Role of noise in image processing by the human perceptive system

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Two psychophysics experiments are described, pointing out the significant role played by stochastic resonance in recognition of capital stylized noisy letters by the human perceptive apparatus. The first experiment shows that an optimal noise level exists at which the letter is recognized for a minimum threshold contrast. A simple two-parameter model that best fits the experimental data is also discussed. In the second experiment we show that a dramatically increased ability of the visual system in letter recognition occurs in an extremely narrow range of increasing noise. Possible interesting future investigations suggested by these experimental results and based on functional imaging techniques are discussed.

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I. INTRODUCTION

Stochastic resonance (SR) is a statistical phenomenon associated with nonlinear systems [1]; for a large class of such systems, an increase in the noise affecting the input signal may induce an increase in the signal-to-noise ratio (SNR) in the system's output. The basic ingredients for SR to show up are a coherent small signal, a form of energetic threshold, and the possibility of varying the amount of noise affecting the signal either by external addition or by some inherent process. In this situation it can be shown [2,3] that there exists an optimal level of noise maximizing the response of the system in a resonancelike behavior. Experimental verifications of this effect have been performed in many areas of applied physics and in biology [4,5] (see, for example, [6,7] for recent and rather complete reviews). The interest of such a phenomenon in the processing of information by the biological neural system is evident at all levels from the lower ''physiological'' levels to the higher ''cognitive'' ones. For sensory systems SR effects have been explored, for example, in experiments on single mechanoreceptors from crayfish tails [8], crayfish [9] and cricket [10] ganglion cells, rat hippocampal cells [11], and human muscle spingles [12]. At higher levels of complexity in cognitive systems, SR effects have been found in a neural network modeling the phenomenon of perceptual alternation occurring in the observation of the so-called *ambiguous pattern* [13], in the human tactile system [14], and in human visual perception [15,16]. An interesting behavioral experiment is described in [17], and in [18] the role of noise in the auditory system is reported. Both these experiments may link stochastic resonance to evolution, that is, the use of SR can obviously have a survival value and thus was selected for. The results of our experiments may also point in the same direction. We are interested in the key question whether and how the human brain exploits noise in order to enhance the quality of external stimuli. This problem has been addressed in [15] with a psychophysics experiment concerning visual perception of noisy patterns. This experiment shows quantitatively that the human brain is helped by noise in detecting small details in stationary images and that this visual enhancement is satisfactorily modeled by a one-parameter SR curve obtained from level-crossing detector theory [19].

In the present paper we discuss two experiments concerned with the visual perception of noisy letters. More precisely, in experiment I, characterized by an experimental paradigm similar to the one in [15], we produce images containing one letter each that we painted over a uniform background and depressed under a fixed threshold, i.e., pixels with gray level lower than the threshold are painted with the same gray level as the background. Then we affect each letter with noise of different standard deviations, and for each presentation we smoothly increase the contrast between the letter signal and the background until the subject recognizes the letter. By plotting the contrast value for which the letter is recognized by the subject versus the value of the standard deviation characterizing the presentation, we can show that an optimal noise level, where the recognition contrast value is minimum, can be detected. As the main results of this experiment we obtain the following.

(1) SR occurs when the human perceptive apparatus is asked to recognize rather big stylized noisy capital letters previously depressed under a fixed threshold.

(2) A quantitative estimate of the optimal noise level can be produced for all the subjects. Knowledge of the corresponding contrast threshold is helpful for the realization of the second experiment in this paper.

(3) The theoretical model describing the detection of small details in the experiment in [15] is here able to follow only coarsely the trend of the noise effect on the contrast threshold of the human visual system. However, we can provide a two-parameter modification of that model fitting our data in a more reliable fashion.

In a second experiment (experiment II) each subject is

TABLE I. Results for experiment I: The mean value of $128C_{\rm th}$ is given for eight different noise levels and seven different subjects. The letters associated with each noise level for each subject are also indicated.

