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Abstract

As neural activity is transmitted through the nervous system, neuronal noise is believed to degrade the encoded information and limit performance. It is therefore important to know how loss of information can be prevented. Using a principled approach we show how information loss in a two layered network depends on the connectivity between the layers and find that the optimal connection profile has a center-surround structure with a spatial extent closely matching the neurons’ tuning curves. In addition we show how the optimal connectivity depends on the correlation structure of the trial-to-trial variability in the neuronal responses. Our results suggest that the ubiquitous center-surround architectures in the nervous system provide a natural way to communicate population coded information.


Introduction

Neural information often passes through many different brain areas. Consider for instance a task where a subject is to reach for a visual target. Information about the target location will have to be transmitted across many stages: retina, LGN, visual, pre-motor, and motor cortices. Due a variety of noise sources, single neurons will be highly variable and unreliable at every stage (Dean, 1981; Shadlen and Newsome, 1998; Faisal, Selen, and Wolpert, 2008). It is believed that robustness is engendered by population codes, in which many neurons are activated by a given stimulus. Population coding has been studied extensively. In particular the role of the tuning curve shape and the neural noise model (Seung and Sompolinsky, 1993; Zhang and Sejnowski, 1999), as well as the effect of correlations in the trial-to-trial variability of different neurons, have been studied in detail (Abbott and Dayan, 1999; Sompolinsky et al., 2002; Wu, Amari, and Nakahara, 2002; Shamir and Sompolinsky, 2004). Moreover, several algorithms have been proposed to ‘read out’ population codes (Lee, Rohrer, and Sparks, 1988; Oram et al., 1998; Deneve, Latham, and Pouget, 1999).

Yet, although it is well-known how much information is available in a given population and how it can be read-out, it is not known how information is preserved when it is transmitted between processing stages. A few studies have addressed the transmission of population codes (Hamaguchi et al., 2005; Hamaguchi, Okada, and Aihara, 2007), but transmission quality has not been quantified. This is functionally important: in the example reaching task above, where each processing stage presumably uses a population code, suboptimal transmission would lead to errors in the perceived target location and thus a decreased performance.

In this study, we use Fisher Information to quantify how information about a stimulus feature degrades as activity is transmitted between layers. Next, we use these results to
find the synaptic weight profile that minimizes information loss and we find it to be center-surround (Mexican-hat), with a width approximately matched to the neurons tuning width. The generality of our results is tested with numerical simulations of integrate-and-fire neurons.

**Materials and Methods**

Briefly, we considered two layers of $N$ neurons with no lateral interactions (Fig. 1A). Neurons in the input layer encode the location of an angular variable through bell-shaped tuning curves, leading to a noisy population ‘bump’ on each trial. Tuning curves are parametrized as

$$f(\phi_i - \theta) = r_p \exp \left[ \frac{\cos(2(\phi_i - \theta)) - 1}{a^2} \right] \equiv f_i(\theta)$$

where $\phi_i = ((2i - 1)/N - 1)90^\circ$, $i = 1, \ldots, N$ is the preferred orientation of cell $i$, $\theta$ is the stimulus orientation and $r_p$ and $a$ are the peak firing rate of the cell and tuning curve width, respectively. We studied the network first using a firing rate model, and then in a network of spiking neurons. In the firing rate model, trial-to-trial response variability in the input layer was assumed to be Gaussian, so that the response probability for the whole layer on a trial is given by an $N$-dimensional Gaussian distribution with mean vector $\{f_i(\theta)\}$ and a covariance matrix

$$C_0(\phi_i, \phi_j) = C_0(\phi_i - \phi_j) = (\sigma_0^2 - c_0) \delta_{ij} + c_0 \exp \left[ -\frac{2|\phi_i - \phi_j|}{\rho_0} \right] \equiv [C_0]_{ij}$$

