Electrical noise modulates perception of electrical pulses in humans: sensation enhancement via stochastic resonance

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Iliopoulos F, Nierhaus T, Villringer A. Electrical noise modulates perception of electrical pulses in humans: sensation enhancement via stochastic resonance. J Neurophysiol 111: 1238–1248, 2014. First published December 18, 2013; doi:10.1152/jn.00392.2013.—Although noise is usually considered to be harmful for signal detection and information transmission, stochastic resonance (SR) describes the counterintuitive phenomenon of noise enhancing the detection and transmission of weak input signals. In mammalian sensory systems, SR-related phenomena may arise both in the peripheral and the central nervous system. Here, we investigate behavioral SR effects of subliminal electrical noise stimulation on the perception of somatosensory stimuli in humans. We compare the likelihood to detect near-threshold pulses of different intensities applied on the left index finger during presence vs. absence of subliminal noise on the same or an adjacent finger. We show that (low-pass) noise can enhance signal detection when applied on the same finger. This enhancement is strong for near-threshold pulses below the 50% detection threshold and becomes stronger when near-threshold pulses are applied as brief trains. The effect reverses at pulse intensities above threshold, especially when noise is replaced by subliminal sinusoidal stimulation, arguing for a peripheral direct current addition. Unfiltered noise applied on longer pulses enhances detection of all pulse intensities.

Noise applied to an adjacent finger has two opposing effects: an inhibiting effect (presumably due to lateral inhibition) and an enhancing effect (most likely due to SR in the central nervous system). In summary, we demonstrate that subliminal noise can significantly modulate detection performance of near-threshold stimuli. Our results indicate SR effects in the peripheral and central nervous system.

Detection enhancement; perception modulation; somatosensory threshold; subliminal electrical noise stimulation; unconscious noise

NOISE HAS A KEY ROLE IN SENSORY processes of biological systems (Collins et al. 1996a; Douglass et al. 1993; Ivey et al. 1998; Juusola and French 1997; Levin and Miller 1996). Usually, noise is considered to be detrimental for signal detection and information transmission since with increasing noise a marker of signal quality, the “signal-to-noise ratio,” obviously decreases. Under certain conditions, however, noise can enhance the detection and transmission of weak input signals (Collins et al. 1996a,b; Douglass et al. 1993; Juusola and French 1997; Levin and Miller 1996). This paradoxical weak input enhancement is a manifestation of stochastic resonance (SR), a phenomenon that takes place in certain bistable nonlinear systems characterized by a delimiting barrier. In sensory systems, “the barrier” is the sensory detection threshold (ST), and according to SR theory there is a particular nonzero level of noise that forces undetectable stimuli to overcome the ST, thus improving the detection performance of the system.

A key question for the understanding of SR mechanisms in higher organisms is whether the interaction between noise and weak input signal occurs already and only in the peripheral nervous system or whether central processes, i.e., in the spinal cord and/or the brain, also play a role. Experiments that test for SR occurring in the central nervous system (CNS) are designed to deliver noise and input signal to different peripheral sensory pathways to ensure that the interacting signals converge only in the CNS.

