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Enhanced corticomuscular coherence by external stochastic noise

Abbreviated title: Stochastic resonance and increased corticomuscular coherence

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Abstract

Noise can have beneficial effects as shown by the stochastic resonance phenomenon which is characterized by performance improvement when an optimal noise is added. Modern attempts to improve human performance utilize this phenomenon. The purpose of the present study was to investigate whether performance improvement by addition of optimum noise is related to increased cortical motor spectral power and increased corticomuscular coherence. Eight subjects performed a visuomotor task requiring to compensate with the right index finger a static force generated by a manipulandum on which Gaussian noise was applied. The finger position was displayed on-line on a monitor as a small white dot which the subjects had to maintain in the center of a green bigger circle. Electroencephalogram from the contralateral motor area, electromyogram from active muscles and finger position were recorded. The performance was measured by the mean absolute deviation of the white dot from the zero position. Optimum noise compared to the zero noise condition induced an improvement in motor accuracy together with an enhancement of cortical motor spectral power and corticomuscular coherence in beta-range. These data suggest that the improved sensorimotor performance via stochastic resonance is consistent with an increase in the cortical motor spectral power and in the corticomuscular coherence.

Keywords: noise, corticomuscular coherence, stochastic resonance, finger, motor, force, humans

Introduction

Stochastic resonance (SR) is a phenomenon in non-linear systems in which an intermediate level of Gaussian noise enhances the response to weak signals (cf. reviews by Wiesenfeld and Moss, 1995; Gammaitoni et al., 1998; Moss et al., 2004; McDonnell and Abbott, 2009; McDonnell and Ward, 2011; Faisal et al., 2008; Ermentrout et al., 2008; Aihara et al., 2010). The signature of the SR phenomenon is an inverted U-curve with best performance for the intermediate level of noise called optimum noise (ON). In the nervous system SR has been studied in sensory, motor, and sensorimotor systems. The first demonstration of this phenomenon in sensory systems was by Douglass et al. (1993) in the crayfish mechanoreceptors. The first demonstration of SR in the motor system was given by Martinez et al. (2007) at the spinal level. The SR phenomenon has also received considerable attention in sensorimotor control, in particular in balance (Priplata et al., 2002, 2006, Collins et al., 2003; Harry et al., 2005; Costa et al., 2007; Galica et al., 2009; Magalhaes and Kohn, 2011; Mulavara et al., 2011) and force control Mendez-Balbuena et al., 2012; Trenado et al., 2014). Recent studies have also shown the application of SR in improving the finger’s tactile sensitivity in healthy subjects and stroke patients (Kurita et al., 2013; Enders et al., 2013).