where $\sigma_0^2$, $c_0$ and $\rho_0$ are the firing rate variance of the neurons, peak correlation and correlation length, respectively. The input to neurons in the output layer consisted of two currents: synaptic inputs from pooling the activity of the input layer, and an external, stimulus-independent noise source that was assumed to have correlations parametrized by $\sigma_1^2$, $c_1$ and $\rho_1$. We estimated the information about the stimulus orientation in the firing rate model in both layers using the Fisher Information, while for the spiking network we
used a linear estimator of the orientation. Although we write the Fourier components of different quantities as ranging from \( n = 0, \ldots, N - 1 \), in the figures we displayed the highest frequencies as negative (\( n = N - m \rightarrow n = -m \)) to highlight the symmetry of the Fourier transforms. A detailed account of our analytical and numerical methods can be found in the supplemental material.

**Results**

As an abstract model for the propagation of information across a hierarchy of processing areas, we analyze the transmission of population coded information between two layers. We consider the network shown in Fig. 1A. Each of the two layers consists of a population of \( N \) neurons encoding an angular variable labeled \( \theta \), which could represent, for instance, orientation. The response of each neuron \( i \) in the input layer depends on the difference between its preferred orientation \( \phi_i \) and \( \theta \), resulting in a population activity ‘bump’ on each trial (Fig. 1A top). We start with an analytical characterization of the process using a firing rate model and then we extend our findings to networks of spiking neurons.

We denote the firing rate of neuron \( i \) in the input layer as \( r_{i}^{\text{in}} \). Its average across trials is given by \( f(\theta - \phi_i) \), where \( f \) specifies the tuning curve shape. Trial-to-trial response variability can in principle be correlated across neurons (so called ‘noise’ correlation, quantified by a covariance matrix \( C_0 \)). The structure of the noise correlation can be dependent on the similarity between the tuning of different cells, i.e., \( [C_0]_{ij} = C_0(\phi_i - \phi_j) \), but is assumed independent of the stimulus. Neurons in the output layer pool the activity of the input layer through a set of synaptic weights \( W \). We assume that the magnitude of the synaptic weight between an input and an output neuron depends only on the difference between their preferred angles, \( W_{ij} = W(|\phi_i - \phi_j|) \), so that activity in the input and output layers is aligned (Salinas and Abbott, 1994). The firing rate of neuron
$j$ in the output layer on a given trial is

$$r_j^{\text{out}} = g(I_j) = g\left(\frac{1}{N} \sum_{i=1}^{N} W_{ji}r_i^{\text{in}} + \eta_j\right)$$

where $I_j$ is the current to neuron $j$ and $g(\ldots)$ represents a non-linearity that maps the input current of a neuron into its firing rate. The terms $\eta_j$ represent stimulus-independent, zero-mean Gaussian noise currents (with covariance matrix $C_1$) to the neurons in the output layer coming from external sources.

We use the Fisher Information (FI) to quantify how much information about the stimulus is available in both layers (see Supplementary Information). Under the above assumptions the FI is elegantly formulated in spatial frequency space (Sompolinsky et al., 2002; Wu, Amari, and Nakahara, 2002), the FI in the input layer is

$$J_{\text{in}} = \frac{N-1}{\sum_{n=0}^{N-1} |\tilde{f}'(n)|^2} \tilde{C}_0(n)$$

where $n$ sums over the Fourier modes, and $\tilde{C}_0(n)$ and $\tilde{f}'(n)$ are the $n^{\text{th}}$ Fourier components of the noise correlation matrix and of the derivative of the tuning curve with respect to $\theta$ (see Supplementary Information). This equation has an intuitive interpretation; it expresses the FI as a sum of signal-to-noise ratios at every spatial frequency. For a given spatial frequency, the signal is the squared magnitude of the Fourier mode of the derivative of the tuning curve, while the noise is the corresponding Fourier mode of the covariance matrix. Because typical neuronal tuning curves are smooth and broad, only low spatial frequencies carry information. Note, however, that for homogeneous networks the zero mode of the signal (which equals the average derivative) carries no information, as the total activity in the network is independent of $\theta$.

