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The role of noise in the image processing by human perceptive system

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Abstract

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

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I. INTRODUCTION

Stochastic resonance (SR) is a statistical phenomenon associated with a non-linear system [1], whereby 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 in order that SR shows 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 resonance-like behaviour. 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 phenomenon in the processing of information by biological neural system is evident at all the elaboration levels, from the lower "physiological" levels to the higher "cognitive" ones. For sensory systems the SR effects have been explored, for example, in experiments on single mechanoreceptors from crayfish tails [8], crayfish [9] and cricket [10] ganglion cells, on rat hippocampal cells [11] and on human muscles spingles [12]. An interesting behavioral experiment is described in [13]. We observe that this experiment, as well as the one described in [14] link stochastic resonance to evolution. At higher levels of elaboration in cognitive systems SR effects have been found in a neural network modelling the phenomenon of perceptual alternation occuring in the observation of the so-called *ambiguous pattern* [15], in human tactile system [16], and human visual perception [17,18]. In particular, we are interested in the key question whether and how human brain exploits noise in order to enhance the quality of external stimula. This problem has been addressed in [17] with a psycophysics experiment concerning visual perception of noisy patterns. This experiment quantitatively shows that 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 Detectors theory [19].

In the present paper we discuss two new experiments, concerned with the visual perception of noisy letters. More precisely in Experiment I, characterized by an experimental paradigm similar to the one in [17], 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 smaller than the threshold are painted with the same gray level of 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 main results of this experiment we obtain that:

- SR verifies when the human perceptive apparatus is asked to recognize rather big stylized capital noisy letters previously depressed under a fixed threshold.
- A quantitative estimate of the optimal noise level can be produced for all the subjects. The knowledge of the corresponding contrast threshold is helpful for the realization of the second experiment in this paper.
- The theoretical model describing the detection of small details in the experiment in [17] is here able only to coarsly follow the trend of the noise effect on the contrast threshold of human visual system. However we can provide a two-parameters modification of that model fitting our data in a more reliable fashion.

In a second experiment (Experiment II) each subject is presented by sequences of noisy letters painted on the background by 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 human visual system exhibits a dramatically increasing ability in recognition of a significative visual stimulus, such as a capital letter, in correspondence of a very small range of increasing values of the noise level affecting the images. In our opinion this result is significant basically for two reasons:

- it shows that SR can explicitly and notably help human visual system to decode weak underthreshold signals.
- The exhistence of an extremely narrow range of noise values in which the performance of human visual system in a recognition task grows from a few percent to 100% of the cases, can be an important hint for the study of the noise role in the elaboration of information by the brain. In fact, as exposed in [18], the presence of noise in the processing of visual images greatly affects the neural activation of primary visual cortex, while language-related tasks involve completely different regions of 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 concerning Experiment I. In section 3, Experiment II relating recognition rate to noise will be discussed.

II. EXPERIMENT I: RECOGNITION CONTRAST VALUE VS NOISE

Both Experiment I and Experiment II utilize a code producing 256x256 images of dark gray letters over a light gray background. More precisely, in the noise free case the background is characterized by a gray level equal to 128 and the letter differs from the background by a quantity equal to $128 \cdot C$, 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 faster time interval than the averaging times in human visual system (this notably helps human perceptive skill). All images are artificially depressed beneath a fixed threshold Δ, i.e., we impose that all pixels which have values smaller than Δ are painted with the same gray level of 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 at the end 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 by 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 $128 \cdot C_{th}$ of the contrast when recognition occurs. This experiment was performed for 7 different subjects and we took care to build up different associations noise-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 of the initial ones, but this time more slowly, i.e., within a σ range from 100 to 350 noise units.

A possible model for these experimental results is based on the theory of Level-Crossing Detectors (LCD) [19]. According to this approach the output signal amplitude B (in our case $B = C_{th} \cdot 128$) can be described in terms of the noise affecting the input signal by the function

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

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 [17] to best-fitting the SR data for the detection of small features in images of strips with K as unique free parameter. However we found that this same function is not very useful to best-fitting our SR data for the recognition of letters. For example in Figure 1 we superimpose the best-fit with dashed line on the experimental data for subject 1 and subject 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 terms 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 could be explained by allowing for possible cooperative effects occuring in 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-parameters function

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

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

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

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

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 of 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 Figure 2 shows that there exists no elementary functional relationship between K_1 and K_2 for the different subjects.