	Subject						
Noise	1	2	3	4	5	6	7
$\sigma=20$	7.7±0.9	12.0±1.1	12.3±1.5	7.9±0.6	6.9±1.1	12.5±1.1	11.0±1.5
Letter	G	P	A	H	S	L	F
$\sigma=30$	2.6±0.4	5.1±0.7	5.6±0.7	3.8±0.4	5.1±0.9	5.1±0.6	5.6±1.1
Letter	T	H	F	G	L	P	A
$\sigma=45$	3.3±0.7	3.6±0.6	4.6±0.7	4.1±0.6	2.8±0.6	3.6±0.6	2.8±0.6
Letter	F	T	H	P	A	H	S
$\sigma=67.5$	3.3±0.7	3.3±0.7	4.6±0.7	3.1±0.7	3.6±0.6	4.9±0.6	2.8±0.6
Letter	P	G	S	L	F	G	T
$\sigma=101.25$	4.4±1.1	6.4±1.4	4.6±0.7	5.6±0.7	3.8±0.9	4.9±0.6	5.1±1.6
Letter	L	A	T	F	G	S	H
$\sigma=151.88$	5.6±0.7	8.7±1.9	6.9±1.5	5.1±1.3	5.6±0.7	6.9±1.5	7.7±1.3
Letter	H	S	G	T	P	A	L
$\sigma=227.81$	8.2±1.1	9.7±2.5	6.9±1.9	8.7±1.1	8.4±1.5	7.2±0.7	10.8±0.7
Letter	A	F	L	S	H	T	P
$\sigma=341.72$	10.5±1.7	13.6±1.5	15.4±2.4	12.5±1.1	8.7±1.1	16.4±1.1	9.2±1.1
Letter	S	L	P	A	T	F	G

presented with sequences of noisy letters painted on the background using a fixed contrast value. Letters belonging to the same sequence are affected by the same noise level and subjects are asked to recognize the letters in the sequence. By plotting the recognition rate versus the noise standard deviation we can show that the human visual system exhibits a dramatically increasing ability to recognize a significant visual stimulus, such as a capital letter, in a very small range of increasing values of the noise level affecting the images. In our opinion this result is significant for two reasons. (1) It shows that SR can explicitly and notably help the human visual system to decode weak underthreshold signals. (2) The existence of an extremely narrow range of noise values in which the performance of the human visual system in a recognition task grows from a few percent to 100% might be an important hint for study of the role of noise in processing of information by the brain. In fact, as shown in [16], the presence of noise in the processing of visual images greatly affects the neural activation of the primary visual cortex, while language-related tasks involve completely different regions of the human brain. Therefore we think that these results deserve further investigation by means of functional imaging techniques.

In the next section we will briefly describe the experimental setup of our experiments and then we will provide the results of experiment I. In Sec. III experiment II relating recognition rate to noise will be discussed.

II. EXPERIMENT I: RECOGNITION CONTRAST VALUE VERSUS NOISE

Both experiments I and II utilize a code producing 256×256 images of dark-gray letters over a light-gray background. More precisely, in the noise-free case the back-