Although the currents have a Gaussian distribution, due to the non-linearity $g(\ldots)$, the firing rates in the output layer do not. However, as long as this function is invertible, e.g. a sigmoid or a powerlaw with positive argument, the FI in the output rates equals
the FI in the currents. Similar to the input layer, the FI in the output layer is a decoupled sum of Fourier components

\[
J_{\text{out}} = \sum_{n=0}^{N-1} \frac{|\tilde{f}'(n)|^2}{C_0(n)} \left[ \frac{|\tilde{W}(n)|^2}{|W(n)|^2 + \tilde{C}_1(n)/\tilde{C}_0(n)} \right]
\]

where \(\tilde{W}(n)\) and \(\tilde{C}_1(n)\) are the Fourier components of the weight profile and of the covariance matrix of the external noise (see Supplementary Information). Compared to the FI in the input layer, Equation 1, the output information at every frequency is attenuated by a factor between zero and one (the term in the square brackets). The output information is therefore always less or equal to the input information. The factor approaches one if the corresponding frequency mode of the synaptic weight is respectively much larger than the effective threshold \(\tilde{C}_1(n)/\tilde{C}_0(n)\). Only if there is no external noise in the output layer \((\tilde{C}_1(n) = 0)\) the attenuation factor is exactly one. In that case no information is lost between the two layers and, save for the completely flat profile, any profile will suffice.

Next, we optimize the connectivity between input and output layer so that it minimizes the information loss between the input and the output layer. The loss is minimal if the attenuation factor in Equation 2 approaches one for all frequencies. This can be trivially achieved if the weights strongly amplify all spatial frequencies, i.e. if \(|\tilde{W}(n)|^2\) is sufficiently large. This is for instance the case if the weight matrix is a large multiple of the identity matrix. In that case the noise in the output layer becomes negligible compared to the synaptic input, and the FI in the output layer approaches the FI of the input layer. However, this solution implies un-physiologically large currents and high firing rates in the output layer. In order to prevent this, we constrain the total power in the weight matrix (other types of constraints give comparable results)

\[
\sum_{n=0}^{N-1} |\tilde{W}(n)|^2 = q
\]
Now different frequency modes of the weights compete, and only those Fourier modes which are most informative are transmitted. The smaller $q$, the stronger the competition. The optimization procedure is schematically illustrated in Fig. 1B. Briefly, in the Fourier domain the optimal weights are approximately a thresholded version of the Fourier transform of the derivative of the tuning curve. The inverse transform yields the optimal weight matrix. The full details of this multi-dimensional constrained optimization are presented in the Supplementary Information.

Optimal weight profiles are shown in Fig. 2A for three different widths of the input tuning curve: When the input tuning curves are very narrow, the intermediate frequencies are most informative, giving the optimal weights an oscillatory character. For wider tuning curves, the low frequencies modes are most informative, yielding a smoother weight profile. The optimal weights depend on the noise as well. If, for instance, the postsynaptic noise is small, the optimal weights will transmit most spatial frequencies. If, in contrast, the postsynaptic noise is large, the weights are concentrated around the large, low frequency modes, yielding broader weight profiles. Fig. 2B shows the Full Width at Half Maximum of the connectivity profile and the output width as the input width is varied. Although the precise relation is complicated as widths can not be straightforwardly expressed in Fourier components, the width of the optimal connectivity approximately matches that of the input tuning curve.