III. EXPERIMENT II: RECOGNITION RATE VS NOISE

With basically the same experimental setup of Experiment I we performed a second experiment (Experiment II) relating in a more impressive way the human perceptive ability to a functionally constructive behaviour of noise. In this case we produced twelve sequences of 64 images containing again one letter each. The letters have been chosen in the same set of eight different ones of Experiment I and for each sequence the order of presentation has been 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 $128 \cdot C$ between the letter signal and the background was set fixed for all the 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 the recognized letters over the 64 ones 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 violently increasing ability in recognizing the letters around a noise level of $22 - 26$ units from 20% to 100% of recognition; then a rather wide *plateau* of constant recognition rate was detected, followed by a slow deterioration for larger values of noise between 120 units to 260 units. Figure 3(a) and 3(b) clearly show this behaviour for subject 1 and subject 2.

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

IV. DISCUSSION

Experiment II clearly shows that the presence of noise on images of letters becomes determinant for the enhancement of recognition sensitivity of human perceptive apparatus and that the range of noise values where noise turns to play a constructive role in recognition ability is extremely narrow. This behaviour can be assimilated to a phase transition in human perceptive ability occuring for a noise level around $22 - 26$ standard deviation units. We think that this result may have important implications as far as a study of the noise effects with fMRI is concerned. More precisely a previous work [18] indicates a strong activation effect in the primary visual area, due to all the large range of noise levels, which makes the identification of activations due to pattern recognition practically impossible. On the other hand, in a functional experiment with noisy letters analogous to Experiment II, language-related performances should induce activations 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 fMEG research: under the same conditions of the present psycophysics experiments neuromagnetic responses to sub-threshold noisy letters can be recorded in order to obtain information about signal frequency organization, topographic distribution and possible sources.

TABLES

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

noise	sub 1	sub 2	sub 3	sub 4	sub 5	sub 6	sub 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
associated 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
associated 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
associated 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
associated 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
associated 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
associated 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
associated 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
associated letter	S	L	P	A	T	F	G

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.

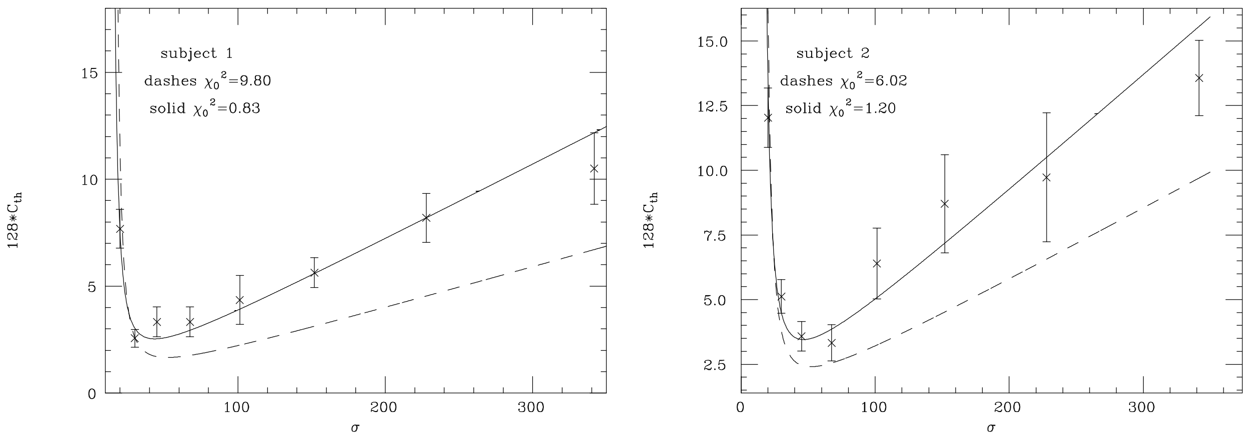
noise	sub 1	sub 2	sub 3	sub 4	sub 5	sub 6	sub 7
$\sigma = 20$	0.40	0.05	0.16	0.05	0.20		0.28
$\sigma = 22$	0.80	0.22	0.30	0.69	0.53	0.13	0.59
$\sigma = 24$	1.00	0.80	0.59	0.86	0.95	0.61	0.89
$\sigma = 26$		0.94	0.94	0.97	0.97	0.98	0.97
$\sigma = 50$			1.00	1.00	1.00	1.00	
$\sigma = 60$	1.00	1.00					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

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	sub 1	sub 2	sub 3	sub 4	sub 5	sub 6	sub 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

FIGURES

FIG. 1. Results for Experiment I: the contrast threshold values are plotted versus the standard deviation of the gaussian noise. The solid and dashed line represent the best-fits obtained respectively from model (2.2) and from model (2.1) . (a) Result for subject 1; (b) result for subject 2.



