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Dynamic Self-Organising Map

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Abstract

We present in this paper a variation of the self-organising map algorithm where the original time-dependent (learning rate and neighbourhood) learning function is replaced by a time-invariant one. This allows for on-line and continuous learning on both static and dynamic data distributions. One of the property of the newly proposed algorithm is that it does not fit the magnification law and the achieved vector density is not directly proportional to the density of the distribution as found in most vector quantisation algorithms. From a biological point of view, this algorithm sheds light on cortical plasticity seen as a dynamic and tight coupling between the environment and the model.

Keywords: self organisation, on-line, cortical plasticity, dynamic

1 Introduction

Vector quantisation (VQ) refers to the modelling of a probability density function into a discrete set of prototype vectors (sometimes called the codebook) such that any point drawn from the associated distribution can be associated to a prototype vector. Most VQ algorithms try to match the density through the density of their codebook: high density regions of the distribution tend to have more associated prototypes than low density region. This generally allows to minimise the loss of information (or distortion) as measured by the mean quadratic error. For a complete picture, it is to be noted that there also exists some cases where only a partition of the space occupied by the data (regardless of their density) is necessary. In this case, one wants to achieve a regular quantification *a priori* of the probability density function. For example, in some classification problems, one wants to achieve a discrimination of data in term of classes and thus needs only to draw frontiers between data regardless of their respective density.

Vector quantisation can be achieved using several methods such as variations of the *k*-means method [1], Linde–Buzo–Gray (LBG) algorithm [2] or neural network models such as the self-organising map (SOM) [3], neural gas (NG) [4] and growing neural gas (GNG) [5]. Among all these methods, the SOM algorithm is certainly the most famous in the field of computational neurosciences since it can give a biologically and plausible account on the organisation of receptive fields in sensory areas where adjacent neurons shares similar representations. The stability and the quality of such self-organisation depends heavily on a decreasing learning rate as well as a decreasing neighbourhood function. This is quite congruent with the idea of a critical period in the early years of development where most sensory or motor properties are acquired and

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38 stabilised [6–8]. However, this fails to explain cortical plasticity since we know that the cortex
39 has the capacity to re-organise itself in face of lesions or deficits [9–11]. The question is then to
40 know to what extent it is possible to have both stable and dynamic representations ?

41

42 Quite obviously, this cannot be achieved using SOM-like algorithms that depends on a time
43 decreasing learning rate and/or neighbourhood function (SOM, NG, GNG) and, despite the
44 huge amount of literature [12, 13] around self-organising maps and Kohonen-typed networks
45 (more than 7000 works listed in [14]), there is surprisingly and comparatively very little work
46 dealing with online learning (also referred as incremental or lifelong learning). Furthermore,
47 most of these works are based on incremental models, that is, networks that create and/or
48 delete nodes as necessary. For example, the modified GNG model [15] is able to follow non-
49 stationary distributions by creating nodes like in a regular GNG and deleting them when they
50 have a too small *utility* parameter. Similarly, the evolving self-organising map (ESOM) [16, 17]
51 is based on an incremental network quite similar to GNG that creates dynamically based on
52 the measure of the distance of the winner to the data (but the new node is created at exact
53 data point instead of the mid-point as in GNG). Self-organising incremental neural network
54 (SOINN) [18] and its enhanced version (ESOINN) [19] are also based on an incremental struc-
55 ture where the first version is using a two layers network while the enhanced version proposed
56 a single layer network. One noticeable result is the model proposed by [20] which does not
57 rely on a incremental structure but is based on the Butterworth decay scheme that does not
58 decay parameters to zero. The model works in two phases, an initial phase (approximately ten
59 epochs) is used to establish a rough global topology thanks to a very large neighbourhood and
60 the second phase uses a small neighbourhood phase to train the network. Unfortunately, the size
61 of the neighbourhood in the second phase has to be adapted to the expected density of the data.

62

63 Without judging performances of these models, we do not think they give a satisfactory
64 answer to our initial question and we propose instead to answer by considering a tight coupling
65 between the environment and representations. If the environment is stable, representations
66 should remain stable and if the environment suddenly changes, representations must dynam-
67 ically adapt themselves and stabilise again onto the new environment. We thus modified the
68 original SOM algorithm in order to make its learning rule and neighbourhood independent of
69 time. This results in a tight coupling between the environment and the model that ensure both
70 stability and plasticity. In next section, we formally describe the dynamic self-organising map
71 in the context of vector quantisation and both neural gas and self-organising map are formally
72 described in order to underline differences between the three algorithms. The next section re-
73 introduces the model from a more behavioural point of view and main experimental results are
74 introduced using either low or high dimensional data and offers side-to-side comparison with
75 other algorithms. Results concerning dynamic distributions are also introduced in the case of
76 dynamic self-organising map in order to illustrate the coupling between the distribution and
77 the model. Finally, we discuss the relevancy of such a model in the context of computational
78 neurosciences and embodied cognition.

79 2 Definitions

80 Let us consider a probability density function $f(x)$ on a compact manifold $\Omega \in \mathbb{R}^d$. A vector
81 quantisation (VQ) is a function Φ from Ω to a finite subset of n code words $\{\mathbf{w}_i \in \mathbb{R}^d\}_{1 \leq i \leq n}$ that
82 form the codebook. A cluster is defined as $C_i \stackrel{\text{def}}{=} \{x \in \Omega | \Phi(x) = \mathbf{w}_i\}$, which forms a partition

83 of Ω and the distortion of the VQ is measured by the mean quadratic error

$$\xi = \sum_{i=1}^n \int_{C_i} \|x - \mathbf{w}_i\|^2 f(x) dx. \quad (2.1)$$

84 If the function f is unknown and a finite set $\{x_i\}$ of p non biased observations is available, the
85 distortion error may be empirically estimated by

$$\hat{\xi} = \frac{1}{p} \sum_{i=1}^n \sum_{x_j \in C_i} \|x_j - \mathbf{w}_i\|^2. \quad (2.2)$$