The phenomenon of enhanced coherence produced by optimal noise has been also described in theoretical models of neurons (Pikovsky and Kurths, 1997; Neiman et al., 1997; Casado, 1997; Lee et al., 1998; Wang et al., 2000; Zhong and Xin, 2000; Gao and Wang, 2012; Franović et al., 2012; Men et al., 2012; Guo and Li, 2009; Jiang and Ma, 2009; Li and Gao, 2008; Torcini et al., 2007; Kreuz et al., 2006; McMillen and Kopell, 2003) and experimentally in physical systems (Lih et al., 1998; Postnov et al., 1998; Giacomelli et al., 2000; Calvo et al., 2001; Perc, 2007; Perc et al., 2008; Ermentrout et al., 2008; Wang et al., 2010; Zhong and Xin, 2000, 2001a, b; Zhong et al., 2001c; Kortlüke et al., 2002; Li and Li, 2003, 2004a,b; Li and Li, 2004; 2006a,b; Xin and Hou, 2006; Li et al., 2008; Shi and Luo,
SR is related to increased local (within one area) and long-range (between different areas) synchrony. In 2002 we demonstrated for the first time that the central nervous system exhibits internal stochastic resonance (Manjarrez et al. 2002). We found in anesthetized cats that the coherence between spinal and cortical somatosensory neurons can be enhanced by the application of a particular level of tactile noise, thus suggesting that spinal and cortical neurons are activated with more synchrony during the noisy tactile sensation. Increased synchrony with SR had also been described by other authors (Kitajo et al., 2003, 2004, 2007; Ward et al., 2006). But what are the neural mechanisms of this phenomenon in the sensorimotor system? Psychophysical studies (Priplata et al., 2002, 2006; Harry et al., 2005; Galica et al., 2009; Costa et al., 2007; Magalhaes and Kohn, 2011; Mulavara et al., 2011) provided evidence that mechanical noise applied to the feet via vibrating insoles and stochastic electrical stimulation applied of the vestibular organs the vestibular system improved balance in standing position. We recently reported the improvement of precision in force control when an optimum Gaussian noise was added to the manipulandum (Mendez-Balbuena et al., 2012; Trenado et al., 2014). In these two psychophysical experiments the motor task mainly involved the metacarpophalangeal joint of the right index finger, requiring the pseudo-isometric compensation of a low static force. In Trenado et al. (2014) we even demonstrated that broad-band 0-300 Hz Gaussian noise is most effective in improving sensorimotor performance and is most pleasant. We suggested the existence of stronger interaction between internal stochastic resonance and the externally applied noise when the noise frequency bandwidth includes the frequencies for which the Pacinian receptors are most sensitive. This suggestion was based on Aihara et al. (2010) who had hypothesized that the optimization of the performance by externally applied noise is related to the interaction between externally applied noise and the internal noise of the system. In fact, in the nervous system internal noise exists from the molecular to the behavioral level (Faisal et al. 2008). The visuomotor task used in our two studies has the advantage that the motor task is less complex than balance and gait, and is well understood in terms of its oscillatory motor activity (Kristeva-Feige et al., 1993; Omlor et al., 2007; Andrykiewicz et al., 2007; Kristeva et al., 2007; Mendez-Balbuena et al., 2012). Several other groups also showed that static force compensation is accompanied by beta-range corticospinal synchronization measured by beta-range corticomuscular coherence (CMC) (Murthy and Fetz, 1992; Sanes and Donoghue, 1993; Conway et al., 1995; Murthy and Fetz, 1996a, b; Baker et al., 1997; Salenius et al., 1997; Halliday et al., 1998; Brown, 2000; Gross et al., 2000; Baker and Baker, 2003; Baker et al., 2006; Perez et al., 2006; Riddle and Baker, 2006; Tecchio et al., 2006; Cheyne et al., 2008; Bressler, 2009; Engel and Fries, 2010; Houweling et al., 2010; Witham et al., 2010). Therefore, combining our psychophysical SR paradigm with electroencephalographic (EEG) and electromyographic (EMG) recordings should give insight in understanding the neuronal basis of the SR in the sensorimotor system. To this aim we designed an experiment in which we compared motor performance, cortical spectral power (SP) over the motor cortex and corticomuscular coherence (CMC) in an experimental condition with a broad-band 0-300 Hz Gaussian noise added to the finger manipulandum with another without noise. Based on our earlier finding about a highest signal-to noise ratio in the somatosensory evoked potentials with ON elicited by a mechanical tactile stimulus we predicted a stronger cortical motor synchrony, reflected in higher cortical motor SP with optimum noise than without...
Synchronous discharge of neurons in the primary motor cortex (Allum et al., 1982; Hatsopoulos et al., 1998) may be more effective in driving spinal motoneurons. Subsequently, Baker et al. (1999) showed that the high beta-range cortical SP was related to a strong corticospinal drive, i.e. to higher CMC. Further, we and others found that higher beta-SP and CMC correlated with better motor performance (Kristeva et al., 2007; Mendez-Balbuena et al., 2012; Pogosyan et al., 2009). Therefore, we expected that the noise condition will be associated with higher beta-range SP and CMC than the condition without noise. This prediction would also be in line with studies showing that optimum noise is characterized by higher local (within an area) and long-range (between areas) synchrony (Kitajo et al., 2003, 2004, 2007; Ward et al., 2006). The findings confirmed our predictions. The improved motor performance with optimum noise was related to higher cortical motor SP and to higher corticomuscular coherence (CMC).

Materials and Methods

Subjects

Eight healthy right-handed subjects (8 females, mean age 30.5 ± 14.35 years) without any history of neurological disease took part in the study. The handedness was assessed with the Oldfield questionnaire (Oldfield 1971). All subjects had previously participated in similar experiments before. All subjects participated according to the declaration of Helsinki from 1964, with informed consent and approval of the local ethics committee.