Numerous studies have shown SR occurrence in animal sensory systems (Bahar et al. 2002; Collins et al. 1996a; Douglass et al. 1993; Freund et al. 2002; Ivey et al. 1998; Jaramillo and Wiesenfeld 1998; Juusola and French 1997; Levin and Miller 1996; Manjarrez et al. 2003). These organisms exhibit SR behavior by exploiting extrinsic noise to optimize performance on survival-related tasks, mostly feeding or predator avoidance. Since such complex behavior implicates higher cognition, memory and/or connectivity processes, researchers assumed SR phenomena to take place in the CNS. The first robust empirical findings that confirmed this notion were published by Manjarrez et al. in 2003. In a study on anesthetized cats, SR was demonstrated to occur in spinal and cortical evoked field potentials elicited by tactile stimuli providing the first proof for SR taking place in animal CNS (Manjarrez et al. 2003). Evidence for SR-related phenomena in humans has also been accumulated over the past 2 decades for the auditory (Morse and Evans 1996; Ward et al. 2001; Zeng et al. 2000), visual (Kitajo et al. 2003; Piana et al. 2000; Simionatto et al. 1999; Ward et al. 2001), and tactile sensory system (Collins et al. 1997; Priplata et al. 2002, 2003; Richardson et al. 1998). Several studies have been performed within one sensory modality with either noise and target signal being of the same or similar stimulation type (e.g., random vibration-weak mechanical indentations; Collins et al. 1996b) or of a different stimulation type (e.g., within the somatosensory system, the effect of electrical noise on the detection of mechanical indentations has been investigated; Richardson et al. 1998). Other studies have shown that SR interactions in humans can also occur between signals of different sensory modalities (cross-modal, e.g., auditory noise enhances visual, tactile, and proprioceptive sensory input; Lugo et al. 2008; Manjarrez et al. 2007).

The somatosensory system has been a main target to investigate improvements of performance with SR (e.g., Magalhães...
and Kohn 2011; Mendez-Balbuena et al. 2012). Based on SR, there is indeed some hope to come up with clinical applications. For example, Kurita et al. (2011) designed a wearable sensorimotor enhancer that improves tactile performance by implementing vibrotactile noise on the fingertips of humans. This peripheral vibrotactile enhancement (Collins et al. 1996b; Priplata et al. 2002; Richardson et al. 1998) is a well-proven effect that enhances the perception of tactile stimuli through SR. Despite these promising perspectives, however, so far some crucially important features for designing and optimizing SR effects in the somatosensory system are unclear, e.g., the optimal timing of “noise signals” in relation to the “test signal” is not known. Furthermore, the current understanding of the neurophysiological mechanisms that underlie SR is extremely limited, e.g., such basic issues as the neural sites of SR (peripheral vs. central?) and its relationship to other neurophysiological events (e.g., lateral inhibition) are poorly studied. We believe that this information is needed to implement “noise enhancement” effectively in both healthy and pathological conditions. The current study aims to give answers to some of these basic questions. To do so, we investigated the interaction of well-defined electrical pulses with simultaneously applied electrical noise (electrical noise stimulation, ENS). This setup can be “controlled” very flexibly and enabled us to build “our model” step by step all the way to the CNS focusing on the temporal interaction between the two signals without eliciting cross-modal effects.

In the first experiment, we investigated the most “trivial” case: noise and single electrical pulses applied on the same sensory input, which, via electrodes attached to individual fingers, was the peripheral finger nerve. By directly stimulating the same peripheral nerve, potential effects arising from receptor transductions such as temporal delays or nonlinear transductions are avoided. To get a detailed view of the synchronous interaction between the two signals, in the next experiment, instead of uniform pseudo-Gaussian distribution, ENS intensity was replaced by a sinusoidal function. After having shown selective enhancement in our model, we investigated the interaction between noise and pulses in somewhat more detail. To test whether the SR effect is purely peripheral, ENS was delivered not only on the same, but also on the adjacent finger. Also, in one experiment, single pulses were replaced by trains of pulses. Whereas in the aforementioned experiments, low-pass noise (“slow ENS”) and short test pulses (0.2 ms) were used, in another experiment the noise signal was unfiltered (“fast ENS”) and combined with long (10-ms) test pulses to allow for noise fluctuation during the application of the test pulses. In this last experiment, a forced-choice paradigm was used to assess sensitivity as a function of signal power.

Thus, in a series of experiments, we systematically varied stimulation and noise characteristics to get closer to the underlying mechanisms. Specifically, we addressed the following questions: 1) under which conditions does subliminal noise lead to facilitatory and/or inhibitory effects on the detection of somatosensory stimuli applied to the same or the adjacent finger; and 2) are there any signs for SR occurrence, and if so is this a result of signal interaction in the peripheral nervous system and/or CNS?