86 Neural maps define a special type of vector quantifiers whose most common approaches are the
87 Self-Organising Map (SOM) [3], Elastic Net (EN) [21], Neural Gas (NG) [4] and Growing Neural
88 Gas (GNG) [22]. In the following, we will use definitions and notations introduced by [23] where
89 a neural map is defined as the projection from a manifold $\Omega \subset \mathbb{R}^d$ onto a set \mathcal{N} of n neurons
90 which is formally written as $\Phi : \Omega \rightarrow \mathcal{N}$. Each neuron i is associated with a code word $\mathbf{w}_i \in \mathbb{R}^d$,
91 all of which established the set $\{\mathbf{w}_i\}_{i \in \mathcal{N}}$ that is referred as the codebook. The mapping from
92 Ω to \mathcal{N} is a closest-neighbour winner-take-all rule such that any vector $\mathbf{v} \in \Omega$ is mapped to a
93 neuron i with the code \mathbf{w}_i being closest to the actual presented stimulus vector \mathbf{v} ,

$$\Phi : \mathbf{v} \mapsto \arg \min_{i \in \mathcal{N}} (\|\mathbf{v} - \mathbf{w}_i\|). \quad (2.3)$$

94 The neuron \mathbf{w}_i is called the *winning element* and the set $C_i = \{x \in \Omega | \Phi(x) = \mathbf{w}_i\}$ is called the
95 *receptive field* of the neuron i . The geometry corresponds to a Voronoï diagram of the space
96 with \mathbf{w}_i as the center.

97 2.1 Self-Organising Maps (SOM)

98 SOM is a neural map equipped with a structure (usually a hypercube or hexagonal lattice)
99 and each element i is assigned a fixed position \mathbf{p}_i in \mathbb{R}^q where q is the dimension of the lattice
100 (usually 1 or 2). The learning process is an iterative process between time $t = 0$ and time
101 $t = t_f \in \mathbb{N}^+$ where vectors $\mathbf{v} \in \Omega$ are sequentially presented to the map with respect to the
102 probability density function f . For each presented vector \mathbf{v} at time t , a winner $s \in \mathcal{N}$ is
103 determined according to equation (2.3). All codes \mathbf{w}_i from the codebook are shifted towards \mathbf{v}
104 according to

$$\Delta \mathbf{w}_i = \varepsilon(t) h_\sigma(t, i, s) (\mathbf{v} - \mathbf{w}_i) \quad (2.4)$$

105 with $h_\sigma(t, i, j)$ being a neighbourhood function of the form

$$h_\sigma(t, i, j) = e^{-\frac{\|\mathbf{p}_i - \mathbf{p}_j\|^2}{2\sigma(t)^2}}. \quad (2.5)$$

106 where $\varepsilon(t) \in \mathbb{R}$ is the learning rate and $\sigma(t) \in \mathbb{R}$ is the width of the neighbourhood defined as

$$\sigma(t) = \sigma_i \left(\frac{\sigma_f}{\sigma_i} \right)^{t/t_f}, \quad \text{with } \varepsilon(t) = \varepsilon_i \left(\frac{\varepsilon_f}{\varepsilon_i} \right)^{t/t_f}, \quad (2.6)$$

107 while σ_i and σ_f are respectively the initial and final neighbourhood width and ε_i and ε_f are
108 respectively the initial and final learning rate. We usually have $\sigma_f \ll \sigma_i$ and $\varepsilon_f \ll \varepsilon_i$.

109 2.2 Neural Gas (NG)

110 In the case of NG, the learning process is an iterative process between time $t = 0$ and time
 111 $t = t_f \in \mathbb{N}^+$ where vectors $\mathbf{v} \in \Omega$ are sequentially presented to the map with respect to the
 112 probability density function f . For each presented vector \mathbf{v} at time t , neurons are ordered
 113 according to their respective distance to \mathbf{v} (closest distances map to lower ranks) and assigned
 114 a rank $k_i(\mathbf{v})$. All codes \mathbf{w}_i from the codebook are shifted towards \mathbf{v} according to

$$\Delta \mathbf{w}_i = \varepsilon(t) h_\lambda(t, i, \mathbf{v}) (\mathbf{v} - \mathbf{w}_i) \quad (2.7)$$

115 with $h_\lambda(t, i, \mathbf{v})$ being a neighbourhood function of the form:

$$h_\lambda(t, i, \mathbf{v}) = e^{-\frac{k_i(\mathbf{v})}{\lambda(t)}} \quad (2.8)$$

116 where $\varepsilon(t) \in \mathbb{R}$ is the learning rate and $\lambda(t) \in \mathbb{R}$ is the width of the neighbourhood defined as

$$\lambda(t) = \lambda_i \left(\frac{\lambda_f}{\lambda_i} \right)^{t/t_f}, \quad \text{with } \varepsilon(t) = \varepsilon_i \left(\frac{\varepsilon_f}{\varepsilon_i} \right)^{t/t_f}, \quad (2.9)$$

117 while λ_i and λ_f are respectively the initial and final neighbourhood and ε_i and ε_f are respectively
 118 the initial and final learning rate. We usually have $\lambda_f \ll \lambda_i$ and $\varepsilon_f \ll \varepsilon_i$.