Experimental paradigm

Paradigm

During the experiment, the subject sat in an electrically shielded, dimly lit room. The right arm was supported by a splint and the subject was instructed to place the right hand over a sphere and the index finger in the ring of a home-made manipulandum (see Fig. 1A).

(Please insert Figure 1 about here)

We employed the same manipulandum as in Trenado et al. (2014). The manipulandum was designed to produce a vertical force in the upward direction on the ring. The subject had to compensate this vertical force, called target force (Fig. 1E) and maintain it by applying force pseudo-isometrically at the level of the metacarpophalangeal joint in the opposite direction (downwards).
**Force profile**

The target force shown in Fig. 1E was set at 8% of the maximum voluntary contraction which was determined for each subject prior to the experiment. We used low force as it has been shown that motor cortical neurons are most sensitive to forces within a low force range (Hepp-Reymond et al., 1989). Each trial comprised three phases: a 1 s *upward ramp phase* (rising cosine function to ensure a smooth start) followed by 12 s-period of *static force* (SF), followed by 1 s *downward ramp phase* (decreasing cosine function) to ensure a smooth end of the generated force.

**Visual feedback**

The feedback of the force exerted by the subject was a white dot (radius 2 mm) within a fixed green circle displayed on a 19'' monitor placed 100 cm in front of him/her (Fig. 1B). Thus the feedback displayed was a positional one, since the finger position proportional to the force applied, was measured. The white dot moved within the fixed green circle (radius 6 mm including the line thickness of 2 mm) representing the range within which the white dot was allowed to move. When the force was applied to the ring and thus to the index finger, the subject had to compensate it by applying a force in the opposite direction and to maintain it pseudo-isometrically in the middle of the green circle. A finger displacement of 1 mm corresponded to 2.85 mm visual feedback. The tolerance for the positional errors was the green circle.

**Experimental conditions**

In the present experiment Gaussian noise in the range 0-300 Hz was continuously applied to the manipulandum and thus added to the target force. We choose this broad bandwidth because, in Trenado et al. (2014) this broad frequency bandwidth was associated with the best sensorimotor performance compared to a noise bandwidth 0-15 Hz and of 250-300 Hz and also was most pleasant.

Fig. 1C shows the spectral power of the noise. The noise was generated by a MATLAB customized program which enabled various amplitude levels of noise intensity up to high noise (approx. 200 mN) (for more details see Trenado et al., 2014).

**Prior to the experiment** the following tests were performed:  
*First*, the subjects performed a few trials to get familiarized with the task and learn “what” to do and “how” to do it.  
*Second*, we defined for each subject the noise level which could be considered as optimum noise (ON). In particular, we made use of a MATLAB customized program that delivered a force at 8% of the maximum voluntary contraction (MVC) during 110 s and added noise levels in an incremental fashion. Immediately after that we calculated the performance as a function of the noise level, i.e. the SR curve. Fig.1D shows the performance inverted U-like curve, which is the signature of the SR, as function of noise intensity for all subjects. We defined the ON as the noise level inducing the best performance, as measured by the smallest absolute deviation from 0 (the highest value of the inverse of the mean absolute deviation, 1/MAD). The procedure was repeated five times to ensure reliability of the measures.

During the experimental session, ten recording series of five trials each were collected for each experimental condition (zero noise, ZN and ON) thus reaching 50 trials for each of them. The two conditions, ZN and ON, were presented in a pseudo-randomised fashion.

To ensure that subjects sustained their attention during the experiment, they had to report after each series of five trials whether the trials were with or without added noise. The subjects
were instructed to avoid any other movements and to fix their gaze on visual feedback during the trials.

To avoid fatigue, rest intervals of 5 to 7 s were included between trials. Rest periods of about 5 min between the series were given to avoid adaptation to the perception of the noise (Berglund and Berglund, 1970).

At the end of the experimental session the subjects reported whether the noise helped them to be more precise.

