Irregular connectivity in neural layers yields temporally stable activity patterns

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Pattern formation in excitable media is a well known phenomenon in biology. It occurs for example in the visual cortex, where hallucinations are believed to be synchronized activity waves in the neural layer [1,2], or in heart tissue [4,5]. In both examples the excitable media can be regarded as two-dimensional. Spatiotemporal patterns that can be observed include spirals and target waves which are typically self-sustained.

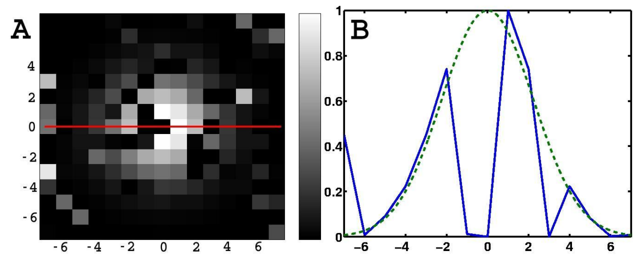

FIGURE 1: ***(A)*** *Typical connectivity matrix of a neuron located at* $(0,0)$. *The connection strength is gray-scaled and normalized (black:* 0, *white:* 1*).* ***(B)*** *The values of the weights along the horizontal line in (A) are shown (solid line) along with the deterministic connections (gaussian function, dashed line). The value of the disorder parameter in (A) and (B) is* $P = 0.3$.

In this work we investigate the role of irregular connectivity in a neural layer for the self-maintainance of structured activity. To address this question we numerically simulated two-dimensional networks of leaky integrate-and-fire neurons. The connection weights of these networks are initially determined via a gaussian distance dependency multiplied with a proportionality factor I_0 Figure 1B). Subsequently, one of two disorder models is applied which removes the regularity in the connectivity matrix. The extent of the disorder is quantified by a *disorder parameter* which is varied in order to produce different disorder levels. As a measure of the ability of the system to produce activity patterns, we determine the minimal proportionality factor $I_{0,\min}$ for which self-sustained target waves can be observed.

The first disorder model introduces perturbations in the coupling weights with a gamma distribution:

$$p(x) = \frac{x^{k-1} e^{-\frac{x}{b}}}{b^k \Gamma(k)}, \qquad \text{where} \quad b = \frac{\mathrm{var}(x)}{\mathrm{mean}(x)} \quad \text{and} \quad k = \frac{\mathrm{mean}(x)^2}{\mathrm{var}(x)}\,.$$

It is characterized by two parameters, b and k, related to the mean and the variance of the distribution. The deterministic interneural coupling strength taken from the distance dependent gaussian (Fig. 1B) fixes the mean. The variance plays the role of our disorder parameter. The use of the gamma distribution provides only a weak noise model preserving the topology of the network: The probability for a strong coupling weight between two distant neurons is very small as the mean of the gamma distribution will be close to zero. Therefore this disorder model mainly affects the coupling of nearby neurons.

We therefore employed a second, stronger disorder model where randomly chosen connections between neurons are exchanged. The disorder parameter P is defined to be the fraction of interchanged interneural connections. The pairs of weights which switch their values are chosen randomly. The model therefore allows for strong couplings also between distant neurons. Hence, large disorder parameters P yield largely disordered neural networks which have lost their 2-dimensional topology.

Simulations were run in order to determine the minimal needed global proportionality factor $I_{0,\mathrm{min}}$ in the connectivity matrix which yields temporally stable activity for different disorder parameters P of the two disorder models. The inset of Figure 2 shows a snapshot of a typical target wave evolving in a network with disordered connections.

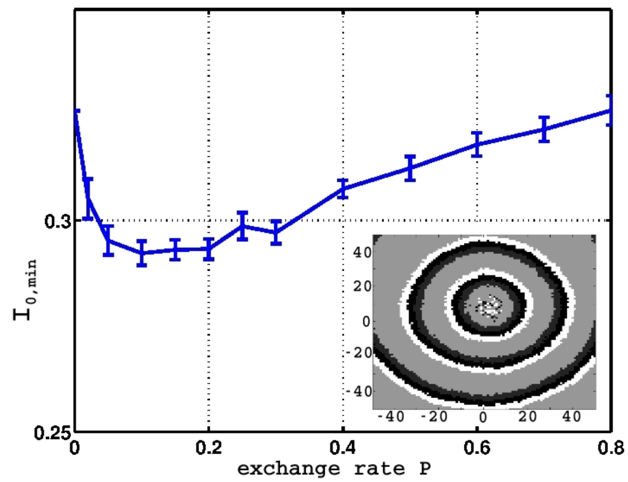

FIGURE 2: *The minimal proportionality factor* $I_{0,\mathrm{min}}$ *which yields self-sustained neural activity patterns as a function of the disorder parameter* P *in the second disorder model; a network of 100*x*100 neurons is used. Inset: Snapshot of target waves in evolution. The activity is gray-colored: White are active, gray are resting, and black are refractory neurons.*

The simulations show that $I_{0,\mathrm{min}}$ decreases with increasing disorder parameter. That is, in both models *disorder in the connectivity yields a facilitated formation of temporally stable patterns*. Moreover, for the second disorder model an optimal exchange ratio P exists, for which self-maintaining activity is most easily achieved (Figure 2). This is due to the fact that for $P \to 1$ the spatial information about the position of a single neuron on the twodimensional lattice gets lost, and large-scale activity patterns become impossible. The observed behaviour resembles the phenomenon of stochastic resonance, where an optimal noise level for the transmission of signals can be found. Here, however, the noise is not in time but in the quenched disorder of the neural connections.

Our results may be related to phenomena like drug induced visual hallucinations [1] in the following way: Reorganization in the – almost – two-dimensional visual cortex caused by a drug increases the disorder in the neural connections which in turn facilitates the occurence of temporally stable activity as shown in our work.

We wish to thank Jack Cowan for pointing out the issue of disordered connectivity to us.

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