Vision Research 48 (2008) 1569–1573

Contents lists available at ScienceDirect

Vision Research

journal homepage: www.elsevier.com/locate/visres

Internal noise determines external stochastic resonance in visual perception

Takatsugu Aihara [a], Keiichi Kitajo [a,b], Daichi Nozaki [a], Yoshiharu Yamamoto [a,*]

[a] *Educational Physiology Laboratory, Graduate School of Education, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan*
[b] *Laboratory for Dynamics of Emergent Intelligence, RIKEN Brain Science Institute, Wako, Saitama 351-0198, Japan*

ARTICLE INFO

Article history:
Received 13 October 2007
Received in revised form 11 April 2008

Keywords:
Stochastic resonance
Internal noise
Psychometric function
Visual detection

ABSTRACT

We provide the first experimental evidence that the internal noise level determines whether external noise can enhance the detectability of a weak signal. We conduct a visual detection experiment in the absence and presence of visual noise. We define three indices of external stochastic resonance effects, consider the spread of the psychometric function without external noise as an internal noise level index, and find that the indices of external stochastic resonance effects negatively correlate with the internal noise level index. Our results suggest that external stochastic resonance depends not only on the external but also on the internal noise level.

1. Introduction

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, Imhoff, & Grigg, 1996; Collins, Imhoff, & Grigg, 1997; Kitajo et al., 2007; Kitajo, Nozaki, Ward, & Yamamoto, 2003; Kitajo, Yamanaka, Ward, & Yamamoto, 2006; Manjarrez, Mendez, Martinez, Flores, & Mirasso, 2007; Sasaki et al., 2006; Simonotto et al., 1997; Zeng, Fu, & Morse, 2000). These studies have revealed that noise can enhance the detectability of an input signal via a certain mechanism. This mechanism is so-called stochastic resonance (SR), wherein the addition of an optimal level of noise to a nonlinear system enhances its response to an input signal, whereas adding large amounts causes it to deteriorate (for review, see Gammaitoni, Hänggi, Jung, & Marchesoni, 1998; Moss, Ward, & Sannita, 2004). For example, it has been reported that the noise contributes to lower detection thresholds in an auditory detection task (Zeng et al., 2000) and in a visual contrast detection task (Sasaki et al., 2006). However, the SR effects observed in these experiments are small (though significant); the effects are 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 are averaged across observers, such small effects may indicate that not all of the observers show SR effects. In fact, in Kitajo et al. (2003), though the overall SR effects were significant, the statistical test performed for each observer demonstrated that 6–9 out of 19 observers (depending on the conditions) did not reach a statistically significant level. This raises an important question as to what determines whether an observer shows external noise-induced sensitization or not.

Most studies on perceptual SR have investigated only the relationship between the perceptual performance and the amount of additional external noise. However, these studies overlook the important point that the perceptual system has a substantial amount of internal noise even when the external noise is absent. The SR effect therefore should depend on the amounts of internal as well as external noise.

Based on the above idea, we hypothesize that the internal noise level determines whether external noise-induced sensitization, external SR, occurs or not; the smaller the internal noise level, the larger the external SR effect. To our knowledge, only one study (Ward, 2004) has suggested 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.

Because we are interested in the effect of *internal* noise on external noise-induced sensitization of weak signal detection, it is desirable to adopt an experimental design where external noise and signals interact *within* the brain. If one uses the single receptor design where external noise and signals are presented to the same eye, external noise and signals first interact in the retina and potentially continue to interact throughout the peripheral visual system. We, therefore, use the double receptor design (Kitajo et al., 2007, 2003, 2006; Mori & Kai, 2002) where external noise and signals were presented to separate eyes. This design guarantees that the random neural activity caused by external visual noise interacts within the central brain with the neural activity caused by visual signals, because both noise and signals from the two eyes first converge in early visual cortex (areas V1 and V2).

* Corresponding author.
E-mail address: yamamoto@p.u-tokyo.ac.jp (Y. Yamamoto).