**Recordings**

The EEG (bandpass DC-500 Hz, sampling rate 2000 Hz) was recorded (SynAmps 2, NeuroScan, El Paso, TX, USA) from 41 scalp positions referenced to Cz with ground at FzA, accordingly to the 10/10 system (Fig. 1A). Electrode impedances were kept under 5 kOhm. The electrooculogram (EOG, same bandpass and sampling rate as for EEG) was recorded to exclude data segments contaminated with eye movements for further analysis. Electromyographic activity (EMG, bandpass DC-500 Hz; sampling rate 2000 Hz) was recorded with surface electrodes using a belly-tendon montage from the pars indicis of the right flexor digitorium superficialis (FDS), the right first dorsal interosseus (FDI), and the right extensor digitorum communis (EDC). Our task requires synergetic co-contraction of these three muscles, which have intermingled cortical representations (Schieber 2002; Spinks et al. 2008; Maier and Hepp-Reymond 1995a, b).

The force and displacement of the finger were recorded in parallel with the electrophysiological data (same bandpass and sampling rate as for EEG). Data were stored and analysed off-line.

**Data analysis**

**EEG-EMG coherence analysis**

For the analysis, markers were put on the force trace (Fig. 1E): T0 at the beginning of the ramp phase of the static force, T1 at 4 s after it and T2 at 8 s after T1. Only data corresponding to the stationary phase of the static force between T1 and T2, i.e. a period of 8 s duration, were taken into consideration in the analysis. This was done to avoid transient effects during the period T0-T1. For ZN and ON data from the same muscle were taken for the analysis.

The ZN and ON data from all trials were concatenated separately. Within each condition, data was further cut into non-overlapping segments of 512 ms length allowing a frequency resolution of 1.96 Hz. Artifact rejection was visually performed off-line trial-by-trial to exclude segments contaminated with eye movements. Based on previous observations large positional deviations occurred also as a result of unexpected muscle contraction and lack of attention. Segments, in which the white point exited the green circle, were excluded from further analysis. They represented approximately 1% of the total number of segments for each experimental condition.

The EEG signal was then transformed into the reference free current source density (CSD) distribution which approximates the underlying cortical activity (Nunez et al. 1997). The CSD algorithm was computed using the spherical spline interpolation method (Perrin et al. 1989) as implemented in the commercial software “Brain Vision 2.0.2” (München, Germany). EMG signals were first high-pass filtered at 30 Hz to avoid artifacts and subsequently rectified.
The discrete 512 points Fourier transform was computed for each segment of the whole 0 to 500 Hz frequency range. Hundred fifty artifact-free segments per condition were selected and analyzed for each subject to base the analysis on the same number of segments per condition as in previous studies. For all subjects, data were pooled separately for each condition, and CMC, spectral power (SP) and performance were compared between conditions.

Calculation of EEG spectral power (SP) and EEG-EMG coherence (CMC)

The maximum EEG SP was found over C3 in 6 subjects and over C1 in 2 subjects. It was also located where the maximum value of the EEG-EMG coherence was obtained with the muscle which was most constantly activated during the task. In four subjects the maximum coherence was found with FDI, in two subjects with the EDC and in two subjects with FDS.

Spectral power (SP) for a given channel \( \text{c} \) was calculated according to the following equation

\[
SP_{c}(f) = \frac{1}{n} \sum_{i=1}^{n} C_{i}(f)C_{i}^*(f),
\]

where \( C_{i} \) represents the Fourier transformed channel \( c \) for a given segment number \( i=1,\ldots,n=150 \) and ‘*’ denotes the complex conjugate.

Coherence values were calculated between the EEG channels corresponding to the primary sensorimotor area contralateral to the active finger and the rectified EMG. Coherence values were calculated on the basis of the following formulae:

\[
Coh_{c1,c2}(f) = \frac{\left| S_{c1,c2}(f) \right|^2}{\left| SP_{c1}(f) \right| \left| SP_{c2}(f) \right|},
\]

where

\[
S_{c1,c2}(f) = \frac{1}{n} \sum_{i=1}^{n} C_{i1}(f)C_{i2}^*(f),
\]

here \( S_{c1,c2}(f) \) denotes the cross-spectrum for the EEG signal channel \( c1 \) and the rectified EMG signal in channel \( c2 \) at a given frequency \( f \) and \( SP_{c1}(f) \) and \( SP_{c2}(f) \) denote the respective spectral power for \( c1 \) and \( c2 \) at the same frequency.

