INTRINSIC NOISE REGULATES EXTRINSIC NOISE-INDUCED SENSITISATION OF VISUAL PERCEPTION

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Abstract

We provide the first experimental evidence that the intrinsic noise level determines whether extrinsic noise can enhance the detectability of a weak input signal. We conduct a visual detection experiment in the absence and presence of various amounts of random visual noise. We define two indices of extrinsic stochastic resonance effects, consider the spread of the psychometric function without extrinsic noise as an intrinsic noise level index, and find that the indices of extrinsic stochastic resonance effects are negatively correlated with the intrinsic noise index. Our results suggest that extrinsic noise-induced sensitisation depends not only on the extrinsic but also on the intrinsic noise level.

An interesting problem in human perception is how it can be affected by the presence of noise. This question has been addressed by adding noise externally to a signal when performing a signal detection task (Collins et al., 1996, 1997; Simonotto et al., 1997; Zeng et al., 2000; Kitajo et al., 2003; Sasaki et al., 2006, 2007). These studies have revealed that noise can enhance the detectability of an input signal via a mechanism known as stochastic resonance (SR), wherein the addition of an optimal level of noise to a non-linear system enhances its response to an input signal, whereas adding large amounts causes it to deteriorate (for review, see Gammaitoni et al., 1998; Moss et al., 2004). For example, Zeng et al. (2000) reported that the presence of noise produced lower detection thresholds than the absence of noise in an auditory detection task, and Sasaki et al. (2006) showed that the visual contrast detection threshold decreased at an optimal level of noise intensity. However, the SR effects observed in these experiments were small (though significant); the effects were about 4 % in Zeng et al. (2000) and 2 dB in magnitude in Sasaki et al. (2006). Because the SR effects shown in both studies were averaged across subjects, such small effects may indicate that not all of the subjects showed SR effects. In fact, in Kitajo et al. (2003), 6 to 9 out of 19 subjects (depending on the condition) did not show significant SR effects, though the overall SR effects were significant. This therefore raises an important question as to what determines whether a subject shows extrinsic noise induced sensitisation or not.

Most studies on perceptual SR have investigated only the relationship between the perceptual performance and the amount of additional extrinsic noise. However, these studies overlook an important point: there is noise generated by the subject, or intrinsic noise, as well as noise added by the experimenter, or extrinsic noise, and therefore SR effects should depend on the amounts of intrinsic as well as extrinsic noise.

Based on the above idea, we hypothesise that the intrinsic noise level determines whether extrinsic noise induced sensitisation, extrinsic SR, occurs or not (Fig. 1); the lower the intrinsic noise level is, the more likely an optimal level of extrinsic noise is to

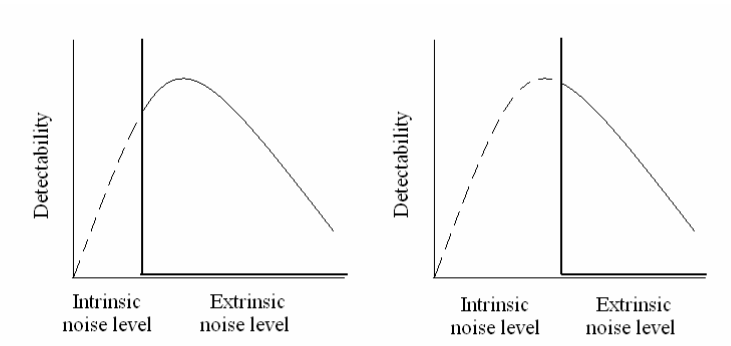

Fig. 1. Illustration of our hypothesis. *Thin axes*: detectability versus noise level (sum of intrinsic and extrinsic noise). *Thick axes*: detectability versus extrinsic noise level. *Left*: extrinsic SR occurs if the intrinsic noise level is low. *Right*: extrinsic SR does not occur if the intrinsic noise level is high.

enhance the detectability of a weak signal, and the higher the intrinsic noise level is, the less likely extrinsic SR is to occur. To our knowledge, only one study (Ward, 2004) suggests a similar idea, but shows no experimental evidence for the idea. Therefore, our main goal in this paper is to test experimentally our hypothesis using a visual detection task (Kitajo et al., 2003).