0042-6989/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.visres.2008.04.022

2. Methods

2.1. Visual detection task

Twenty-one adults (20–32 years, 18 males and 3 females) with normal or corrected-to-normal vision gave their informed written consent and participated in the experiment. The experiment was approved by the ethics committee of the Graduate School of Education, The University of Tokyo.

The observers viewed two images on an 18-in. 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. 1) in a darkened room. The stereoscope was used to fuse the two images, each of which was separately presented to the left and the right eye. The CRT monitor was covered with a neutral density filter (ND 3.0, Fuji Photo Film Co., Ltd., Tokyo). A chin rest maintained the observers' head position throughout the experiment. The images were squares (250 × 250 pixels) with spatially uniform gray levels (0–255; luminance 0.002–0.031 cd/m^2) against a dark background (background gray level = 110). There was a fixation point (white 10 × 10 pixel square; gray level = 255) at the center of each image. The gray levels of the images varied temporally; the gray level of the right image was increased for 1 s and then decreased to the baseline (baseline gray level = 128) again once every 2 s, and this served as the signal. Six different signal amplitudes, including no signal, were used [*s*0, *s*1, *s*2, *s*3, *s*4, *s*5 (*s*0 indicates no signal)]. The signal amplitudes were different for each observer. The amplitude *s*3 was the threshold in an external noise free condition, estimated from a preliminary experiment with an adaptive procedure. On the other hand, the gray level of the left image was set to a random variable on each frame (100 Hz frame rate) which was sampled from the Gaussian distribution (mean gray level = 128), and this served as noise. Five different noise levels, including no noise, [noise standard deviations (NSD) = 0, 2, 4, 8, 16] were used.

The observers were asked to press a button with their right index finger when they detected the signal in the fused image. Within each experimental block consisting of 90 trials, the NSD was kept constant, whereas the signal amplitude of each trial was randomly set to a value out of 6 values, including no signal. The noise level was randomly varied across blocks, and the order of block presentation was counterbalanced across observers. In total, 25 blocks were conducted for each observer (5 blocks for each of the 5 levels of NSD, including the no noise condition).

2.2. Estimation of psychometric function

We estimated the psychometric function for each noise level in order to estimate the spread (inverse slope), threshold and hit rate which are used for later analysis. First, the hit rate was calculated for each signal and noise level. Then, the psychometric function $P_i(x)$ was estimated by fitting the cumulative Gaussian function to the hit rate for each noise level i ($i = 0$ indicates NSD = 0) using the least square method:

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

where x is the signal amplitude, T_i is a threshold parameter and S_i is a spread parameter. T_i and S_i correspond to the mean and SD of the Gaussian distribution, respectively. The T_i represents a signal amplitude when the hit rate is 0.5. The S_i has conventionally been assumed to reflect fluctuations in the decision variable or the decision criterion or both (Macmillan & Creelman, 2005; Wickelgren, 1968).

2.3. Evaluation of internal noise level

We measured noise as fluctuations in behavior and assumed that the spread (S_i) reflects the level of noise. Note that the internal noise is defined as any fluctuations in the absence of externally added noise. We then used S_0 (the spread obtained without external noise) as an estimate of the internal noise level of each observer. If such an assumption is valid, the value of S_i will increase with the level of external noise because the fluctuations in the decision variable are assumed to increase with the level of external noise (Gong, Matthews, & Qian, 2002); we will test this later.

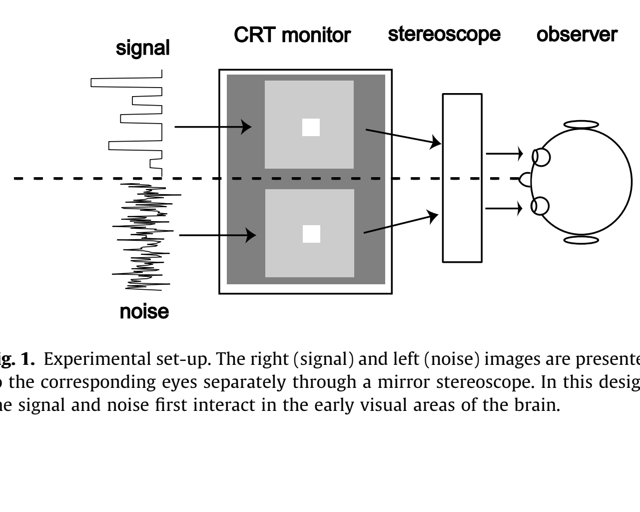

Fig. 1. Experimental set-up. The right (signal) and left (noise) images are presented to the corresponding eyes separately through a mirror stereoscope. In this design, the signal and noise first interact in the early visual areas of the brain.