For frequency \( f \), the coherence value \( Coh_{c1,c2}(f) \) corresponds to the squared magnitude of a complex correlation coefficient. The function \( Coh_{c1,c2}(f) \) is a real number between 0 and 1.

Coherence between a pair of signals was considered to be significant if the resulting value lies above the confidence level \( (CL) \) (Rosenberg et al., 1989)

\[
CL(\alpha) = 1 - \left( 1 - \alpha \right)^{\frac{1}{\pi-1}},
\]
where \( n \) is the number of segments and \( \alpha \) is the desired level of confidence. Coherence values were significant when they lied above the 95% confidence limit. For 150 segments the 95% confidence level for each subject was 0.019. Following the approach introduced by (Evans and Baker, 2003) to determine whether the grand-average coherence is significantly different from zero, we firstly calculated the probability density function of a single-subject coherence values under the null hypothesis of no-coupling by using the formula:

\[
\text{Prob}(Coh) = (1 - N)(1 - Coh)^{N-2}
\]  

which is obtained by differentiating the formula for the cumulative probability of coherence given in Rosenberg et al. (1989). The probability density of the grand-average coherence was estimated by convolution of the individual coherence densities. The 95% percentile of this probability distribution function was used as a significant level for the averaged coherence (P<0.05), which yields 0.023.

**Calculation of performance**

To test the effects of the SR phenomenon on the finger performance, the mean absolute deviation (MAD) was computed on the basis of the formula:

\[
MAD = \frac{1}{n} \sum_{i=1}^{n} \left| x_i \right|
\]  

where \( x_i \) is the value of finger position relative to the applied force at the sampling point \( i \). MAD measures the deviation amplitude of the white dot relative to the center of the green circle during the application of the force on the manipulandum in the y-direction (upwards and downwards).

**Statistical analysis**

**Statistical analysis of the EEG spectral power (SP)**

To test for statistical difference in cortical spectral power between ZN and ON, we measured the individual areas under the SP curve, \( A_{pow} \). The frequency windows for EEG \( A_{pow} \) were 15-45 Hz (beta and gamma ranges), 15-30 Hz (beta-range) and 30-45 Hz (gamma-range). To prepare data for statistical analysis, data were logarithmically transformed to yield symmetric distributions according to the formula:

\[
A'_{pow} = \log_{10}(0.001 + A_{pow}) - \log_{10}(0.001)
\]
where the first value (0.001) has been selected to fulfil: a) homogeneity of variance, and b) symmetry of distribution. The second one \( \log_{10}(0.001) \) was defined in such a way that the transformation maps 0 to 0.

**Statistical analysis of CMC**

To test for statistical difference in CMC between ZN and ON, we measured the individual area under the coherence curve and above the significance level, \( A_{coh} \). The considered frequency windows for the \( A_{coh} \) were 15-30 Hz, 15-45 Hz and 30-45 Hz. To prepare these data for the statistical analysis, individual values for \( A_{coh} \) were first transformed logarithmically to yield symmetric distributions according to the formula:

\[
A'_{CMC} = \log_{10}(0.002 + A_{CMC}) - \log_{10}(0.002),
\]  

(8)

where the first value (0.002) has been selected to fulfil: a) homogeneity of variance, and b) symmetry of distribution. The second one \( \log_{10}(0.002) \) was defined in such a way that the transformation maps 0 to 0.

**Statistical analysis of performance**

To account for the inter-subject variability and achieve symmetry on the data distribution, the MAD values were also first logarithmically transformed according to the formula:

\[
MAD' = \log_{10}(100000 + \text{MAD}) - \log_{10}(100000),
\]  

(9)

where the first value (100000) has been selected to fulfil: a) homogeneity of variance, and b) symmetry of distribution. The second one \( \log_{10}(100000) \) was defined in such a way that the transformation maps 0 to 0.

For EEG SP, CMC and performance paired Wilcoxon test was performed with the null hypotheses that the differences of the means between ZN and ON were zero.

To investigate changes in the performance, SP and CMC between both conditions Spearman correlation coefficient was computed.

**Results**

**Behavioral performance**

All eight subjects performed the task according to the instructions. None of them reported fatigue or anxiety during the experimental session. All subjects reported that they felt the ON during the experiment.

