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Internal noise determines external stochastic resonance in visual perception

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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).

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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 [$s0$, $s1$, $s2$, $s3$, $s4$, $s5$ ($s0$ indicates no signal)]. The signal amplitudes were different for each observer. The amplitude $s3$ 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:

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

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.

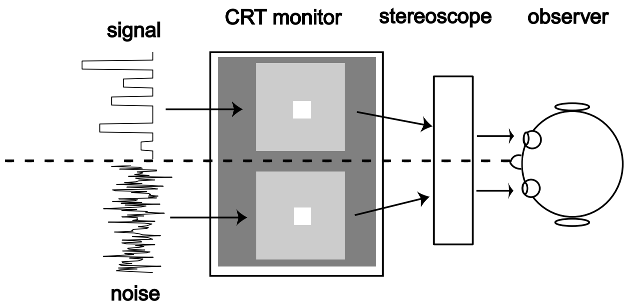

Fig. 1. Experimental set-up. The right (signal) and left (noise) images are presented to the corresponding eyes separately through a mirror stereoscope. In this design, the signal and noise first interact in the early visual areas of the brain.

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):

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

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):

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

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:

$$d' = z(\mathrm{HR}) - z(\mathrm{FA}), \tag{4}$$

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 $s1$,$s2$ and $s3$ 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:

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

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.

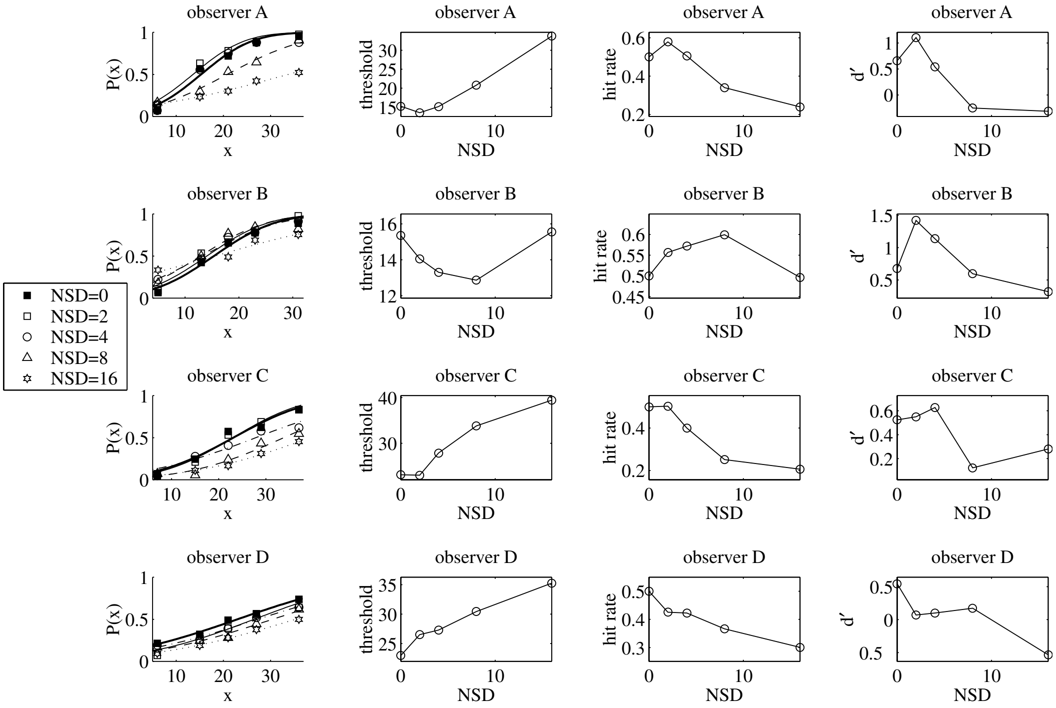

Fig. 2. Effects of external noise level on the detection performances in four representative observers. Each row corresponds to one observer. The first column: the signal amplitude x versus hit rate $P(x)$. The markers are for real data and the lines are the fitted psychometric functions (NSD = 0, black 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). The second column: NSD versus threshold T_i. The third column: NSD versus hit rate $P_i(T_0)$. The fourth column: NSD versus averaged signal detection theory measure $\overline{d'}\left(=\frac{1}{3}\sum_{x=s1,s2,s3} d'(x,i)\right)$.