119 2.3 Dynamic Self-Organising Map (DSOM)

120 DSOM is a neural map equipped with a structure (a hypercube or hexagonal lattice) and each
 121 neuron i is assigned a fixed position \mathbf{p}_i in \mathbb{R}^q where q is the dimension of the lattice (usually 1 or
 122 2). The learning process is an iterative process where vectors $\mathbf{v} \in \Omega$ are sequentially presented
 123 to the map with respect to the probability density function f . For each presented vector \mathbf{v} , a
 124 winner $s \in \mathcal{N}$ is determined according to equation (2.3). All codes \mathbf{w}_i from the codebook \mathbf{W}
 125 are shifted towards \mathbf{v} according to

$$\Delta \mathbf{w}_i = \varepsilon \|\mathbf{v} - \mathbf{w}_i\|_\Omega h_\eta(i, s, \mathbf{v}) (\mathbf{v} - \mathbf{w}_i) \quad (2.10)$$

126 with ε being a constant learning rate and $h_\eta(i, s, \mathbf{v})$ being a neighbourhood function of the form

$$h_\eta(i, s, \mathbf{v}) = e^{-\frac{1}{\eta^2} \frac{\|\mathbf{p}_i - \mathbf{p}_s\|^2}{\|\mathbf{v} - \mathbf{w}_s\|_\Omega^2}} \quad (2.11)$$

127 where η is the *elasticity* or *plasticity* parameter. If $\mathbf{v} = \mathbf{w}_s$, then $h_\eta(i, s, \mathbf{v}) = 0$

128 3 Model

129 As we explained in the introduction, the DSOM algorithm is essentially a variation of the SOM
 130 algorithm where the time dependency has been removed. Regular learning function (2.4) and
 131 neighbourhood function (2.5) have been respectively replaced by equations (2.10) and (2.11)
 132 which reflect two main ideas:

- 133 • If a neuron is close enough to the data, there is no need for others to learn anything: the
 134 winner can represent the data.
- 135 • If there is no neuron close enough to the data, any neuron learns the data according to
 136 its own distance to the data.

137 This draws several consequences on the notion of neighbourhood that is now dynamic and
 138 leads to a qualitatively different self-organisation that can be controlled using a free elasticity
 139 parameter.

140 3.1 Dynamic neighbourhood

141 Learning rate is modulated using the closeness of the winner to the data. The figure 1 represents
 142 this learning rate modulation as a function of a data \mathbf{v} , a neuron i (with code \mathbf{w}_i) and a winner
 143 s (with code \mathbf{w}_s). If the winner s is very close or equal to \mathbf{v} (bottom line on the figure), learning
 144 rate of any neuron different from the winner s is zero and only the winner actually learns the
 145 new data. When the winner s is very far from the data (top line), any neuron benefits from
 146 a large learning rate and learns the new data (modulated by their own distance to the data
 147 but this extra modulation is not represented on the figure). This notion of closeness of the
 148 winner to the data is thus critical for the algorithm and modifies considerably both the notion
 149 of neighbourhood and the final codebook. Most VQ tries to capture data density through the
 150 density of their codebook as introduced in [23] where authors considers the generalised error

$$E_\gamma = \int_{\Omega} \|\mathbf{w}_s - \mathbf{v}\|^\gamma P(\mathbf{v}) d\mathbf{v} \quad (3.1)$$

151 and introduces the relation $P(\mathbf{w}) \propto \rho(\mathbf{w})^\alpha$ with $\rho(\mathbf{w})$ being the weight vector density and
 152 α being the *magnification exponent* or *magnification factor*. If we consider the intrinsic (or
 153 Hausdorff) dimension d of the data, the relation between magnification and d is given by $\alpha = \frac{d}{d+\gamma}$
 154 and an ideal VQ achieves a magnification factor of 1. However, DSOM algorithm clearly states
 155 that if a neuron is already close enough to a presented data, there is no need for the neighbours
 156 to learn anything and this results in a codebook that does not follow the magnification law as
 157 illustrated on figure 2 for three very simple two-dimensional non homogeneous distributions.
 158 Said differently, what is actually mapped by the DSOM is the structure or support of the
 159 distribution (Ω using notations introduced in section 2) rather than the density.

160 3.2 Elasticity

161 The DSOM algorithm is not parameter free since we need to control when a neuron may be
 162 considered to be close enough to a data such that it prevents learning for its neighbours. This
 163 is the role of the elasticity parameter that modulates the strength of the coupling between
 164 neurons as shown on figure 3 for a simple two-dimensional normal distribution. This notion
 165 of elasticity shares some common concepts with the Adaptive Resonance Theory (ART) as
 166 it has been introduced in [24]. In the ART model, the vigilance parameter has a critical
 167 influence on learning since it controls the actual partition of the input space: high vigilance
 168 level produces high number of very precise memories while low vigilance level produces fewer
 169 and more generic memories. This is very similar to the elasticity parameter: if elasticity is
 170 high, neurons tend to pack themselves very tightly together (code vectors are relatively close)
 171 while a lower elasticity allows for looser coupling between neurons. However, in the case of
 172 ART, the vigilance parameter also governs the number of final prototypes since they can be
 173 created on demand. In the case of DSOM, the number of prototypes (i.e. neurons) is fixed
 174 and they are supposed to span the whole input space to ensure convergence. Consequently,
 175 there exists a relation between the diameter of the support (defined as the maximum distance
 176 between any two points in Ω), the number of neurons and the elasticity parameter. In the one
 177 hand, if elasticity is too high, neurons cannot span the whole space and the DSOM algorithm
 178 does not converge, in the other hand, if elasticity is too low, coupling between neurons is weak
 179 and may prevent self-organisation to occur: code-vectors are evenly spread on the support but
 180 they do not respect the neighbourhood relationship anymore. There certainly exists an optimal
 181 elasticity for a given distribution but we did not yet investigate fully this relationship and we
 182 do not have formal results. As a preliminary work, we have studied the relationship between
 183 elasticity and the initial conditions in the one dimensional case using a very simple experimental