Method

We conducted a visual detection task using the method of constant stimuli (Gescheider, 1985) to measure psychometric function, the probability of a signal being detected as a function of signal amplitude, for each noise level. Twenty-one adults (20-32 years, 18 males and 3 females) with normal or corrected-to-normal vision gave their informed consent and took part in the experiment. The subjects viewed two images presented on an 18-inch CRT monitor (800×600 resolution; 100 Hz refresh rate) at a distance of 58 cm through a mirror stereoscope (TKK 129, Takei Scientific Instruments; Fig. 2) in a darkened room. The CRT monitor was covered with a neutral density filter (ND 3.0, Fuji Photo Film Co., Ltd., Tokyo). A chin rest maintained the subjects' head position throughout the experiment. The right and left images were squares (250×250 pixels) with spatially uniform grey levels against a dark background and were presented to the right and left eyes, respectively. The grey levels of both the images were spatially uniform but varied temporally (baseline grey level = 128); the grey

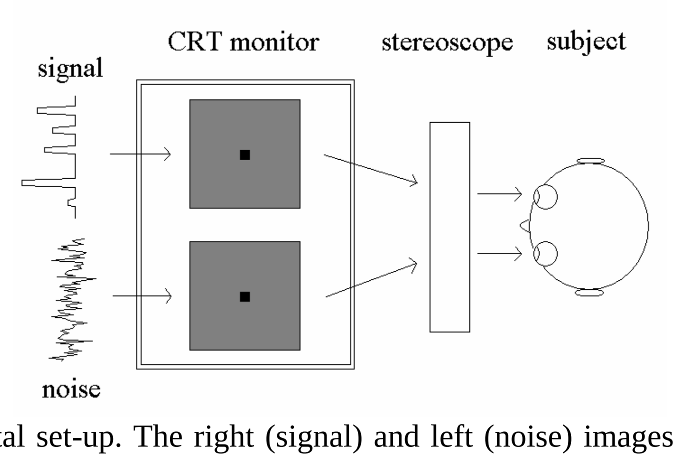

Fig. 2. Experimental set-up. The right (signal) and left (noise) images were presented to the corresponding eyes separately through a mirror stereoscope. In this design, signal and noise first interact in early visual areas.

level of the right image was increased for 1-sec and then decreased to the baseline again once every 2-sec (signal), whereas that of the left image was sampled from a Gaussian distribution with zero mean (noise). The subjects were asked to gaze at fixation points (white 10×10 pixel squares) at the centre of each image and to press a button with their right index finger whenever they detected such a signal in the fused image. The experiments consisted of 25 blocks of 90 trials. Within each block, the noise standard deviation (NSD) of each trial remained constant, whereas the signal amplitude of each trial was randomly sampled from 1 of 6 amplitudes, including amplitude = 0 (no signal). We conducted 5 blocks for each of 5 NSDs, including NSD = 0 (no noise).

We introduce two indices of extrinsic SR effects: amounts of the normalised maximum positive detectability shift ($nPDS$) and the normalised maximum negative threshold shift ($nNTS$). Positive detectability shifts indicate that the presence of certain levels of extrinsic noise produces higher detectabilities than the absence of extrinsic noise. Negative threshold shifts indicate that the presence of certain levels of extrinsic noise produces lower detection thresholds than the absence of extrinsic noise. The normalisation is done because each subject has different estimation errors in both detectability and threshold. In this paper, the threshold is defined as the signal amplitude when the probability of a signal being detected is 0.5, whereas the detectability is defined as the probability of a signal being detected when the signal amplitude is the threshold value obtained without extrinsic noise. The calculation of these indices for each subject is conducted as follows.

First, we estimate psychometric function $P_i(x)$ by fitting the cumulative Gaussian function for each noise level:

$$P_i(x) = \frac{1}{\sqrt{2\pi}S_i}\int_{-\infty}^{x} \exp\left[-\frac{(y-T_i)^2}{2S_i^{\,2}}\right]dy \qquad (1),$$

where x is the signal amplitude, T_i is the threshold (mean of the Gaussian distribution), S_i is the spread (SD of the Gaussian distribution), and the subscript i indicates i'th smallest NSD (subscript 1 indicates NSD=0). Thus, the form of psychometric function is characterised by the two parameters; T_i and S_i . By estimating the psychometric functions, we obtain the detectability $D_i (= P_i(T_i))$ for each NSD, and the degree of the maximum positive detectability shift (PDS) and the maximum negative threshold shift (NTS):

