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Sign-changing filters similar to cells in primary visual cortex emerge by independent component analysis of temporally convolved natural image sequences

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Abstract

It has been reported that independent component analysis (ICA) of natural image sequences yields spatio-temporal filters of non-separable spatio-temporal properties. On the contrary, sign changing filters with separable spatio-temporal properties have not been found via ICA. We show that extending the ICA to temporally convolved inputs develops such receptive fields (RFs). We argue that temporal convolution may arise from the response function of lagged and non-lagged cells of the LGN. The properties of the emerging RFs as a function of convolution time and the dimension of compression are studied. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Spatio-temporal filters; Sign changing filters; Independent component analysis; Temporal sequences; Temporal convolution

1. Introduction

It has been argued by [1,2,6,7] that the visual cortex makes use of a factorial code for filtering visual information. The factorial code assumption is supported by recent computational advances. Several studies [11,3] have shown that a variety of information transfer optimizing algorithms give rise to receptive field (RF) properties

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similar to those of simple cells of the primary visual cortex. Sparse coding [11] and independent component analysis [3] (ICA) are the two major methods to be mentioned here. The study conducted by [8] is of particular interest to our work. In that work, the ICA on natural scenes was extended to ICA of natural scene sequences. The analysis produced non-separable spatio-temporal filters similar to those found experimentally [6]. According to the model of [12] spatio-temporal filters bridging 100 ms or so can be formed in the primary visual cortex because of the convergence of non-lagged ON- and OFF- and lagged ON- and OFF-inputs onto the cortical cell. That is, the assumption of ICA of temporal sequences (TICA) may be well founded [8]. Non-instantaneous response function [12,4] corresponds to temporal convolution of the input. RFs that can be developed via ICA using temporally convolved image sequences are studied in this paper. To our best knowledge, RFs fields that have separable spatio-temporal filters and undergo sign-change by time have not been developed via ICA, although such RFs form another major constituent of the cells in the primary visual cortex [6,5]. In turn, the derivation of such RFs is a falsifying issue for every model, including ICA/TICA processing.

2. Methods

A hexagonal window of 169 pixels arranged on a hexagonal grid was used with pixel size approximately equal to image pixel size. Hexagonal sampling allows us to avoid artifacts that could arise for orthogonal grids [11]. Pixel values of the window were interpolated from those of the original image. To further simplify parameter dependence, here, we show results when motion was restricted to one-dimensional translations on an image representing a natural scene. The hexagonal window was translated on the image along randomly chosen straight lines. We have chosen this to avoid artifacts from uneven sampling. In case of moving pictures, different directions of motion may not be distributed evenly. This uneven distribution was explicit for temporal sequences of highway and city traffic scenes.[1] Nevertheless, we found that analysis of temporal sequences of movies gives rise to results similar to those reported here. We restricted the analysis to uniform distribution of motion directions. Further, motions were restricted to constant speed translations by fixing the sampling distance on an image. The chosen sampling distance along the direction of movement was the size of 2.1 pixel of the image. 'Sampling time', i.e., the time difference between 2.1 pixel translations was taken as unit time for the sake of simplicity. Some of the computer runs were concerned with reproducing previous results [8,10]. Other computer runs were concerned with the effect of temporal convolution. In these computer runs, temporal convolution induced by exponential temporal kernels—corresponding to leaky integration—were studied. Two time constants with 10 and 35 sampling time units were used in the exponential temporal kernel. Care was taken to avoid transients

[1] Database provided kindly by Honda Future Technology Research, Offenbach, Germany with permission from Prof. Werner von Seelen, Ruhr-Universität Bochum, Institut für Theoretische Biologie.

arising from the exponential kernel. Temporally convolved inputs were derived from a series of 50 steps taken along straight lines on the image. The inputs used in the experiments were the last seven samples of such series. In some cases, temporally convolved inputs were analyzed in non-sequential experiments. Such experiments correspond to the limit when the time window of temporal convolution is long compared to propagation time along the dendritic tree of the neurons. ICA was performed on 7000 inputs by using the FastICA algorithm [9]. For ICA on temporal sequences, we have utilized PCA compression. Receptive field properties as a function of the compressing dimension was also studied.

3. Results

Results are visualized by reorganizing the filters of the independent components according to their spatial and temporal positions. Pixels of the same temporal indices were collected into a frame. RFs of temporal sequences are shown by frame sequences. Frames of the sequences are ordered by time increasing from left (the first frame) to the right (the last frame). RFs are interpolated between pixels by nearest neighbor averaging. Fine hexagonal grid is superimposed on the RFs to help visualization.