The formalism can be extended to correlated noise. Noise correlations reduce the information of neural codes, as they limit the potential for averaging out noise by pooling over neurons (Britten et al., 1992; Zohary, Shadlen, and Newsome, 1994), which is reflected in a saturation of the FI in the presence of limited range correlations (Sompolinsky et al., 2002; Wu, Amari, and Nakahara, 2002). Limited range correlations reduce the signal-to-noise ratio predominantly at low spatial frequencies. As a results the optimal weights emphasize the intermediate frequencies more, leading to a narrower profile,
Although the precise shape of the optimal weight profile depends on the exact model parameters, it has several general properties. Because there is no information about the stimulus in the total activity of the population, the optimal weights are ‘balanced’: their zero-frequency mode (the area under the weight profile) is zero. Secondly, if the tuning curves are not too narrow, most information is in the lowest spatial frequencies, which are amplified the most by the optimal profile. In summary, the optimal weights have most power in the low frequency modes and none at zero, which implies that they have a center-surround or ‘Mexican-hat’ structure.

In order to test the generality of the results we investigated a two layer network of spiking integrate and fire neurons (see Supplementary Information). The connectivity profile in the simulations is parametrized by the width of the excitatory center and the strength of the inhibition, while the gain in the connectivity is tuned so that the response amplitudes in the layers are identical. A long lasting stimulus is applied and the spikes in the output layer of the network are collected in time bins and the stimulus is estimated, Fig. 3A. Although these simulation have the advantage of being realistic, measuring the true FI in simulations of spiking neurons is computationally prohibitive for non-Gaussian, correlated noise. Instead we use an optimal linear discriminator to measure the accuracy of the population code in the output layer (see Methods) (Salinas and Abbott, 1994; Seriès, Latham, and Pouget, 2004). In Fig. 3B the trial-to-trial standard deviation in the stimulus angle (a lower bound on the inverse square root of the FI) is plotted as a function of the width of the connectivity profile and various levels of inhibition. The error can be compared to the error in the input layer (gray line).

Using an excitatory-only weight profile, the error in the output layer (dotted curve) is substantially higher than in the error in the input. The error in the output is largest for wide weight profiles, as in this case the output activity is smeared, Fig. 3C(iii). Adding
surround inhibition substantially improves the accuracy in the output layer. Using a balanced, center-surround profile (solid line) with a half-width approximately matching the width of the activity profile (arrow), the error is minimal. The output activity profile is in this case similar to the input, Fig. 3(ii).

The amount of inhibition required is not very critical as long as the width of the profile is matched to that of the tuning curve. A three-fold increase in the inhibition yields similar performance for a profile with an optimally tuned width (dashed curve). However, strong inhibition decreases performance if the weight and tuning widths become significantly different. (Fig. 3C(i)). These simulation results are in line with the theoretical analysis above: in order to preserve information, the connectivity profile needs to amplify spatial frequencies that convey the most information, while filtering out the high and zero spatial frequencies.

**Discussion**

We have considered information transmission in a setup where information is processed in stages and thus needs to be represented in multiple brain regions. We believe that quantifying information transmission across stages is an important extension to reading out information at a certain stage. A read-out algorithm can be thought of as a map from the high dimensional population activity to a low-dimensional encoded quantity, such as stimulus orientation. But in the nervous system, although the encoded quantity is processed as activity flows through, say, the sensory-motor stream, each subsequent stage does not read-out the previous one. Instead, the high-dimensional nature of the encoding process is preserved until the very last stages where a small set of muscles are driven by the corresponding motor-neurons. Our results show that, in general, the information about a stimulus feature encoded by a population of broadly tuned neurons is best transmitted through center surround connectivity profiles.
Center surround profiles have been shown to be useful for minimizing redundancy at early states of the visual processing stream, as they remove broad stimulus-induced correlations (Atick and Redlich, 1990). For the transmission of population-coded information considered here however, the center-surround solution has a different origin, i.e., the need to filter out the uninformative high- and zero spatial-frequency modes.

While the current study only considers transmission of activity, the ultimate goal is to understand information processing. The findings here are also applicable to computing networks: In an earlier study using recurrent networks to implement an optimal read-out algorithm, the width of the connectivity profile had to be set approximately equal to the tuning curve width (Deneve, Latham, and Pouget, 1999). Another study found that spiking feedforward networks employing a width matched center-surround connectivity accurately computed with population codes (van Rossum and Renart, 2004). Finally, in man-made readout of population codes a match between activity and connectivity was found (Georgopoulos, Taira, and Lukashin, 1993).