$$PDS = \max(D_i) - D_1 = \max\{P_i(T_1)\} - P_1(T_1) \qquad (2),$$

$$NTS = T_1 - \min(T_i) \qquad (3).$$

Next, we perform 2,000 Monte Carlo simulations to assess the estimation errors in both detectability and threshold for each subject. In these simulations, a true psychometric function is set to be the psychometric function obtained by a real psychophysical experiment without extrinsic noise. From the simulation results, we obtain SD's of both detectability (SD_D) and threshold (SD_T) from all 2,000 simulated psychometric functions. We then normalise both PDS and NTS by SD_D and SD_T , respectively:

$$nPDS = \frac{PDS}{SD_D} \qquad (4),$$

$$nNTS = \frac{NTS}{SD_T} \qquad (5).$$

We cannot measure the intrinsic noise level directly, but instead can measure the spread S_1 of the psychometric function obtained without extrinsic noise. We thus regard S_1 as an estimate of the intrinsic noise level, because the spread of the psychometric function is considered to reflect the level of noise, i.e. the total amount of intrinsic and extrinsic noise (Macmillan and Creelman, 2005; Gescheider, 1985; Hecht et al., 1942).

To test the dependency of the extrinsic SR effects on the internal noise level, we calculate Spearman rank correlation coefficients between $nPDS$ and S_1 and between $nNTS$ and S_1.

Results and Discussion

We removed the data for one subject from the analysis because even the probability of the largest signal being detected was far less than 0.5 for every NSD. Thus, we analysed the data for the remaining 20 subjects.

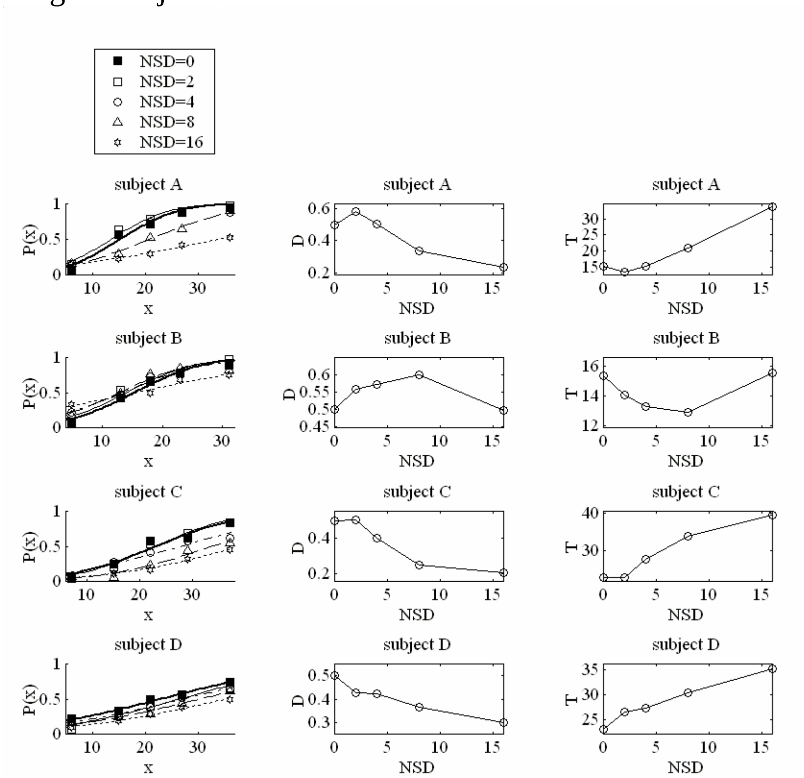

Fig. 3. Effects of extrinsic noise level on the detection performances in four representative subjects. Each row corresponds to one subject. *Left column*: the signal amplitude x versus detection probability $P(x)$. The markers are for real data and the lines are the fitted psychometric functions (NSD=0: black squares and thick solid lines, NSD=2: white squares and thin solid lines, NSD=4: white circles and dash-dot lines, NSD=8: white triangles and dashed lines, NSD=16: white hexagrams and dotted lines). *Middle column*: NSD versus detectability D. *Right column*: NSD versus threshold T.