For one observer, the hit rate shift was 0.168 for NSD = 2, and this increase in the hit rate was equivalent to a situation where the signal amplitude was increased by 9.045 from the threshold for the no external noise condition. This value is unrealistically large and may have been due to an error in estimating the psychometric function. Indeed, in the other observers, the signal amplitude to accomplish their hit rate shifts was 2.278 at most. Hence, the data of this observer was eliminated from the following analysis.

To test our hypothesis, we examined the relationship between external SR effects and the internal noise level. Fig. 3A–C, show scatter plots of S_0 (internal noise level index) versus the threshold, hit rate and d' shifts (external SR effect indices), respectively. The S_0 had significant negative correlations with the threshold (Spearman rank correlation coefficient $r_s = -0.589$; $p < 0.01$), hit rate ($r_s = -0.655$; $p < 0.01$) and d' shifts ($r_s = -0.591$; $p < 0.01$). These results support our hypothesis that the external SR effect is larger for observers whose internal noise level is smaller.

To test the validity of our assumption that the spread of the psychometric function (S_i) reflects the total amount of internal and external noise, we investigated the relationship between the external noise level and the corresponding spread. A one-way ANOVA revealed that the spread changed significantly across external noise levels [$F(4,90) = 3.891$; $p < 0.01$]. The spread averaged over all observers yields a positive slope when fitted with a linear regression line (Fig. 3D, slope = 0.487). Thus, the spread is a monotonically increasing function of external noise levels, suggesting that the spread reflects the total amount of internal and external noise and that S_0 can therefore be regarded as reflecting the amount of internal noise.

Finally, the threshold obtained without external noise (T_0) has significant negative correlations with the threshold (Fig. 4A, $r_s = -0.496$; $p < 0.05$), hit rate (Fig. 4B, $r_s = -0.607$; $p < 0.01$) and d' shifts (Fig. 4C, $r_s = -0.745$; $p < 0.01$). In addition, the T_0 has a strong positive correlation with the S_0 (Fig. 4D, Pearson correlation coefficient $r = 0.739$; $p < 0.001$).

4. Discussion

In this study, we address the question of what determines whether an observer shows external noise-induced sensitization or not. The main finding of the present study is that the spread of the psychometric function obtained without external noise (S_0) is negatively correlated with external SR effects (the threshold, hit rate and d' shifts; Fig. 3A–C). This finding strongly supports our hypothesis that the level of internal noise determines whether external SR occurs or not; the lower the internal noise level, the larger the external SR effect. Although this is based on our assumption that the spread obtained without external noise reflects the amount of internal noise, the validity of this assumption *per se* is supported by our additional finding that the spread averaged over all observers is a monotonically increasing function of external noise levels (Fig. 3D), suggesting that the intercept at NSD = 0 reflects a degree of internal uncertainty (noise) of the observers.

Chapeau-Blondeau and Godivier (1997) proposed a theory of SR by static nonlinear systems. They numerically examined the case where an input–output transformation has a smooth nonlinearity with a sigmoidal form (logistic function):

$$g(u) = \frac{1}{1+\exp[-(u-\theta)/\lambda]},$$

where u is the input, $g(u)$ is the output, θ is a threshold parameter, and λ is a spread parameter. As λ approaches zero, the nonlinearity $g(u)$ resembles the Heaviside function, and therefore SR occurs in the output signal-to-noise ratio (SNR); as λ becomes greater, $g(u)$ approaches a linear function, and therefore SR does not occur in