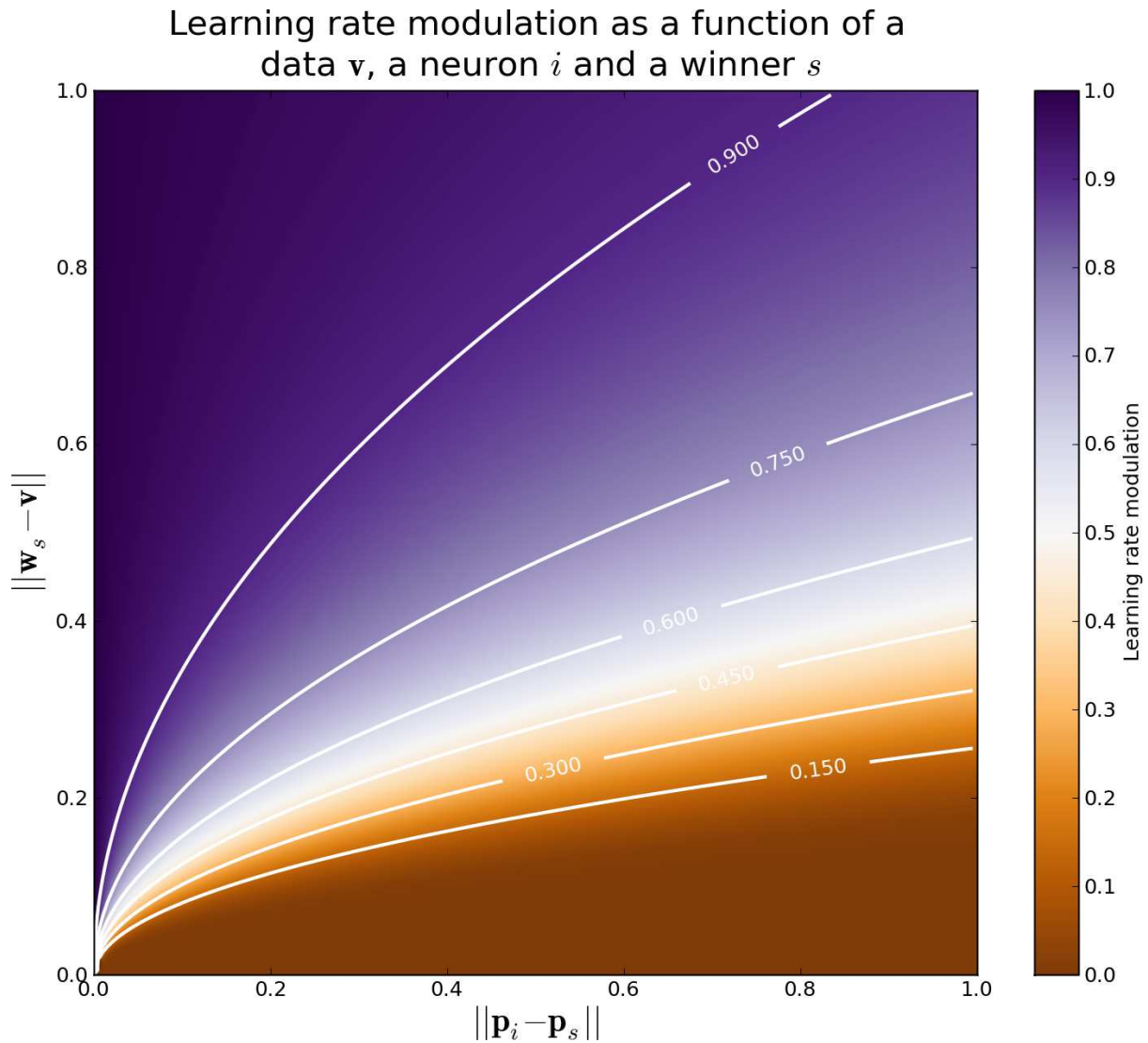


Figure 1: At each presented data \mathbf{v} , the learning rate of each neuron i is modulated according to both the distance $\|\mathbf{w}_s - \mathbf{v}\|$ (which represents the distance between the winner s and the presented data \mathbf{v}) and the distance $\|\mathbf{p}_i - \mathbf{p}_s\|$ (which represent the distance between code words of neuron i and neuron s). If the winner s is very close or equal to \mathbf{v} (bottom line on the figure), learning rate of any neuron different from the winner s is zero and only the winner actually learns the new data. When the winner s is very far from the data (top line), any neuron benefits from a large learning rate and learns the new data (modulated by their own distance to the data but this extra modulation is not represented on the figure).