**MATERIALS AND METHODS**

All experiments were performed at the Department of Neurology at Charité Hospital (Charité - Universitätsmedizin Berlin, Campus Mitte). The protocols were approved by the local ethics committee; participants gave informed, written approval before participation and had no history of neurological or psychiatric disorder.

Electrical finger nerve stimulation was performed with a bipolar constant-current stimulator (DS5; Digitimer, Welwyn Garden City, Hertfordshire, United Kingdom) and steel wire ring electrodes. All signal waveforms were created using LabVIEW and generated as analog voltage signals through a National Instruments (NI) 6229 data acquisition (DAQ) card (Fig. 1). The analog outputs were channeled in two DS5 stimulators, which convert the voltage signal in current (direct current, DC) by constantly measuring the conductivity of the subject’s finger. All current signals were concurrently recorded in the analog inputs of the DAQ card. Further analysis was based on these recordings. The DS5 apart from stimulating also acted as an isolator to ensure the subjects’ safety.

Electrodes were fixated using small pieces of polymeric sponge in a stable and comfortable position, making sure that the lateral sides of the finger were well in contact with the electrode. Typical distances between the electrodes were ~1.5 cm depending somewhat on the anatomic features of the subjects’ fingers. After electrode fixation, a gel that facilitates conductivity was applied on the metal-cutis contact. The gel contained natriumchloride, hydroxyethylcellulose, propyl englykol, and sterilized water. In experiments 1 and 2, three electrodes were placed on the left index finger (all subjects were right-handed). For experiments 3–5, two additional electrodes were placed on the adjacent middle finger (Fig. 1). Stimulation of an adjacent finger excludes signal interaction in the peripheral nervous system; hence, any interaction is assumed to take place in the CNS.

Target pulses were single monophasic square-wave pulses with a duration of 200 μs generated at 5-kHz sampling rate, which is the maximum sampling frequency of the implemented acquisition card. Trials were presented at jittered interstimulus intervals (ISI) between 2.0 and 3.3 s. ISI randomization followed a uniform distribution. The noise signal had a zero-mean Gaussian distribution and was low-passed at 200 Hz. Noise was delivered in blocks of 20-s duration, always in an intermitted sequence (20-s noise on, 20-s noise off, and so on; Fig. 2). Both signals were recorded along with the subjects’ responses using the same sampling frequency.

Before starting to record measurements, participants received training during which they were presented test pulses of various intensities and were made comfortable in identifying them. At the beginning of...
all measurements, the ST of each participant was determined following the method of limits and subsequent forced choice (Windhorst and Johansson 1999). The detection rate values used to calculate the ST and in the subsequent analysis are given by:

\[
\text{number of detected trials/total number of presented trials. (1)}
\]

The peak-to-peak noise level value used in all subsequent measurements was calculated based on this ST value. The noise level was maintained subliminal throughout all measurements in this study (equaled 0.05 × ST as long as the detection curve was valid and well-centered on the 50% of detected trials). We checked for subliminality of each noise level by asking the subjects to press a button immediately if they felt any kind of stimulation during a 20-s noise block. After each 20-s block, we asked the subjects once more whether they had felt anything.

In those experiments in which two fingers were involved, electrodes were placed on both fingers. Subjects were not told which finger was stimulated, and they were asked whether they perceived any stimulus in general without specifying the stimulated finger. We made sure that this noise level remained subliminal throughout the whole measurement by consulting the subject after every measurement. If the subject detected any kind of stimulation in any finger during this step or any stimulation on finger 3 (which never received test pulse stimulation), this participant would have been excluded. This, however, never actually happened.

Before and after each run, the detection threshold was determined again, and the intensity of the near-threshold pulses in the respective subsequent run was adjusted accordingly.

