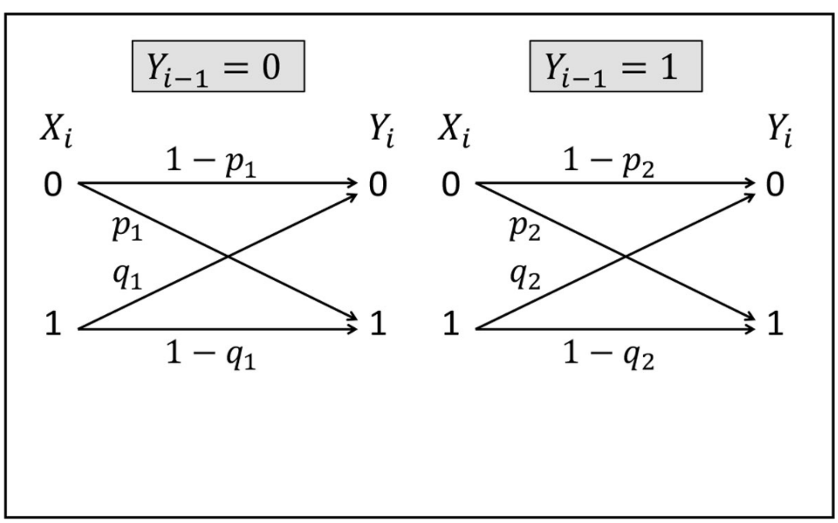

Figure 1

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assume that the release probability is reduced following a release, that is $p_2 \le p_1$ and $1 - q_2 \le 1 - q_1$.

Each individual channel in Figure 1 will have a mutual information rate, either r_1 or r_2. As X_i is Bernoulli-distributed, $r_i = h(\alpha p_i + \bar{\alpha}\overline{q_i}) - \alpha h(p_i) - \bar{\alpha} h(\overline{q_i})$ for i = 1,2, where $h(\cdot)$ is the entropy of a Bernoulli random variable and $\bar{x} = 1 - x$. We prove that the mutual information rate of the release site with depression is a linear summation of the information rates of these two channels. The mutual information rate $I(X;Y)$ between the input process X nd the output process Y, is $I(X;Y) = \theta r_1 + (1 - \theta) r_2$ where

$$\theta = \frac{\alpha\overline{p_2} + \bar{\alpha} q_2}{\alpha(p_1 + \overline{p_2}) + \alpha(\overline{q_1} + q_2)}.$$

The closed form expression of the mutual information rate allows us to study the effect of depression analytically. Through simulations we show that for a range of parameters, depression improves the rate of information transfer at the release site. We also show that when the level of depression is increased (i.e., with smaller p_2 and larger q_2), the release site's information capacity is reached at lower input spike rates. Therefore, the optimal spike rate of the presynaptic neuron has a reverse relationship with the depression level of its release site. This means that synaptic depression can save energy while maintaining information rate. The two-channel model of release site is a building block for the construction of more precise models of synaptic transmission. These advanced models will enable us to evaluate and study the synaptic information rates analytically.

Acknowledgement
This work was supported by the BMBF grant 01EO1401 (German Center for Vertigo and Balance Disorders).

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Published: 18 December 2015

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doi:10.1186/1471-2202-16-S1-P149
Cite this article as: Salmasi *et al.*: Information-theoretic analysis of a dynamic release site using a two-channel model of depression. *BMC Neuroscience* 2015 **16**(Suppl 1):P149.