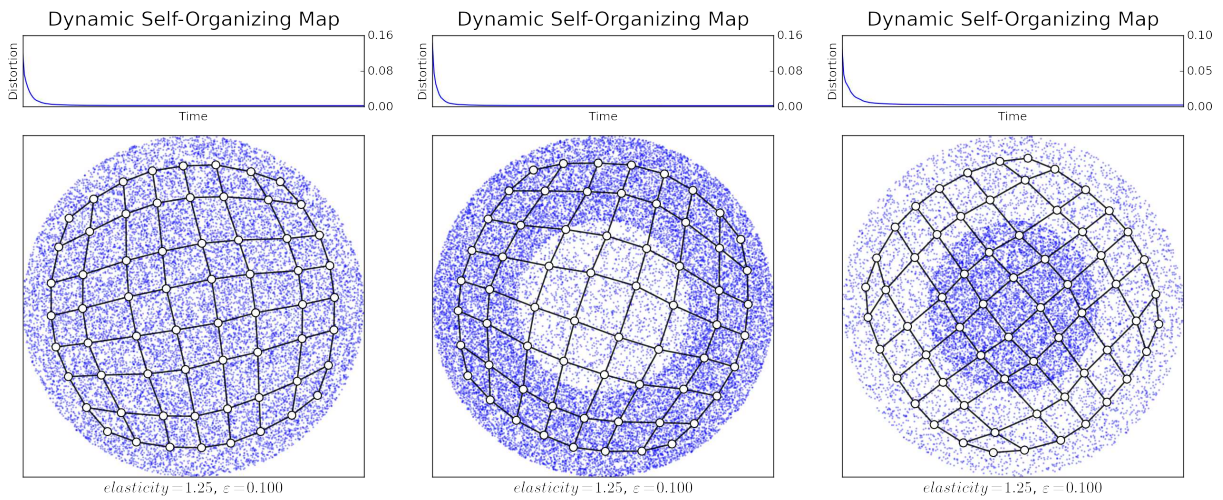


Figure 2: Three DSOM have been trained on a disc distribution using different density areas. **Left.** The density is uniform all over the disc (0.25). **Center.** Outer ring has higher density (.4) than inner disc (.1). **Right.** Outer ring has lower density (.1) than inner disc (.4). Despite these different density distributions, the three DSOM self-organise onto the support of the distribution (the whole disc) and does not try to match density.

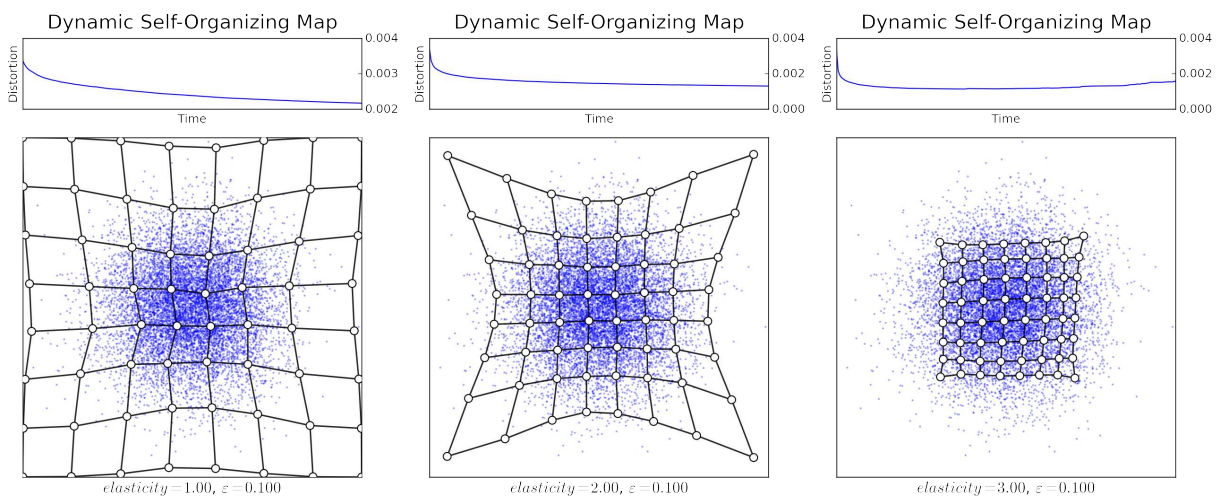


Figure 3: Three DSOM with respective elasticity equal to 1, 1.5 and 2 have been trained for 20 000 iteration on a normal distribution using a regular grid covering the $[0, 1]^2$ segment as initialisation. Low elasticity leads to loose coupling between neurons while higher elasticity results in a tight coupling between neurons.

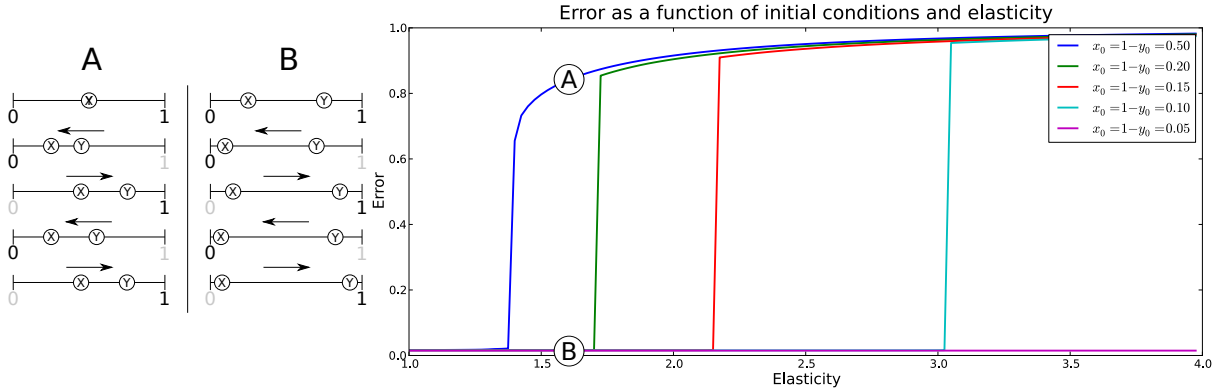


Figure 4: Several one-dimensional DSOM with two nodes have been trained for 2500 epochs using a dataset of two samples (0 and 1) that were presented alternatively. Each point of each curve represents the error of a network with given elasticity and initial conditions. Point A represents a case where elasticity is too high and makes the network to oscillate while point B represents a case where elasticity was low enough to allow the network to properly converge (towards $x = 0$ and $y = 1$).

184 setup where the dataset is made of only two samples (one at 0 and the other at 1) as explained
185 on figure 4. This figure clearly shows a discontinuity in the error when elasticity is varying from
186 1.0 to 4.0 but at different places for different initial conditions. The reason comes from the
187 dependency of the learning to the distance between the winner node and the presented data.
188 When this difference is large, a large correction of weights occur on all networks nodes and this
189 is only attenuated by their distance to the winner and the network elasticity. In the presented
190 experimental setup, data (0 and 1) were presented alternatively and lead to a convergence
191 when elasticity was low enough and to an oscillatory behaviour (not visible on the figure) when
192 elasticity was too high. This oscillatory behaviour can be understood most simply when looking
193 at scheme A on the figure. Each correction made to the network in one way is immediately
194 counter-balanced in the other way when next data is presented. This preliminary study lead
195 us to think that the choice of an optimal elasticity not only depends on the size of the network
196 and the size of the support but also on the initial conditions. If we were to generalise from the
197 simple study above, the initial configuration of the network should cover the entire support as
198 much as possible to reduce elasticity dependency.