**Single pulses vs. single pulses with noise at the same finger.** Subjects were asked to respond as fast as possible after any felt test pulse by pressing a button using their right thumb. Single monophasic square-wave pulses of three different intensities were applied, 10% below ST, 10% above ST, and on the ST calculated value, and noise was delivered in blocks of 20 s. Four runs were performed per subject on a total of 10 healthy subjects (4 men, 6 women, age 20–34 yr). Each measurement had a duration of 5.33 min, and a total of 144 trials was presented.

**Single pulses vs. single pulses with sinusoidal noise at the same finger.** In this experiment, the exact same protocol as in experiment 1 was followed. The only alteration was that the subliminal noise signal was replaced by a 30-Hz subliminal sine signal (Fig. 3). Four 5.33-min measurements were performed per subject on a total of 10 new healthy subjects (6 women, 4 men, age: 19–36 yr).

**Single pulses vs. single pulses with noise at the same or adjacent finger.** In this configuration, pulses were continuously delivered to the index finger while noise was applied either to the index finger or alternatively to the adjacent finger. Following the same paradigm as before, noise was delivered in blocks of 20 s. Noise blocks were applied in a pseudorandomized sequence. Four measurements of 5.33-min duration were repeated per subject on a total of 11 healthy subjects (6 women, 5 men, age: 22–33 yr).

**Pulse trains vs. pulse trains with noise at the same or adjacent finger.** For a better understanding of the simultaneous single stimulus-noise interaction, this experiment was performed by presenting pulse trains instead of single pulses. In each trial, a train of 6 pulses was presented (10 Hz; Fig. 4). Again, subjects were instructed to respond as fast as possible every time they felt a test stimulus. The protocol, the block pseudorandomization, the noise features, as well as all of the remainder of the parameters in this configuration were identical to those in experiment 3. We measured 11 healthy subjects (6 women, 5 men, age: 22–34 yr).

**Long single pulses vs. long single pulses with fast noise at the same or adjacent finger.** In contrast to all previous configurations in which noise and target signal interacted simultaneously for 200 μs, maintaining a single intensity value for this interval, in this experimental arrangement, noise was not filtered, and each single pulse had 10-ms duration. This allowed the noise signal to shift polarity several times during each pulse (Fig. 5).

Furthermore, in this experiment, we followed an approach based on signal detection theory (SDT). In SDT, the sensitivity or discrimination capacity to a “real stimulus” is compared with a “null trial” typically in a forced-choice task, i.e., subjects are instructed to answer always with yes or no whether during a certain time period a pulse was felt or not. This leads to four different possible outcomes: a hit (correctly identified stimulus; H), a miss (negative response to an existing stimulus), a correct rejection, and a false alarm (identification of a stimulus when in fact it is absent; F). The most used index of SDT for calculating sensitivity is the sensitivity or discriminability index or just D’ (Macmillan and Creelman 2005) is calculated from H and F through the inverse of the normal distribution function (z) also known as z-transformation:
In Fig. 7, the characteristic “twisting” noise at the same finger. for all 3 intensities, and 1 got worse in detecting all 3 pulses (Fig. 6). One out of 10 subjects improved performance enhancement on the detection of the 2 lowest pulses and an induced a similar effect on 8 out of 10 subjects: a significant enhancement is higher when the test pulse intensity is lower. ENS averaged trials of all measurements for all subjects. The en-

RESULTS

Experiment 1: single pulses vs. single pulses with noise at the same finger. Figure 6 shows the detection rates for the averaged trials of all measurements for all subjects. The enhancement is higher when the test pulse intensity is lower. ENS induced a similar effect on 8 out of 10 subjects: a significant enhancement on the detection of the 2 lowest pulses and an insignificant decrease on the detection of the highest intensity pulses (Fig. 6). One out of 10 subjects improved performance for all 3 intensities, and 1 got worse in detecting all 3 intensities.