2.4. Evaluation of SR effect

The presence of perceptual SR has been assessed with some of the three measures: the detection threshold (e.g., Sasaki et al., 2006; Zeng et al., 2000), a classical detectability measure such as percent correct (e.g., Collins et al., 1996, 1997; Manjarrez et al., 2007), and the signal detection theory measure d' (e.g., Kitajo et al., 2007, 2003, 2006). Accordingly, we introduced the following three indices to evaluate the magnitude of external SR effects.

First, we used the detection threshold. That the detection threshold shifts negatively in the presence of certain levels of external noise is a characteristic of external SR. We therefore defined the first index as the amount of the maximum negative threshold shift (hereafter referred to simply as the threshold shift):

$$\text{threshold shift} = T_0 - \min_i(T_i). \quad (2)$$

Second, we used the hit rate at the threshold obtained without external noise, $P_i(T_0)$. That the hit rate shifts positively in the presence of certain levels of external noise is a characteristic of external SR. We therefore defined the second index as the amount of the maximum positive hit rate shift (hereafter referred to simply as the hit rate shift):

$$\text{hit rate shift} = \max_i\{P_i(T_0)\} - P_0(T_0), \quad (3)$$

Third, we used the signal detection theory measure d'. Unlike the threshold and hit rate, the d' reflects only the observer's sensitivity and is not susceptible to the shift of the decision criterion. The d' is defined as:

$$d' = z(\text{HR}) - z(\text{FA}), \quad (4)$$

where $z(\cdot)$ is the functional inverse of the standard Gaussian cumulative distribution function, HR is the hit rate, and FA is the false alarm rate (Gescheider, 1985; Macmillan & Creelman, 2005). According to this definition, we calculated the d' for each signal and noise level. Because SR does not occur when the signal is suprathreshold, we used the d' at *s*1,*s*2 and *s*3 where the signal amplitudes were smaller or equal to the threshold estimated from the preliminary experiment. That the d' shifts positively in the presence of certain levels of external noise is a characteristic of external SR. We therefore defined the third index (hereafter referred to as the d' shift) as:

$$d'\text{shift} = \max_i\left[\frac{1}{3}\sum_{x=s1,s2,s3}\{d'(x,i) - d'(x,0)\}\right], \quad (5)$$

where $d'(x,i)$ indicates the d' at the signal level x and noise level i.

In all the three indices of external SR effects, a larger value indicates a larger external SR effect, and the zero value indicates the absence of external SR effects. To test the dependency of the external SR effects on the internal noise level, we calculated Spearman rank correlation coefficients between the internal noise level index S_0 and the above three indices.

3. Results

We eliminated the data for one observer from the analysis because the hit rate was too low to estimate the psychometric function accurately; even the probability of the largest signal being detected was far less than 0.5 for every NSD. In the remaining 20 observers, the probability of the largest signal being detected was larger than 0.5 for every NSD, and the psychometric function for each NSD was a monotonically increasing function well fitted by the cumulative Gaussian function.

Fig. 2 shows the effects of the external noise level on the detection performances in four representative observers. Observers A and B clearly show external SR effects, decreased thresholds, increased hit rates and increased d' at certain levels of external noise. In observer A, the optimal level of external noise was the same (NSD = 2) for all three measures. In observer B, on the other hand, the optimal level of external noise was different across the measures; it was NSD = 8 for both the threshold and hit rate but it was NSD = 2 for the d'. In observer C, the performances are slightly improved, but these external SR effects are fairly small. By contrast, observer D shows no external SR effects; the performance deteriorates with the level of the external noise.