199 3.3 Convergence

200 It is well known that the convergence of the Kohonen algorithm has not be proved in the general
201 case [25] even though some conditional convergence properties have been established in the one-
202 dimensional case [26]. Furthermore, in the case of continuous input, it has been shown that
203 there does not exist an associated energy function [27] and in the case of a finite set of training
204 patterns, the energy function is highly discontinuous [28]. In the case of the dynamic SOM, the
205 proof of convergence is straightforward since we can exhibit at least one case where the DSOM
206 does not converge, when the number of nodes is less then the number of data as illustrated on
207 figure 5. Most generally, in case where the number of nodes is less than the total number of
208 presented data, we can predict that the dynamic SOM will not converge. Moreover, a similar
209 problem occurs if the number of nodes is exactly equal to the number of data and if nodes are
210 initially distributed uniquely on each data. In such an initial setup, the learning parameter is

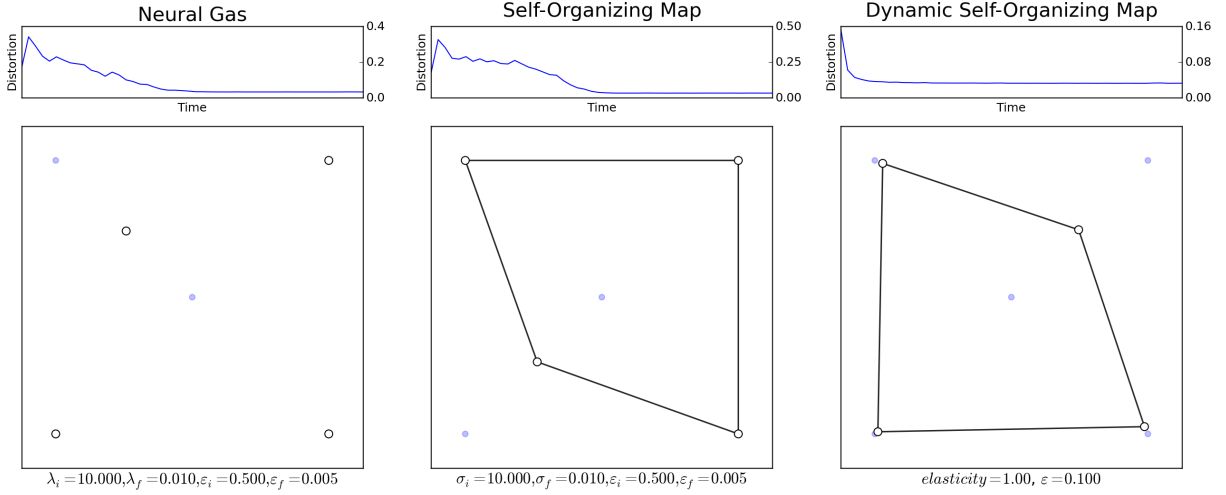


Figure 5: Due to its dynamic nature, the dynamic SOM cannot converge when the number of nodes (4 here) is less than the number of data (5 here). NG and SOM can converge on an approximated solution thanks to both their decaying learning rate and neighborhood and this explains why three nodes are exactly aligned with their corresponding data while the last node found a mid-distance position. In the case of DSOM and because of the constant learning rate, every node is moving at each presented data and thus cannot converge at all.

211 zero for any presented data and this prevents the network to learn anything at all. We could
212 say that it does converge in such a case (network is frozen) but if the initial configuration does
213 not correspond to a proper unfolded one, the answer would not be really satisfactory. A proof
214 of convergence would then require to identify configurations (initial conditions, size, elasticity,
215 learning rate) where the network may have chances to converge but we think this is currently
216 out of the scope of this paper.

217 4 Experimental results

218 We report in this section some experimental results we obtained on different types of distribution
219 that aim at illustrating DSOM principles. We do not have yet formal results about convergence
220 and/or quality of the codebook. As a consequence, these results do not pretend to prove
221 anything and are introduced mainly to illustrate qualitative behaviour of the algorithm.
222 Unless stated otherwise, the learning procedure in following examples is:

- 223 1. A distribution is chosen (normal, uniform, etc.)
- 224 2. A discrete sample set of samples is drawn from the distribution
- 225 3. Model learns for n iterations
- 226 4. At each iteration, a sample is picked randomly and uniformly in the discrete sample set
- 227 5. Distortion is measured on whole sample set every 100 iterations using equation (2.2).