Experiment 2: single pulses vs. single pulses with sinusoidal noise at the same finger. In Fig. 7, the characteristic “twisting” effect of the 30-Hz sinusoidal function is seen. Trace analysis shows that the effect of the sine DC waveform on the coinciding pulses depends on the distribution of negative-positive values and the intensity of each pulse. A sine function has an equal distribution of negative and positive traces during each measurement. By using a sine signal, the sign trace distribution is maintained symmetrical throughout each measurement. Consequently, the “seesaw twist” effect on the grand average (Fig. 7) is more symmetrical than the noise effect (Fig. 6) as seen in the extreme pulse detection rates.

Both ENS/sine waveform and pulse signals in experiments 1 and 2 described above were generated in the same sample frequency (5 kHz) as the single pulses. Hence, whenever a pulse was delivered simultaneously with noise, the two signals interacted “instantly” for 200 μs (sum trace interval). The value of the applied intensity of the sine waveform in the same moment a pulse is delivered is a sine intensity trace. A trace analysis was performed in all such traces to identify common attributes of successfully detected vs. undetected traces (Fig. 8).

The analysis of the instantaneous noise (or sinusoidal) intensity during the 200-μs time period of near-threshold pulse application showed that simultaneous voltage addition in the nerve seems to play a key role for the detection enhancement mechanism between target and sine signal. Figure 8, right, illustrates that when stimulating using a sinusoidal signal the sum of the simultaneous DC addition between sine trace and test pulse intensity is what determines whether a test pulse is detected. Positive sinusoidal traces improved the detection of the test pulses, which by default are always positive. From the top row (Fig. 8, right), it can be derived that negative sine traces increased the likelihood of pulses to remain undetected. In the case of the lowest intensity, most of the trials are undetected when ENS is absent. Negative DC values have no real effect on pulses of this intensity since already undetected trials remain undetected. The opposite effect takes place for the highest intensity, i.e., negative noise values decrease the detectability of the highest intensity pulses. Whether pulses of the middle intensity are becoming more or less detectable depends on the sign distribution that coincides with pulses of this intensity. A positive DC “population” increases detection rates, whereas negative DC values tend to reduce detection rates for pulses of this intensity (Fig. 8, right).

Experiment 3: single pulses vs. single pulses with noise at the same or adjacent finger. ENS when applied on the adjacent finger had no significant effect on the detection of pulses at the two lowest intensities. The only significant effect of ENS on the adjacent finger was the decrease of the detection rate of the highest intensity pulses ($P = 0.00486$ and 0.0266 for ENS at the same and adjacent finger, respectively; Fig. 9).

Experiment 4: pulse trains vs. pulse trains with noise at the same or adjacent finger. In this experiment, the highest detection rates occur when noise and pulse trains are both delivered on the index finger (Fig. 10). By using trains instead of single

\[ D' = z(H) - z(F). \]  

(2)

The temporal order of null trials and target trials was pseudorandomized. Each trial had a duration of 3.5 s. A single beep sound marked the beginning of each trial followed by a double beep sound 1.5 s after the first, indicating the moment of response. Between the acoustic markers, stimuli were presented with a 1-s time jitter. Noise was applied in 28-s blocks. Each condition (“just pulse,” “pulse and noise on the index finger,” “pulse on the index and noise on the adjacent finger,” and “null trials”) was presented in equal trial numbers for each subject.
pulses, the probability of a positive noise trace to coincide with a part of the target stimulus increases. The more single pulses are contained in a pulse train, the higher this probability. The detection rate for the highest intensity pulses (always close to 100%) remains unaffected. Subliminal ENS applied on the same finger significantly increases the total detection rates of all near-threshold pulse trains, thus shifting the ST of the subjects toward lower values. This total detection rate enhancement occurred for all 11 subjects. Notwithstanding, subliminal noise applied on the adjacent finger induced a significant decrease ($P = 0.0389$) of the highest intensity detection rate that reaffirms the effect also seen using single-pulse stimuli (experiment 3).