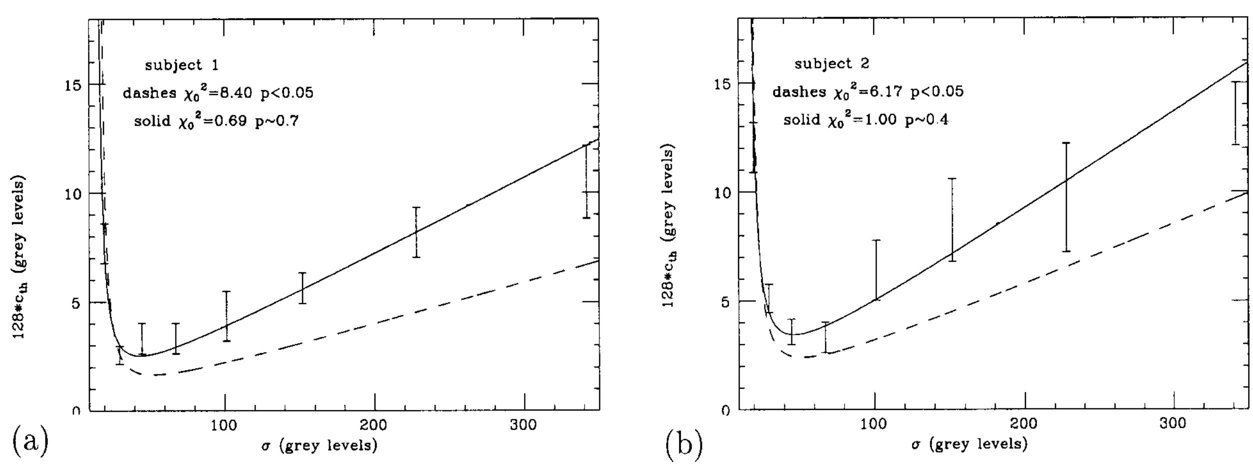

FIG. 1. Results for experiment I: the contrast threshold values are plotted versus the standard deviation of the Gaussian noise. The solid and dashed lines represent the best fit obtained, respectively, from model (2.2) and model (2.1). (a) Result for subject 1; (b) result for subject 2.

ground is characterized by a gray level equal to 128 and the letter differs from the background by a quantity equal to $128C$, with C a small real input variable modulating the contrast. Gaussian noise with zero mean and standard deviation σ is added pixel by pixel in a dynamical way: subsequent frames are produced and a new noise realization is performed for each frame; the frame rate is 60 Hz, 16.6 ms per frame, which is a much shorter time interval than the averaging times in the human visual system (this notably helps human perceptive skill). All images are artificially depressed beneath a fixed threshold Δ, i.e., we impose the requirement that all pixels that have values smaller than Δ are painted with the same gray level as the background of the noise-free image. In the following we will always assume $\Delta = 180$. Note that all pixels with values over the threshold are characterized by a gray tone lighter than the background (gray level zero is black while gray level 256 is white). Nevertheless, for practical reasons we perform a gray-level reflection of the images so that finally the letters are painted in a noisy dark-gray figure over a noisy light-gray background.

In the paradigm of experiment I, eight different values of the standard deviation σ are associated with eight different letters and each subject is presented with a sequence of 40 letters overall, in which each letter is randomly presented five times. For each presentation and starting from $C = 0$, the value of C is gradually increased and the subject is asked to declare the name of the letter as soon as recognized. The corresponding value $C = C_{th}$ provides the value $128C_{th}$ of the contrast when recognition occurs. This experiment was performed for seven different subjects and we took care to build up different associations of noise and letter for each subject and different sequences of letters, in order to make the recognition ability sufficiently independent from the form of the letter itself. For each subject and each noise level, we computed the mean value of the recognition contrast (the mean is obviously made over the five values corresponding to the same letter, i.e., to the same noise level) with their errors. The results, together with the associated capital letter, are contained in Table I: for all the subjects the recognition contrast value rapidly decreases to a minimum value with C_{th} around 0.05 and corresponding to a noise level between 30 and 80 noise units, while for larger values of σ, C_{th} increases to values of the same order as the initial ones, but this time more slowly, i.e., within a σ range from 100 to 350 noise units.

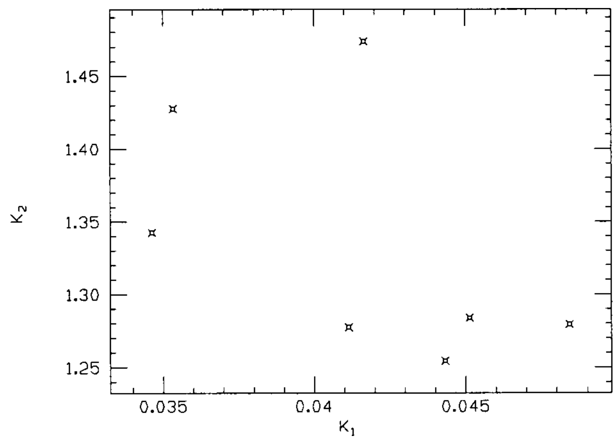

FIG. 2. Best-fitting parameters K_1 and K_2 of model (2.2) for all seven subjects.

A possible model for these experimental results is based on the theory of level-crossing detectors [19]. According to this approach the output signal amplitude B (in our case

TABLE II. Results for experiment II: the value of the recognition rate is given for seven different subjects and twelve noise levels. The presentation is given from low to high noise.