228 The distortion error is plotted above each graphics to show rate of convergence.

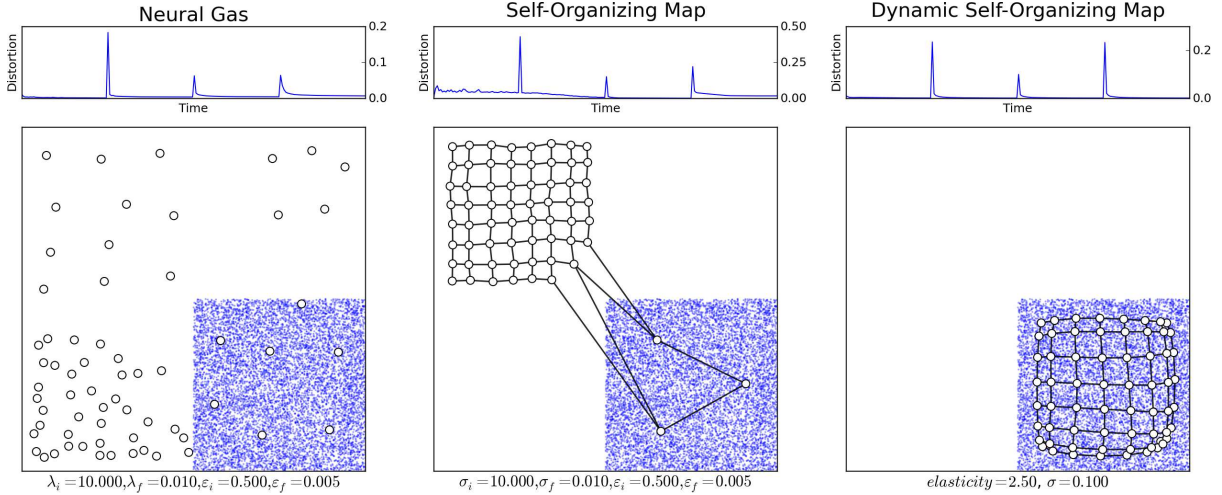


Figure 6: Three networks (NG, SOM, DSOM) have been trained for 20 000 iterations on a dynamic distribution that vary along time: a uniform distribution (1) on $[0.0, 0.5] \times [0.0, 0.5]$ from iterations 0 to 5000, a uniform distribution (2) on $[0.5, 1.0] \times [0.5, 1.0]$ from iterations 5000 to 10000, a uniform distribution (3) on $[0.0, 0.5] \times [0.5, 1.0]$ from iterations 10000 to 15000 and a final uniform distribution (4) on $[0.5, 1.0] \times [0.0, 0.5]$ from iterations 15000 to 20000.

229 4.1 Non-stationary distributions

230 In order to study dynamic aspect of the DSOM algorithm, three networks (NG, SOM, DSOM)
 231 have been trained for 20 000 iterations on a dynamic distribution that vary along time: a
 232 uniform distribution (1) on $[0.0, 0.5] \times [0.0, 0.5]$ from iterations 0 to 5000, a uniform distribution
 233 (2) on $[0.5, 1.0] \times [0.5, 1.0]$ from iterations 5000 to 10000, a uniform distribution (3) on $[0.0, 0.5] \times$
 234 $[0.5, 1.0]$ from iterations 10000 to 15000 and a final uniform distribution (4) on $[0.5, 1.0] \times [0.0, 0.5]$
 235 from iterations 15000 to 20000. NG shows some difficulties in tracking various changes and the
 236 final state reflects the history of the distribution: there are many code words within the first
 237 distribution and very few in the final one. In the case of SOM, the algorithm can almost cope
 238 with the dynamic nature of the distributions as long as its learning rate and neighbourhood
 239 function are large enough to move the codebook into the new data region. This is the case for
 240 distributions (1) to (3) but the final change makes the SOM network unable to map the final
 241 distribution as expected because of the time dependency of the algorithm. In the case of DSOM,
 242 the network is able to accurately track each successive distribution with a short transient error
 243 correlated to the distribution change. We think this behaviour reflects cortical plasticity seen
 244 as a tight coupling between the model and the environment.

245 4.2 High-dimensional distributions

246 Until now, we have considered only trivial two-dimensional distributions whose intrinsic dimen-
 247 sion matched the topography of the network. We now consider higher dimensional distribution
 248 with unknown intrinsic dimension. Using the standard Lena grey-level image as a source input,
 249 samples of 8×8 pixels have been draw uniformly from the image and presented to the different
 250 networks. 1000 such samples have been drawn and all three networks have learnt during 10
 251 000 iterations. As illustrated on figure 7, the strong influence of neighbourhood in the case
 252 of SOM leads to a final codebook where vectors tend to be very homogeneous and composed
 253 of a mean value with little variations around this mean value. In the case of NG, things are

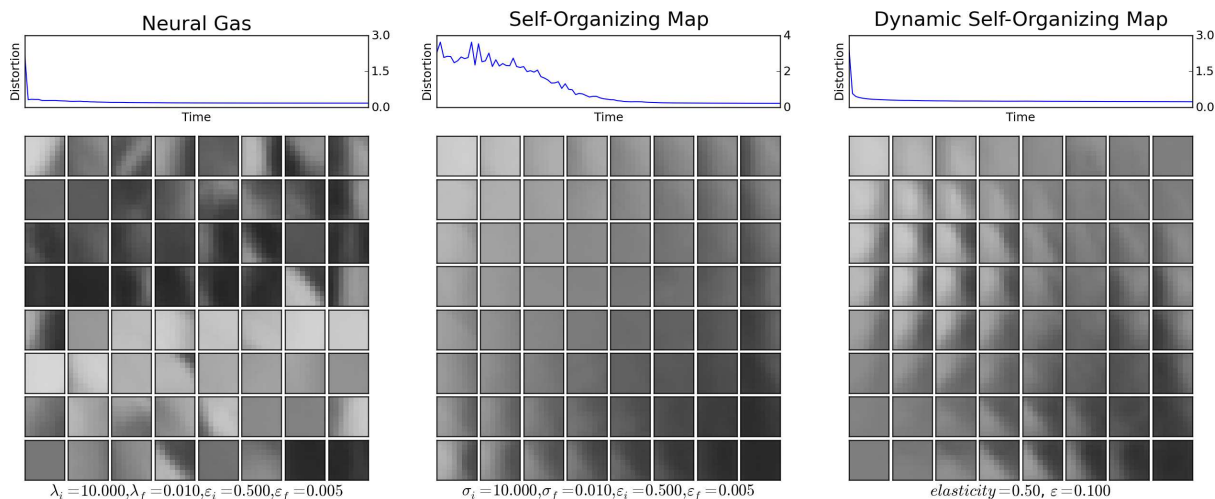


Figure 7: Three networks (NG, SOM, DSOM) have been trained for 20 000 iterations on 1000 samples of size 8×8 pixels that have been drawn uniformly from the standard lena grey image.