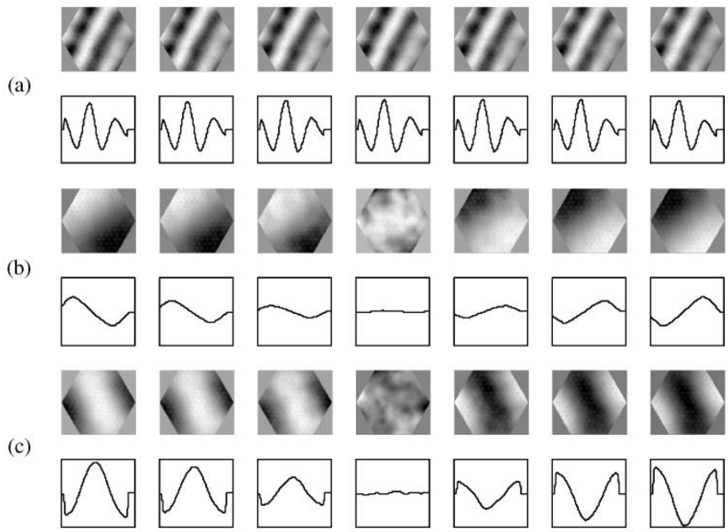

Fig. 1. Space-time separable RFs emerge in computer experiments using temporal sequences with temporal convolutions. Typical RFs that emerged with ICA on temporal sequences in case of temporal convolution. Length of sequence: 7. Convolution time is 10, 35, and 10 [a.u.] for RFs (a), (b), and (c), respectively. Number of pixels: 169. Number of neurons: 32. The spatio-temporal filters were 'moving', 'standing' or 'sign-changing'. 3 filters are shown; 1 'standing' filter and 2 'sign-changing' filters. Averaged filter components projected onto the approximate symmetry plane of the RF strength function are also shown.

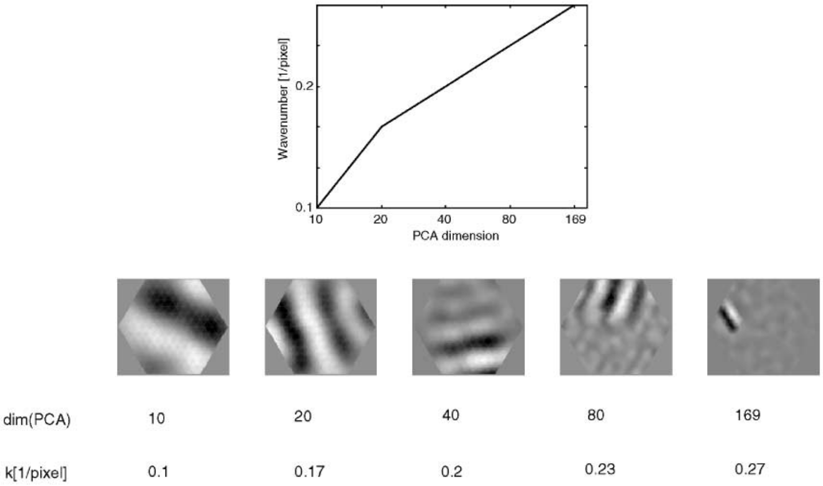

Fig. 2. RF size vs. PCA compression dimension. Wave numbers were measured along the approximate symmetry axis of the RFs. Number of pixels: 169. PCA compression dimension (i.e., number of 'neurons'): 10, 20, 40 80, 169, respectively, k denotes the number of waves per pixel. Error bars of the data are approximately 20%. RF size increases with compression dimension. Ratio of length and width tuning may vary.

ICA on non-sequential/sequential inputs without temporal convolution reproduced previous results [11,8]. In case of input-sequences, we found little sensitivity of the formed spatio-temporal RFs with frame number between 4 and 14. We used PCA compression; the $7 \times 169 = 1183$ dimensional input was compressed to 32 output dimensions.

RFs with temporal convolution showed markedly different properties. As expected, increasing the convolution time decreased the speed of motion represented by the filters. Given our sampling conditions, convolution time of 10 sampling time units gave rise to filters with oriented RF structure that were not moving. Fig. 1a depicts the seven sub-fields of a typical non-moving spatio-temporal filter. This filter has little if any temporal characteristics. The diameter of the RF covers more than one wavelength of the spatial frequency. Filters that have non-moving Gabor patch like RFs, but switch sign have also emerged in these computations. Two examples are shown in Figs. 1b and c. Such filters are common in the primary visual cortex [6,5].

Fig. 2 depicts typical RFs that emerged for different PCA compressions for single inputs. The size of RFs is a strong and monotone function of the PCA dimension. This property is as expected; the stronger the compression the fewer the details that can be transmitted. It is possible that the ratio of the RF length tuning to RF width tuning varies as a function of PCA dimension as it can be seen by inspection of the subfigures of Fig. 2. The parameter range that we could study in our computer experiments was, however, small to establish functional relationship between the parameters of the RFs.

4. Discussion and concluding remarks

Sign-switching characteristics has emerged for concatenated and temporally convolved inputs undergoing ICA. RFs with sign-switching characteristics are shown in Fig. 1. It seems that temporal convolution is necessary to produce such RFs. The experimentally found response function is long and can be approximated by an exponential temporal kernel [4]. The falsifying question whether TICA can provide spatio-temporal RFs with separable spatial and temporal dependencies can be given a positive answer. Yes, TICA can provide such filters if temporal convolution originated by properties of LGN cells is taken into account. The selectivity (the role) of such filters is not clear. The role of these filters may not be explained without considering the full set of RFs. The unclear role of these RFs, in our view, puts emphasis on first order principles (such as maximization of information transfer) that are capable of producing those. ICA on image sequences of natural scenes that takes temporal convolution into account yields spatio-temporal filters similar to simple cells in primary visual cortex.

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