Our findings have implications for the interpretation of neural connectivity. In sensory systems center-surround has been interpreted as a contrast enhancement mechanism. However, it has been unclear why contrast enhancement would be needed at every stage. Our results suggests that the abundance of center-surround connectivity in many parts of the nervous system (e.g. Hartline, Wagner, and Ratcliff, 1956; Hubel and Wiesel, 1962; Enroth-Cugell and Robson, 1966; Trappenberg et al., 2001), is important for accurate population code processing.

References


Figure Legends

Figure 1. The network architecture and a schematic of the procedure to find the weight that optimally preserve information. **A**, Architecture of the two-layer network. The stimulus orientation (vertical arrow) is encoded in the population activity of the input layer (top). Neurons in the output layer (bottom) pool the activity of the input layer through a set of synaptic weights (middle, black), and also receive noise (middle, gray). The synaptic weights are optimized to maximize the coding accuracy in the output layer. **B**, Schematic of the weight optimization procedure (for details see Supplementary Information). Top left panel: From the population activity (solid line), the spatial derivative (the ‘signal’) is calculated (dashed line) and Fourier transformed. In the Fourier domain only the strong Fourier modes that exceed a certain threshold are selected and are transmitted by the weights (right panels). Transformed back into the spatial domain, the weight profile typically resembles a centre-surround structure. The bottom panel shows the net current received by neurons in the output layer.

Figure 2. Exact optimization of synaptic weights in the firing rate model. **A**, Input layer activity (top), optimal synaptic weights (middle) and output synaptic current (bottom) for three different tuning curve widths: narrow ($a = 1/6$, left), medium ($a = 1/3$, center) and wide tuning ($a = 1$, right). Other parameters: $q = 2$, $c_{0,1} = 0$, $\sigma_{0,1} = 2$ Hz$^2$, $r_p = 20$ Hz, $N = 501$. **B**, Output width (half-width at half-height) of optimal synaptic weights (solid) and output currents (dashed) as a function of tuning width in the input layer. Output and input widths are approximately matched. **C-F**, The effect of noise correlations is to sharpen the optimal weights (parameters as in A, $a = 0.85$). Three cases were considered: No noise correlations (black), noise correlation in the input layer only and uncorrelated external noise (light gray, empty), and identical correlation structure in input layer and external noise (dark gray, filled). The correlations, when present, are
given by $c_{0,1} = 0.2$ and $\rho_{0,1} = 1$. C, Tuning curve in the input layer (solid) and correlation structure (dotted). D, Correlations strongly reduce the Fisher Information in the input layer (dark and light gray, overlapping), compared to the uncorrelated case (black). Inset, Effective threshold for the synaptic weights at each frequency ($\tilde{C}_1(n)/\tilde{C}_0(n)$, see Equation 2; dark gray and black, overlapping). E, Fourier representation of the optimal weights. In the absence of correlations the weights amplify only the most informative, low frequency modes (black). The effective threshold across frequencies is the same when the input and external correlations are equal, as in the case where correlations are absent. But since correlations decrease the information at the lowest frequency modes (see panel D), more weight is devoted to higher frequencies (dark gray). Finally, when the external noise is uncorrelated, the low frequency thresholds decrease (D, inset). The information in the lowest frequencies can be now transmitted with smaller weights, allowing further emphasis of higher frequencies (light gray). F, After inverse Fourier transformation, the optimal weights are narrower when correlations are present.