	Subject						
Noise	1	2	3	4	5	6	7
$\sigma = 20$	0.40	0.05	0.16	0.05	0.20		0.28
$\sigma = 22$	0.80	0.22	0.30	0.69	0.53	0.13	0.59
$\sigma = 24$	1.00	0.80	0.59	0.86	0.95	0.61	0.89
$\sigma = 26$		0.94	0.94	0.97	0.97	0.98	0.97
$\sigma = 50$			1.00	1.00	1.00	1.00	
$\sigma = 60$	1.00	1.00					1.00
$\sigma = 90$			0.95	0.95		0.95	
$\sigma = 100$	0.97	0.98			0.98		
$\sigma = 110$							1.00
$\sigma = 120$				0.86			
$\sigma = 130$				0.88		0.86	
$\sigma = 140$	0.84	0.78		0.86			
$\sigma = 150$		0.73	0.75		0.84	0.77	0.77
$\sigma = 160$	0.88	0.81			0.61		0.72
$\sigma = 170$			0.53		0.59		0.78
$\sigma = 180$	0.73		0.61	0.55	0.55	0.72	
$\sigma = 200$	0.72	0.41	0.53	0.64	0.64	0.66	0.52
$\sigma = 220$	0.69	0.39	0.45			0.63	0.52
$\sigma = 240$	0.36			0.39	0.34	0.41	
$\sigma = 260$	0.44	0.34	0.36			0.44	0.47