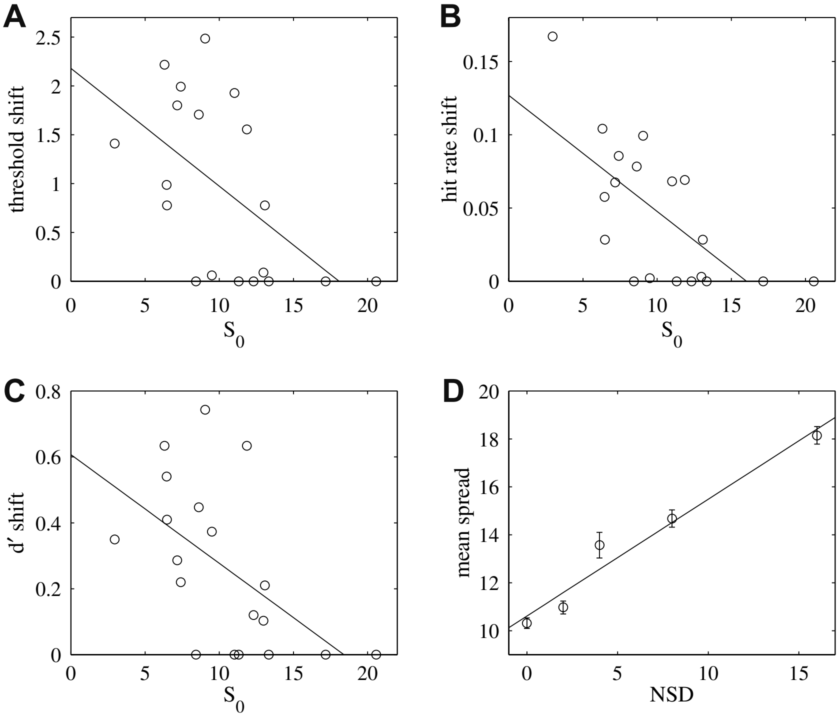

Fig. 3. (A) S_0 versus the threshold shift. Each observer contributes one point. (B) S_0 versus the hit rate shift. (C) S_0 versus the d' shift. (D) NSD versus S_i averaged over observers. Error bar indicates the standard error.

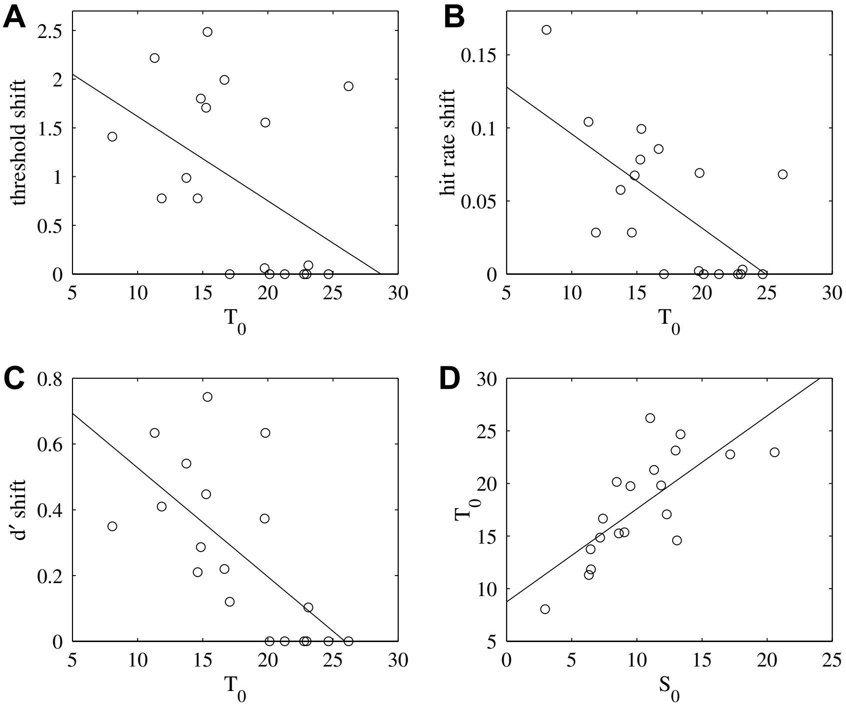

Fig. 4. (A) T_0 versus the threshold shift. Each observer contributes one point. (B) T_0 versus the hit rate shift. (C) T_0 versus the d' shift. (D) S_0 versus T_0.

the output SNR. Furthermore, Ward, Neiman, and Moss (2002) also obtained similar results in another measure closely related to a measure of signal detectability (d'). Given that the psychometric function can be regarded as the input–output transformation function, these theories are consistent with our observations in the sense that the smaller spread causes the larger SR effect. However, these theories fail to explain our observations completely; the threshold changes with noise in our observations, but the threshold is fixed in these theories.