The 1/MAD values were significantly higher (which means better performance) in the ON than in the ZN condition, as can be seen in the grand average of the performance displayed in
Fig. 2A and in the individual 1/MAD values for both conditions in Fig. 2B (p=0.008, Wilcoxon paired test; N=8 throughout the whole text).

(Please, insert Fig. 2 about here)

**EEG spectral power (SP) over the motor cortex**

From the grand average of log SP curves (Fig. 2C) and individual spectral power values (Fig. 2D), the ON was characterized by significantly higher cortical motor SP (p=0.008, Wilcoxon paired test) in beta-range. The difference was also significant in beta-gamma range (15-45Hz) (p=0.008, Wilcoxon paired test), but not for gamma-range only (30-45 Hz).

The high SP in the beta-range during ON indicates stronger cortical motor synchrony.

**Corticomuscular coherence (CMC)**

All eight subjects exhibited CMC for both ZN and ON and six of them had CMC in the beta-range. For the other two subjects the maximum peak of CMC was at the border of the gamma-range. For all subjects the maximum CMC occurred over the left sensorimotor cortex, particularly at C3 (6/8) and at C1 (2/8). The highest CMCs occurred with the FDI (4/8), EDC (2/8) and FDS (2/8).

Figure 2 displays the grand average CMC curves (E) and the individual values of coherence for both conditions in beta-range (F). It is noticeable that ON had higher CMC than the ZN (p=0.008, Wilcoxon paired test) for the beta-range. The difference between conditions for the gamma-range (30-45 Hz) is at the border of significance (p=0.08).

The high CMC in the beta-range during ON indicates a stronger corticospinal synchronization during ON than during the ZN condition.

(Please, insert Fig. 2 about here)

The statistical analysis gives support for the hypothesis that the improved performance during ON is consistent with increased beta-range SP and beta-range CMC.

No significant correlations between improvement in performance and increase in SP and CMC in ON were found.

**Discussion**

Here we show that stochastic resonance generated by an optimal external tactile-proprioceptive stimulus applied on the fingertip improves performance in a visuomotor task. This improvement was consistent with an increase of cortical motor spectral power (SP) and of corticomuscular (EEG-EMG) coherence (CMC) in the beta-range. These findings provide evidence for local and long-range synchronization as neural correlates of SR in the sensorimotor system.

**Stochastic resonance is related to higher cortical motor and corticospinal synchrony**

It is well known that synchronization subserves the selective and effective transmission of information in the neuronal networks involved in sensorimotor integration (Fell and Axmacher, 2011; Siegel et al., 2012). As suggested by Mendez-Balbuena et al. (2012), an explanation of the improved performance in our task during optimal noise is related to an enhanced neuronal synchronization at spinal, cortical and corticospinal level.
During static force control as required in our task, the oscillatory activity of cortical motor areas and contralateral spinal motoneurones are synchronized in the beta-range (15-30 Hz), as reflected in CMC. Recently, we have demonstrated that the EEG-EMG coherence was related to the precision of performance in a visuomotor task (Kristeva et al., 2007; Mendez-Balbuena et al., 2012). The improved precision in the pseudo-isometric compensation of a static force correlated with higher beta-range cortical motor spectral power and higher beta-range CMC. This implies that a better performance is related to more effective corticomuscular synchronization. Corticomuscular synchrony is not only an efferent phenomenon as Baker et al. (2006) provided direct evidence that during sensorimotor processing sustained afferent discharge from muscle receptors was coherent with central oscillations. In addition, applying directed coherence analysis, Witham et al. (2011) have demonstrated that both descending and ascending pathways contributed to corticomuscular coherence CMC. Hence, one can postulate that the optimum noise applied in our study enhanced the sensitivity of cutaneous receptors, muscle spindle afferents and Golgi tendon organs and thus improved the sensorimotor integration at spinal, cortical and corticospinal level. This leads to a stronger local cortical motor synchrony and motor cortex drive to the muscles and to a better performance. Stronger beta-range cortical motor synchrony, as reflected in higher beta-range SP and higher beta-range CMC, has been also shown by others to be associated with better performance (Baker, 2007; Pogosyan et al., 2009).