Experiment 5: long single pulses vs. long single pulses with fast noise at the same or adjacent finger. The D’ analysis results demonstrate that the subjects became significantly more sensitive in detecting pulses of the two lowest intensities when noise was applied on the same finger (Fig. 11). Moreover, noise applied on the adjacent finger also improved the likelihood for detection of near-threshold pulses, particularly for pulses of midintensity. Although this partial enhancement was not statistically significant ($P = 0.0600$), the total detection rates for trials of all 3 pulse intensities are significantly higher during the presence of adjacent ENS ($P = 0.0364$). More important, 7 out of 12 subjects exhibited both a significant improvement on the detection rates and on the D’ values for the 2 lower intensities. We corrected for undefined ($\pm \infty$) values of hit and false alarm rate by adding 0.5 to all data cells (hits, misses, false alarms, and correct rejections) before calculation (Hautus 1995; Miller 1996). Six subjects scored zero false alarms, five subjects scored one single false alarm, respectively (the wrongly identified test pulses actually occurred in different trials), and one subject scored two false alarms. Two of the false alarms corresponded to null trials in complete signal absence, three were committed during subliminal ENS on the adjacent finger, and two false alarms were given during ENS at the same finger (both responses given by the same subject).

The slightly higher rate of false alarm responses in experiment 5 compared with experiments 1–4 (along with an overall different performance as seen in the D’ plots) may be due to the somewhat increased overall attention associated with trials in experiment 5 based on the forced-choice setup; furthermore, there were differences in the applied signals (faster noise and longer pulses), and there was also a different time jitter.

However, given that there was never any significant number of false-positive hits and also never any significant change of false-positive hits by additional noise, we can conclude that the enhancing effect (of D’) of additional noise is mainly driven by the increase of the hit rate to actual stimuli.

As for experiments 1–4, they did not follow a strict “forced-choice design”: rather, before each experimental block, subjects were asked to report immediately whenever they felt any stimulation. In these experiments, we never had any false alarm, and (formally) no responses to “pseudonull” trials (which we inserted retrospectively) were given, i.e., all responses followed test pulses.

Figure 12 gives the result of a binning analysis performed by calculating the noise signal power applied along (during) each pulse stimulus. First, we segmented the parts of the noise waveform contained in each test pulse stimulation (Fig. 5). Then, we calculated the noise power deposited to the finger during each test pulse using the mean square root of each noise segment:

$$\text{power of noise segment} = \sqrt{\text{noise segment}}.$$  (3)

After sorting the trials according to the respective noise power, trials were classified in five equidistant zones (bins). Each group containing trials of the same power noise (as calculated in Eq. 3) is defined as a noise power bin. Trials belonging to the same noise power bin are trials during which the same amount of electrical energy was deposited on the nerve. Since the pulse presentation was uniformly randomized, each bin would be as likely to contain the same number of trials. In this sense, the “bin distribution” is uniform as well. For each bin, a D’ value is determined after taking the corresponding “null trials responses” into account. This process was followed separately for each of the three pulse intensities.

Regarding the detection enhancement of the lowest-intensity pulses, 7 of the 12 subjects exhibited classic SR-type behavior: as the intensity of the input electrical noise increased, D’ increased likewise to a peak and then decreased back to the same initial values (Fig. 12). In 2 of the other subjects, D’

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Footnote 1: “Pseudo” since there was no cue to announce a trial or a decision.
reached a significant peak for the maximum noise level. In this case, the noise intensity range may be limited to the 1st half (increasing portion) of the classic SR curve. Regardless, in 9 of 12 subjects, the introduction of a particular level of electrical noise on the index finger significantly enhanced their overall ability to detect near-threshold electrical stimuli.