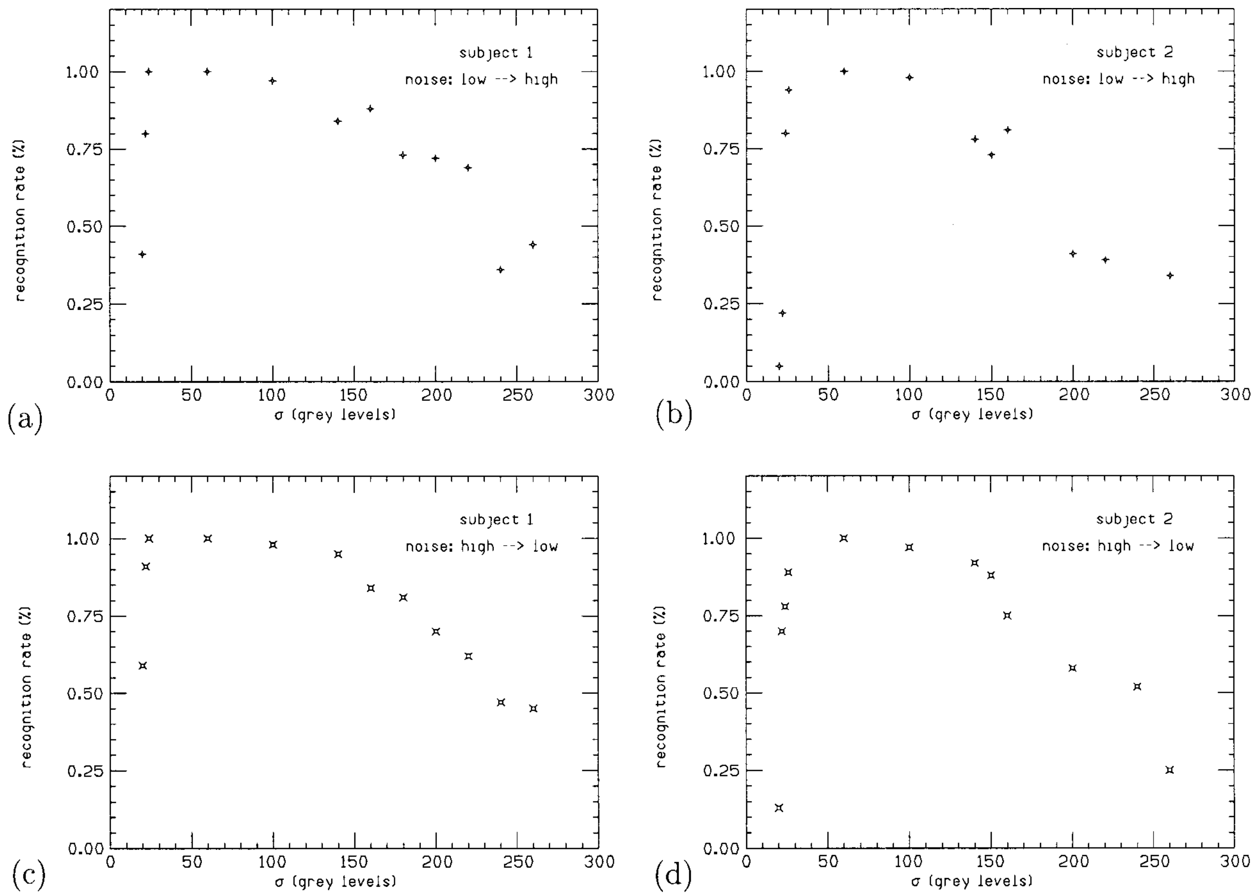

FIG. 3. Results for experiment II: the recognition rate of the letters is plotted versus the values of the standard deviation of the noise. In (a) and (b) results are given, respectively, for subjects 1 and 2 when the presentation is given from low-level to high-level noise. In (c) and (d) results are given, respectively, for subjects 1 and 2 when the presentation is given from high-level to low-level noise.

$B=128C_{\rm th}$) can be described in terms of the noise affecting the input signal by the function

$$B=K\sigma\exp\left(\frac{\Delta^2}{2\sigma^2}\right) \tag{2.1}$$

with K a term related to the signal-to-noise ratio of the output signal and Δ the external threshold. Equation (2.1) has been used in [15] to best-fit the SR data for the detection of small features in images of strips with K as a unique free parameter. However, we found that this same function is not very useful for best-fitting our SR data for the recognition of letters. For example, in Fig. 1 we superimpose the best fit as a dashed line on the experimental data for subjects 1 and 2. The figure clearly shows that the function decreases more slowly than the experimental data for small values of noise and increases more slowly than the experimental data for large values of noise. In other words, it seems that in actual measurements the action of noise in the task of letter recognition is in some way emphasized with respect to what model (2.1) foresees, both in the constructive part of the noise value range and in the deteriorating one. The observed more incisive role played by noise in letter recognition might be explained by allowing for possible cooperative effects occuring in the human perceptive apparatus. In fact, the possible cooperative effects among the rare overthreshold signals at low noise levels can imply a positive contribution to letter recognition while at higher noise levels the same cooperative effects can easily result in a degradation of the pattern perception. Therefore we think that a better fit of actual data could be obtained with the two-parameter function

$$B=K_1\sigma\exp\left(\frac{\Delta^2}{2K_2\sigma^2}\right), \tag{2.2}$$

where K_1 and K_2 are two parameters to fix with a least-squares fit.

We performed the best fit of our experimental data by using Eq. (2.2) and for all the subjects we obtained values of χ^2 much smaller than with Eq. (2.1). In particular, in Fig. 1 the solid line represents the new best fit for subjects 1 and 2. By combining Eqs. (2.1) and (2.2) we obtain

$$\frac{\Delta^2}{2\sigma^2}=\frac{K_2}{1-K_2}\ln\frac{K}{K_1}, \tag{2.3}$$

which has solutions in the range $K_2<1, K_1<K$. This implies that in this range of parameters there exists a noise level $\overline{\sigma}$ such that for $\sigma<\overline{\sigma}$ the new fit is under the old one and for $\sigma>\overline{\sigma}$ the new fit is over the old one. We observe that the best-fitting values of K_1 are of the same order of magnitude as the best-fitting values of K in the one-parameter model, while the best-fitting values of K_2 are two orders of magnitude greater. Furthermore, Fig. 2 shows that there exists no elementary functional relationship between K_1 and K_2 for the different subjects.

TABLE III. Results for experiment II: the value of the recognition rate is given for seven different subjects and twelve noise levels. The presentation is given from high to low noise.