An unexpected finding was the absence of correlation between the improvement in performance and the increase in cortical motor SP and CMC during ON: This surprising finding strongly suggest that the performance improvement also depends on other factors besides of the application of external noise, e.g. different internal noise for the various subjects. As shown by Aihara et al. (2010) the SR in visual perception is substantially influenced by the internal noise within the brain. In our study the absence of correlations is probably due to high interindividual variability in both internal noise and generation of the corticomuscular coherence.

Our findings are consistent with data reported by Kitajo et al. (2007) who demonstrated that both detection of weak visual signals to the right eye and phase synchronization of EEG signals from widely separated areas of the human brain were increased by addition of weak visual noise to the left eye. They found a close relationship between the resulting noise-induced changes in behavioral performance and the changes in phase synchronization between widely separated brain areas. In the visual system, noise-induced SR also engaged modulation of EEG spectral power in the alpha band in the left occipital region (Mori and Kai, 2002). And in the human auditory system, Ward et al. (2010) provided evidence that intra- and interregional EEG neuronal synchronization are facilitated by the addition of moderate amounts of random noise.

To conclude, our findings showing that in the sensorimotor system optimum noise that maximizes performance is consistent with increase in cortical motor spectral power and in the corticomuscular coherence in beta-range, contribute to the understanding of the physiological mechanisms of the stochastic resonance phenomenon.

**Autor contribution**

CT, EM, JSM, IMB, FH, MCHR and RK designed the experiment and the methods. CT, RK, IMB carried out the experiment. CT, BF, JSM and RK analyzed experimental data. RK, CT, EM, IMB, JSM, FH, BF, MCHR interpreted data and wrote the manuscript. All authors approved the manuscript.
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**Figure legends**

**Figure 1. Experimental setup.** (A) Home-made index finger manipulandum producing a target static force (8% of individual maximum voluntary contraction) on which noise in the frequency bandwidths 0-300 Hz is added. Profile of the target static force in E. EEG (41 channels), electrooculogram (EOG), and EMG from the right first dorsal interosseus (FDI), the right flexor digitorium superficialis (FDS) and the right extensor digitorum communis (EDC) muscles were recorded. (B) Visual feedback of the finger position as a solid white dot within a green circle indicating the tolerance for position errors, displayed on a monitor in front of the subject. (C) Spectral power of the noise of the manipulandum in arbitrary units (au) for the 0-300 Hz frequency bandwidth. (D) Effect of the SR on the motor performance for all subjects recorded prior to the experimental session and computed as the inverse of the mean absolute deviation (1/MAD) of the finger position. Note the inverted U-shape like curve. During the experimental session only two noise levels were individually chosen, i. e. zero noise (ZN, black filled dots) and optimal noise (ON, red filled dots). (E, F) Original curves for target force and finger position (representing the exerted force) for ZN (E) and ON (F) for the frequency bandwidth noise 0-300 Hz. Transitory phase of the task between markers T0 and T1 and stationary phase between markers T1 and T2. Note in the magnified position traces the better performance for ON than for ZN.

**Figure 2. Motor performance, cortical motor spectral power and corticomuscular coherence for zero noise (ZN, black) and optimum noise (ON, red).** Upper panel: Grand average of the inverse of the mean absolute deviation (1/MAD) of the finger position in A and individual values of (1/MAD) in B. Note the stochastic resonance (SR) effect with better performance for ON. Middle panel: Grand average for cortical motor log SP in C for ZN and ON and plots of the individual values of area under the curve of log SP for both conditions in beta range D. Note the stronger cortical motor log power for beta-range. Lower panel: Grand average of CMC in E and individual plots for all values (areas under the curve and above the significance level) in beta range F. Note the higher CMC for ON in beta-range. In E and F for ZN and ON data from the same muscle were taken for the analysis.
Figure 1
Figure 2

Performance (1/MAD)

A. Grand average

B. Individual values

EEG spectral power

C. Grand average

D. 15-30 Hz

CMC

E. Grand average

F. 15-30 Hz
Figure 3.

A. Manipulandum

B. Feedback monitor

C. Manipulandum noise 0-300 Hz

D. Graphs showing data for S1, S2, S3, S4, S5, S6, S7, S8.

E. Zero noise (ZN)

F. Optimal noise (ON)