**DISCUSSION**

We tested SR effects for electrical stimulation of finger nerves. Specifically, we show that the addition of subliminal noise enhances detection performance, particularly of pulse intensities below the 50% threshold, whereas detection of pulses above ST tends to be worsened. A similar effect is seen for subliminal sinusoidal stimulation. The effect becomes stronger when, instead of single near-threshold pulses, pulse trains are applied. Noise applied on an adjacent finger has two opposing effects. Low-pass filtered noise worsens detection of pulses above ST, and this applies for both single pulses as well as pulse trains. Unfiltered (fast) noise, however, on the adjacent finger is shown to enhance detection. To the best of our knowledge, this is the first time that these fundamental and basic questions concerning the effect of ENS on the detection of near-threshold pulses are answered.

Previously, it has been shown that the addition of noise can lead to improvements for various processes in humans. Enhancing effects have been reported for different noise modalities: the addition of mechanical noise has been shown to improve postural control and balance (Priplata et al. 2002, 2006; Reeves et al. 2009) and blood pressure regulation (Hi-daka et al. 2000) and enhance the detectability of weak tactile stimuli (Collins et al. 1996b, 1997; Ivey et al. 1998). Acoustic noise has been shown to improve tone perception (Lugo et al. 2008; Tanaka et al. 2009; Ward et al. 2010) as well as tactile, visual, and proprioceptive sensations (Lugo et al. 2008), whereas optical noise was shown to increase performance in visual as well as in sensorimotor tasks (Kitajo et al. 2003).

In contrast to these noise modalities that act primarily on receptors in the respective sensory system, ENS directly stimulates the nerve fiber that permits assessing precise timing characteristics of the interacting signals. The circumscribed local effect and the precise timing allow for tracking specific pathways in the peripheral system as well as in the CNS, a unique property of the electrical modality. Various studies performed using electrical noise showed enhancing effects emerging by implementing ENS peripherally or in the CNS. Electrical noise has been shown to improve postural control and balance (Gravelle et al. 2002; Mulavara et al. 2011; Reeves et al. 2009) and detectability of weak tactile stimuli (Richardson et al. 1998) and enhance spindle function (Cordo et al. 1996). Additionally, Yamamoto et al. (2005) showed that galvanic vestibular noise stimulation improves autonomic and motor responsiveness, and Terney et al. (2008) showed that transcranial random noise stimulation has an important, enhancing, general impact on brain excitability as seen through cognitive, learning, and motor tasks. This creates expectations for central ENS to evolve into a technique that may facilitate...
different types of synaptic transmission in the brain, potentially improving higher cognitive functions.

In our experiments, we carefully selected ENS amplitude such that it was always clearly subliminal. Pilot testing showed that slow (low-passed) ENS is more likely to be felt than fast (unfiltered) ENS. A typical magnitude difference in our test results is that a fast (5-kHz) ENS signal would start to become supraliminal for an amplitude range ~10 times higher than the corresponding slow (low-passed at 200 Hz) ENS signal for the same subject. Most probably, this is due to the fact that faster shifts of polarity leave less time for ions to transit the semi-permeable membrane, making action potentials less likely to occur. This finding differentiates the effect of electrical noise on the somatosensory system from other types of noise modalities: e.g., for vibrotactile noise, it has been shown that the slower the signal, the less likely receptors were excited (Collins et al. 1997). In this case, the excitation of rapidly adapting afferents is limited when the mechanical noise is low-passed at 30 Hz.

In all studies, we tested how the addition of a subliminal “background” noise influenced the detection of near-threshold stimuli pursuing the hypothesis (McDonnell and Abbott 2009): detection (subliminal noise + near-threshold stimuli) > detection (near-threshold stimuli). We show that enhancement depends on the relative attributes of the target (pulses) and the noise signal. In experiment 5, we have followed a SDT approach. ENS is faster, and the test pulses are longer than before. Consequently, one cannot make quantitative direct comparisons between the effects of fast and slow ENS (implemented in experiments 1–4) based on the data of the present study. Still, the dynamic temporal relationship between the interacting signals affirms a crucial general remark: when noise is relatively slow as to the target signal, i.e., frequency content (ENS) ≤ frequency content (pulses), and both signals are applied to the same peripheral nerve (index finger), enhancement occurs only for the lowest test pulse intensity. In the same experiments, higher-intensity pulses, however, become harder to detect while noise is present. Hence, in this paradigm (experiments 1 and 2), there is a tradeoff between selective enhancement and selective inhibition. Interestingly, the overall ability of the subjects to perceive near-threshold pulses as indexed by the total detection rate of all pulses remains approximately constant with and without ENS (experiment 1).