Noise	Subject 1	2	3	4	5	6	7
$\sigma=20$	0.59	0.13	0.19	0.45	0.50		0.48
$\sigma=22$	0.91	0.70	0.41	0.69	0.83	0.56	0.66
$\sigma=24$	1.00	0.78	0.70	0.88	0.97	0.83	0.89
$\sigma=26$		0.89	0.95	0.97	0.98	1.00	0.95
$\sigma=50$			1.00	1.00	1.00	1.00	
$\sigma=60$	1.00	1.00					1.00
$\sigma=90$			0.97	0.94		0.98	
$\sigma=100$	0.98	0.97			1.00		
$\sigma=110$							0.97
$\sigma=120$				0.94			
$\sigma=130$				0.86		0.89	
$\sigma=140$	0.95	0.92		0.92			
$\sigma=150$		0.88	0.81		0.83	0.78	0.88
$\sigma=160$	0.84	0.75			0.78		0.78
$\sigma=170$			0.66		0.78		0.78
$\sigma=180$	0.81		0.69	0.67	0.69	0.66	
$\sigma=200$	0.70	0.58	0.69	0.59	0.64	0.63	0.75
$\sigma=220$	0.63	0.52	0.56			0.66	0.64
$\sigma=240$	0.47			0.45	0.38	0.50	
$\sigma=260$	0.45	0.25	0.23			0.42	0.25

III. EXPERIMENT II: RECOGNITION RATE VERSUS NOISE

With basically the same experimental setup as in experiment I, we performed a second experiment (experiment II) relating in a more impressive way the human perceptive ability to a functionally constructive behavior of noise. In this case we produced twelve sequences of 64 images containing again one letter each. The letters were chosen from the same set of eight of experiment I and for each sequence the order of presentation was randomly chosen. All the letters belonging to the same sequence were affected by Gaussian noise characterized by the same standard deviation so that we had twelve different noise levels for the twelve sequences. Again an artificial threshold of $\Delta=180$ was imposed but this time the difference $128C$ between the letter signal and the background was fixed for the whole presentation ($C=0.05$ is the value chosen, of the order of the minimum threshold contrast in experiment I). Starting from the sequence characterized by the smallest noise level, the subject was asked to recognize the letters of the sequence. In this way, for each sequence and therefore for each noise level, we could plot the number of recognized letters as a fraction of the 64 belonging to the sequence. The responses of the seven subjects we investigated were very similar and are reported in Table II: all of them present a greatly increased ability to recognize the letters around a noise level of 22–26 units, from 20% to 100% of recognition; then a rather wide plateau of a constant recognition rate was detected, followed by a slow deterioration for larger values of noise between 120 and 260 units. Figures 3(a) and 3(b) clearly show this behavior for subjects 1 and 2.

In order to verify the presence of some hysteresis effect, we performed the same experiment this time starting from the sequence associated with the largest noise level and proceeding with sequences of decreasing noise amounts; the results are given in Table III for all the subjects and, although exhibiting a weak habituation effect, they show essentially the same behavior as in the case of the low noise–high noise direction. In Figs. 3(c) and 3(d) we plotted the results for subjects 1 and 2.

IV. DISCUSSION

Experiment II clearly shows that the presence of noise in images of letters enhances the recognition sensitivity of the human perceptive apparatus and that the range of noise values where noise plays a constructive role in the recognition ability is extremely narrow. This behavior can be described as a phase transition in human perceptive ability occurring for a noise level around 22–26 standard deviation units. We think that this result may have important implications for the study of noise effects with functional magnetic resonance imaging. More precisely, previous work [16] indicated a strong activation effect in the primary visual area, due to the large range of noise levels, which makes the identification of activation due to pattern recognition practically impossible. On the other hand, in a functional experiment with noisy letters analogous to experiment II, language-related performance should induce activation in completely different brain areas and this could help the detection of a different activation topology in the occipital visual region.

Further implications concerning brain functionality can be investigated by means of electrophysiological studies (electroencephalography, magnetoencephalography) under the same conditions as the present psychophysics experiments neuromagnetic responses to subthreshold noisy letters can be recorded in order to obtain information about signal frequency organization, topographic distribution, and possible sources.

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