254 different because of the absence of topographic constraints: NG converges rapidly toward a
 255 stable solution made of qualitatively different filters, part of them are quite homogeneous like
 256 in SOM but some others clearly possess a greater internal variety. In the case of DSOM, we can
 257 also check on the figure a greater variety of filters that are self-organised. The meaning of such
 258 a greater variety of filters in the case of DSOM is difficult to appreciate. In the one hand, if
 259 we were to reconstruct the original image using those filters, we would certainly obtain a larger
 260 distortion error. In the other hand, if those filters were supposed to extract useful information
 261 from the image, they would certainly give a better account of the structure of the image.

262 5 Conclusion

263 One of the major problem of most neural map algorithms is the necessity to have a finite set
 264 of observations to perform adaptive learning starting from a set of initial parameters (learning
 265 rate, neighbourhood or temperature) at time t_i down to a set of final parameters at time t_f . In
 266 the framework of signal processing or data analysis, this may be acceptable as long as we can
 267 generate a finite set of samples in order to learn it off-line. However, from a more behavioural
 268 point of view, this is not always possible to have access to a finite set and we must face on-line
 269 learning. As explained in the introduction, if we consider the existence of a critical period in
 270 the early years of development, the problem may be solved using decreasing learning rate and
 271 neighbourhood over an extended period of time. But if this may explain to some extents the
 272 development of early sensory filters, this fails at explaining cortical plasticity at a more broad
 273 level. As explained in [29], we know today that “cortical representations are not fixed entities,
 274 but rather, are dynamic and are continuously modified by experience”. How can we achieve
 275 both stability and reactivity ?

276
 277 We proposed to answer this question by introducing a variant of the original SOM learning
 278 algorithm where time dependency has been removed. With no available formal proof of conver-
 279 gence and based on several experiments in both two-dimensional, high-dimensional cases and
 280 dynamic cases, we think this new algorithm allows for on-line and continuous learning ensuring
 281 a tight coupling to the environment. However, the resulting codebook does not fit data den-

282 sity as expected in most VQ algorithms. This could be a serious drawback in the framework
283 of signal processing or data compression but may be a desirable property from a behavioural
284 point fo view. For example let us consider a picture of a (very) snowy landscape with a small
285 tree in the middle. If we want to mimic visual exploration of the scene using eye saccades,
286 we can randomly pick small patches within the image and present them to the model. Not
287 very surprisingly, the vast majority of these patches would be essentially white (possibly with
288 some variations) because the whole image is mainly white. From a pure VQ point of view, the
289 codebook would reflect this density by having a vast majority of its representations into the
290 white domain and if the tree is small enough, we could even have only white representation
291 within the codebook. While this would serve data compression, how much is it relevant in
292 general ? We do not have the answer in the general case but we think this must be decided
293 explicately depending on task. DSOM allows such explicit decision since it maps the structure
294 of the data rather than their density. This means that in a more general framework, we could
295 expect an external structure to attach some kind of motivation for each data that would modu-
296 late its learning. If some region of the perceptive space is judged behaviourally relevant, model
297 could develop precise representations in this region but if learning is driven solely by data density
298 (like in most VQ), such modulation would certainly be strongly attenuated or not possible at all.
299

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302 A Notations

303 Ω : a compact manifold of \mathbb{R}^d where $d \in \mathbb{N}^+$

304 $f(x)$: a probability density function (*pdf*) $\Omega \rightarrow \mathbb{R}$

305 $\{x_i\}$: a set of p non-biased observations of f .

306 \mathcal{N} : a set of n elements, $n \in \mathbb{N}^+$.

307 Φ : a function defined from $\Omega \rightarrow \mathcal{N}$

308 $\mathbf{w}_i \in \mathbb{R}^d$: code word associated to an element i of \mathcal{N}

309 $\{\mathbf{w}_i\}$: codebook associated to \mathcal{N}

310 C_i : cluster associated to element i such that $C_i = \{x \in \Omega | \Phi(x) = \mathbf{w}_i\}$

311 $\|x\|$: euclidean norm defined over \mathbb{R}^d

312 $\|x\|_\Omega$: normalised euclidean norm defined over Ω as $x \mapsto \frac{\|x\|}{\max_{y,z \in \Omega} (\|y-z\|)}$

313 ξ : distortion error defined as $\sum_{i=1}^n \int_{C_i} \|x - \mathbf{w}_i\|^2 f(x) dx$

314 $\hat{\xi}$: estimated distortion error defined as $\frac{1}{p} \sum_{i=1}^n \sum_{x_j \in C_i} \|x_j - \mathbf{w}_i\|^2$

315 $\varepsilon(t)$: learning rate at time t

316 $\lambda(t)$ **or** $\sigma(t)$: neighbourhood width at time t

317 η : elasticity or plasticity

318 **B Online resources**

319 **Python code sources**

320 <http://www.loria.fr/~rougier/DSOM/dsom.tgz>

321

322 **Movie of self-organisation onto a sphere surface**

323 <http://www.loria.fr/~rougier/DSOM/sphere.avi>

324

325 **Movie of self-organisation onto a cube surface**

326 <http://www.loria.fr/~rougier/DSOM/cube.avi>

327

328 **Movie of self-reorganisation from sphere to cube surface**

329 <http://www.loria.fr/~rougier/DSOM/sphere-cube.avi>

330

331 **Movie of self-reorganisation from one sphere to two spheres surface**

332 <http://www.loria.fr/~rougier/DSOM/sphere-spheres.avi>

333

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