(a) (b)

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

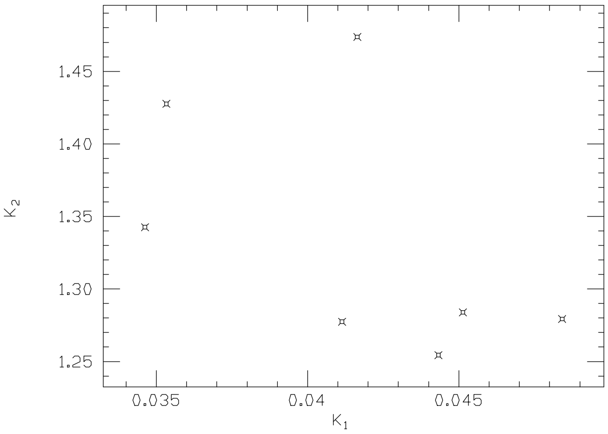
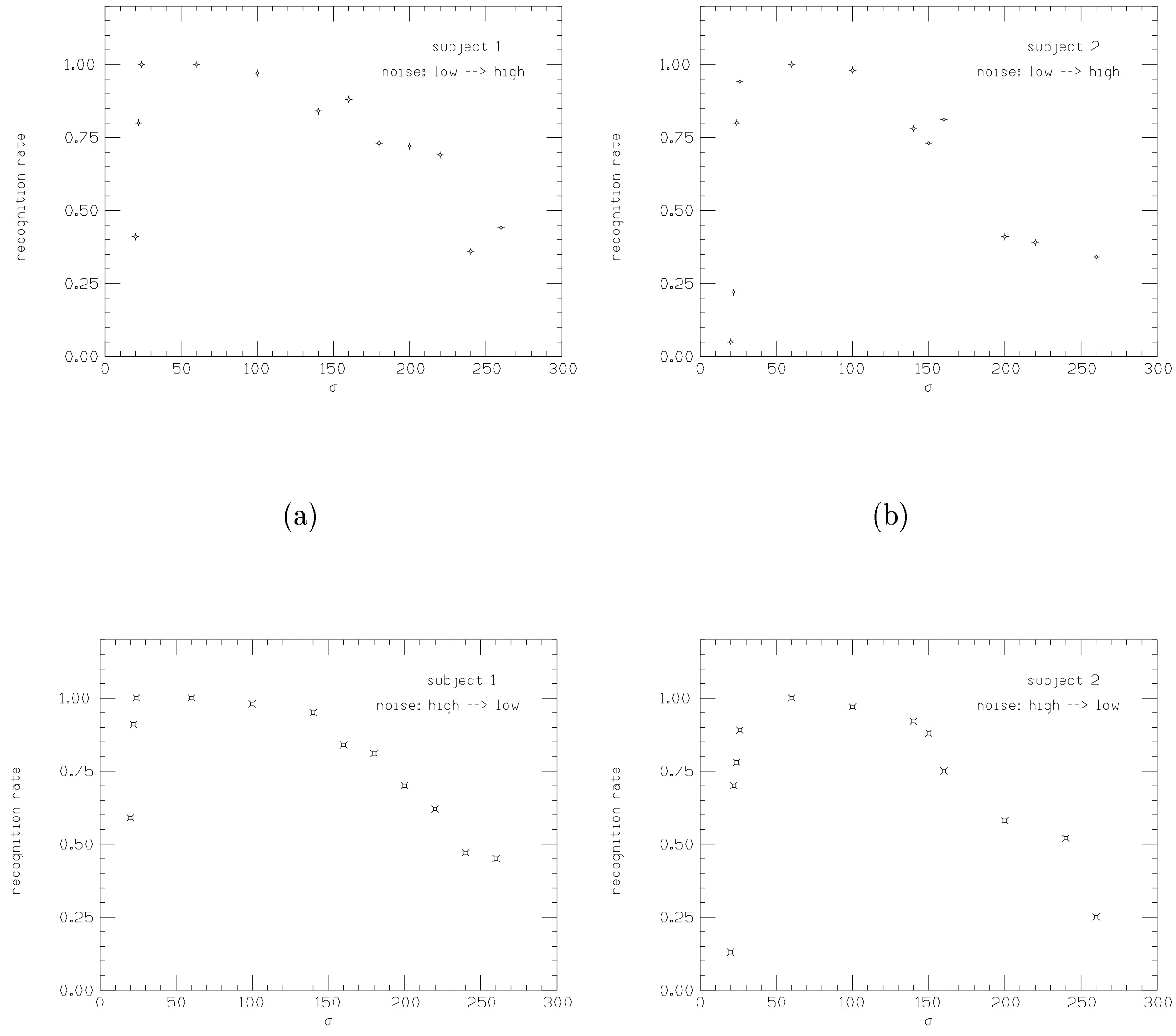


FIG. 3. Results for Experiment II: the recognition rate of the letters is plotted versus the values of the standard deviation of the noise. In (a) and (b) results respectively for subject 1 and subject 2 when the presentation is given from low-level noise to high-level noise. In (c) and (d) results respectively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



(a)

(b)

(c)

(d)

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