Wannamaker, Lipshitz, and Vanderkooy (2000) also investigated various static nonlinear systems in the context of the dithering effect. They analyzed arbitrary static nonlinearities and computed dither-averaged input–output transfer characteristics. Their theory is consistent with our observations in the sense that the slope of the transfer characteristics, which may correspond to the psychometric function in our case, becomes shallower as the dithering amplitude (i.e., the noise level) increases. Furthermore, these authors showed that a threshold shift is an expected consequence of the presence of the dithering at the input to a hysteretic quantizer. However, the threshold shift observed in our experiments, with the threshold being a concave function of the external noise level, is qualitatively different from theirs. We, therefore, consider that their theory is not an exclusive explanation of the current observations.

Theoretical (Jung, 1994) and experimental (Collins et al., 1997; Manjarrez et al., 2007) studies have shown that the level of signal determines whether external noise-induced sensitization occurs or not; external noise-induced sensitization occurs if the signal is subthreshold, and the sensitization does not occur if the signal is suprathreshold. This evidence may provide another explanation for the observer-to-observer variability in external SR effects. However, this explanation fails to account for the observations of Kitajo et al. Kitajo et al. (2003) and of this study that some observers do not show external noise-induced sensitization while a signal is subthreshold.

Thus, the most plausible explanation for our observations seems, at this point, to be the hypothesis we have put forward. According to our hypothesis, there is a possibility that the internal noise level is already optimal for SR in some observers. In fact, there are papers which have suggested the presence of internal SR (Hô & Destexhe, 2000; Linkenkaer-Hansen, Nikulin, Palva, Ilmoniemi, & Palva, 2004; Stocks & Manella, 2001), although the measure of the internal noise level in these studies is qualitatively different from ours. For example, Linkenkaer-Hansen et al. (2004) found that, for pre-stimulus electro-encephalogram (EEG) oscillations at 10, 20 and 40 Hz detected over the sensorimotor cortex, intermediate amplitudes are associated with the highest probability of conscious detection and the shortest reaction times. They suggested that ongoing oscillations may optimize the processing of sensory stimuli with the same mechanism as noise sources in SR. It would be intriguing further to hypothesize that the variability of the response (noise) may be caused by ongoing brain activity. The relationship between the spread of the psychometric function and ongoing brain activity should therefore be studied in the future.

Recently, Kitajo et al. (2007) found that both the detection of weak visual signals and the phase synchronization of EEG signals from widely-separated areas of the human brain are increased by the addition of weak visual noise, implying that noise-induced large-scale neural synchronization may be responsible for behavioral SR. This, combined with our hypothesis, leads to a prediction that an observer with large internal noise should not show noise-induced large-scale neural synchronization and therefore should not show behavioral SR. Thus, we should study this prediction in the future.

In our experiments, the threshold obtained without external noise (T_0) is negatively correlated with external SR effects (the threshold, hit rate and d' shifts; Fig. 4A–C). This may be due to a strong correlation between the spread and threshold obtained without external noise (Fig. 4D), which seems to be natural because scale-invariance is ubiquitous in psychophysics (Gescheider, 1985; Gibbon, Malapani, Dale, & Gallistel, 1997). Therefore, we consider that this is just an epiphenomenon of the negative correlations between the spread obtained without external noise and external SR effects.

In conclusion, our results suggest that the external SR effects depend on internal noise levels. This idea can account for the observer-to-observer variability in external SR effects and 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.

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