**Figure 3.** Center surround connectivity of width matched to the tuning curve is optimal in networks of spiking integrate-and-fire neurons. A, Snapshot of one second of the activity in the input (top) and output (bottom) layers. B, Error of the optimal linear estimator (see Supplementary Information) of the stimulus as a function of the width of the connectivity profile based spike count in 25 ms bins. The error in the estimator in the input layer is shown by the gray line. Without inhibition estimation is suboptimal for all widths (dotted). With balanced inhibition (solid) the optimal width is similar to, but slightly larger than, the tuning curve width (arrow). Stronger inhibition (dashed) is also optimal if matched to the tuning curve width, but the error is larger when the profile is mis-tuned than in the case of balanced inhibition. C, Examples of the input and output ‘bumps’ of activity for three different situations: Narrow connectivity with
strong inhibition \((i)\), balanced inhibition at the optimal width \((ii)\) and wide connectivity with no inhibition \((iii)\). Input and output activity profiles are similar in the optimal case (using 200 ms bins for clarity).
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Fig.1 Renart & Van Rossum. Format: 1.5 columns, 11.6 cm
Figure 2. Exact optimization of synaptic weights in the firing rate model. A, Input layer activity (top), optimal synaptic weights (middle) and output synaptic current (bottom) for three different tuning curve widths: narrow ($\alpha = 1/6$, left), medium ($\alpha = 1/3$, center) and wide tuning ($\alpha = 1$, right). Other parameters: $q = 2$, $c_{0,1} = 0$, $\sigma_{0,1} = 2$ Hz$^2$, $r_p = 20$ Hz, $N = 501$. B, Output width (half-width at half-height) of optimal synaptic weights (solid) and output currents (dashed) as a function of tuning width in the input layer. Output and input widths are approximately matched. C-F, The effect of noise correlations is to sharpen the optimal weights (parameters as in A, $\alpha = 0.85$). Three cases were considered: No noise correlations (black), noise correlation in the input layer only and uncorrelated external noise (light gray, empty), and identical correlation structure in input layer and external noise (dark gray, filled). The correlations, when present, are given by $c_{0,1} = 0.2$ and $\rho_{0,1} = 1$. C, Tuning curve in the input layer (solid) and correlation structure (dotted). D, Correlations strongly reduce the Fisher Information in the input layer (dark and light gray, overlapping), compared to the uncorrelated case (black). Inset, Effective threshold for the synaptic weights at each frequency ($\tilde{C}_1(n)/\tilde{C}_0(n)$, see Equation 2; dark gray and black, overlapping). E, Fourier representation of the optimal weights. In the absence of correlations the weights amplify only the most informative, low frequency modes (black). The effective threshold across frequencies is the same when the input and external correlations are equal, as in the case where correlations are absent. But since correlations decrease the information at the lowest frequency modes (see panel D), more weight is devoted to higher frequencies (dark gray). Finally, when the external noise is uncorrelated, the low frequency thresholds decrease (D, inset). The information in the lowest frequencies can be now transmitted with smaller weights, allowing further emphasis of higher frequencies (light gray). F, After inverse Fourier transformation, the optimal weights are narrower when correlations are present.

Fig.2 Renart & Van Rossum. Format: 2 columns, 17.6 cm
Figure 3. Center surround connectivity of width matched to the tuning curve is optimal in networks of spiking integrate-and-fire neurons. A, Snapshot of one second of the activity in the input (top) and output (bottom) layers. B, Error of the optimal linear estimator (see Supplementary Information) of the stimulus as a function of the width of the connectivity profile based spike count in 25 ms bins. The error in the estimator in the input layer is shown by the gray line. Without inhibition estimation is suboptimal for all widths (dotted). With balanced inhibition (solid) the optimal width is similar to, but slightly larger than, the tuning curve width (arrow). Stronger inhibition (dashed) is also optimal if matched to the tuning curve width, but the error is larger when the profile is mis-tuned than in the case of balanced inhibition. C, Examples of the input and output ‘bumps’ of activity for three different situations: Narrow connectivity with strong inhibition (i), balanced inhibition at the optimal width (ii) and wide connectivity with no inhibition (iii). Input and output activity profiles are similar in the optimal case (using 200 ms bins for clarity).