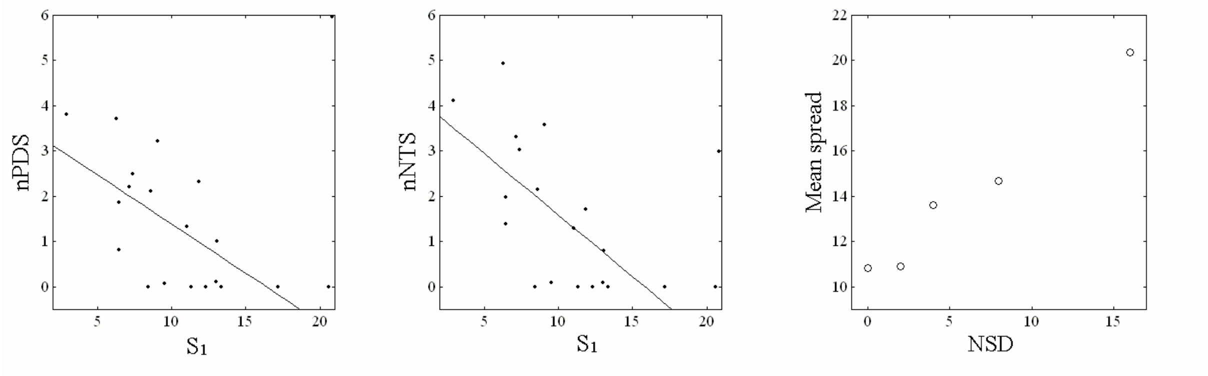

Fig. 4. *Left*: S_1 versus $nPDS$. Each subject contributes one point. *Middle*: S_1 versus $nNTS$. *Right*: NSD versus the spread averaged over subjects.

Fig. 3 shows the effects of the extrinsic noise level on the detection performances in four representative subjects. Subjects A and B clearly show extrinsic SR effects, increased detectabilities and decreased thresholds at certain levels of extrinsic noise (NSD=2 and NSD=8, respectively). In subject C, the performances are slightly improved at NSD=2, but these extrinsic SR effects are fairly small. In contrast, subject D shows no extrinsic SR effects; the higher the extrinsic noise level is, the poorer the performances are.

Our main findings are shown in the left and middle panels of Fig.4. These panels show scatter plots of S_1 (intrinsic noise level index) versus $nPDS$ and $nNTS$ (extrinsic SR effect indices), respectively. S_1 has significant negative correlations with both $nPDS$ (Spearman rank correlation coefficients r_s=-0.4494; $p<0.05$) and $nNTS$ (r_s=-0.6046; $p<0.01$). These results support our hypothesis that the extrinsic SR effects are determined by the intrinsic noise level; the lower the intrinsic noise level is, the more likely an optimal level of extrinsic noise is to enhance the detectability of a weak visual signal, and the higher the intrinsic noise level is, the less extrinsic SR occurs (Fig. 1).

This conclusion is based on our premise that S_1 reflects the amount of intrinsic noise. To test the validity of this premise, we investigate the relationship between the extrinsic noise level and the corresponding spread. The spread averaged over all subjects is a monotonically increasing function of the extrinsic noise levels (Fig. 4, *right panel*; ANOVA, $p<0.01$), suggesting that the spread reflects the total amount of intrinsic and extrinsic noise, and therefore, the spread obtained without extrinsic noise, S_1, can be regarded as reflecting the amount of intrinsic noise.

According to our hypothesis, there is a possibility that an intrinsic noise level is already optimal for SR in some people. In fact there are some papers which suggest the presence of intrinsic SR (Linkenkaer-Hansen et al., 2004; Ho and Destexhe, 2000), although the measure of the intrinsic noise level in these studies is qualitatively different from ours. For example, Linkenkaer-Hansen et al. (2004) found that psychophysical performance in humans is enhanced at an optimal level of background EEG activity. It would be intriguing further to hypothesise that the intrinsic noise may be caused by brain activity. The relationship between the spread of psychometric function and background brain activity should thus be studied in the future.

In conclusion, our results suggest that the extrinsic SR effects depend not only on extrinsic but also on intrinsic noise levels, and our hypothesis can account for the subject-to-subject variability in extrinsic SR effects. This implies that humans with a lesser degree of uncertainty in visual detection tasks can benefit more from adding visual uncertainty (noise) externally. Such a "counter-intuitive" finding deserves further investigation into the mechanism and is also of great significance in designing new types of human interface devices.

Acknowledgements

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