Thus the effect of slow noise could be utilized to enhance or reduce detection of the extreme pulses, respectively, but there is another interesting implication of this seesaw twist effect. Considering that the slope of a sigmoid detection curve is an analog of the transfer gain function (system theory), noise in this context can serve as a transfer function moderator (Freeman 1975, 1991; Gordon 1990; Skarda and Freeman 1987). Since a fundamental behavioral attribute classically associated to the slope of such curves is arousal, slow noise could play the role of an arousal moderator/modulator in similar electrical stimulation tasks.

The analysis of instantaneous signal interaction (Fig. 8) demonstrates that the instantaneous addition of noise (or sinusoidal noise) and the pulse amplitude plays a major role for signal detection as postulated by SR. This “DC addition mechanism” becomes most evident when noise is replaced by subliminal sinusoidal stimulation (experiment 2). Here, the equibalanced distribution between positive and negative DC additions elicited a strikingly symmetrical seesaw twist (Fig. 7). Comparing the effect of sinusoidal stimulation with the effect of noise, it seems that the effect of noise cannot be fully explained by DC addition/subtraction since the noise effect seems to lack a clear symmetry (regarding the enhanced perception of low-intensity pulses vs. the attenuated perception of high-intensity pulses) as seen when comparing Figs. 6 and 7. Clearly, this issue requires further investigation.

In experiment 5, where unfiltered (fast) noise interacts with longer pulses, pilot testing showed that subjects were incapable to distinguish between the longer (10-ms) and the shorter (200-μs) pulses even after adjustment for intensity, i.e., typically a subject with a 2.1-mA threshold for short and 0.72-mA for long pulses would sense these two pulses identically. By submitting the participants to a forced-choice task, we followed a SDT approach. Detection in the hypothesis for this experiment now stands for the subjects’ sensitivity in perceiving all near-threshold single pulses. In this paradigm, ENS targeted to the index finger led to a powerful enhancement of sensitivity as D’ gets larger. By analyzing the impact of the summed input (by binning the sums of test pulse intensity and instantaneous noise), we show that the effect of noise addition for the lowest-intensity pulses follows the classic inverse U-shape SR curve (Fig. 12). This is strong evidence that SR effects dominate detection at this pulse intensity since detection enhancement is driven by noise power. Binning analysis on the two other intensity pulses did not show a consistent behavioral pattern. Since the possible enhancement depends on the intensity of the pulse itself, it is possible that the range of noise amplitudes implemented was not wide enough; i.e., the tested region may have been limited to a partial portion (ascending half) of the SR curve for the specific intensity.

**Fig. 11. Experiment 5.** Grand average of all 12 subjects: blue points correspond to long pulses applied without the presence of noise. Red points correspond to long pulses applied during unfiltered noise stimulation on the same finger. Green points correspond to long pulses applied during noise stimulation on the adjacent finger. Left: proportion of “Yes” rates of detected trials. Right: discriminability index (D’) plots. *Significant increase in total detection rates when both noise and stimuli are applied to the same and to the adjacent finger.
At this point, a theoretical clarification needs to be made: a well-known method that also exploits noise in signal detection is dithering, which is an antialiasing technique that uses noise in quantization (or requantization) processes as to randomize quantization error. When added to low-amplitude or highly periodical signals before any digital sampling, dithering decorrelates the quantization error from the input signal, and any remaining distortion will exhibit a random distribution after sampling, i.e., a kind of “noise smoothing” is achieved. In this context, the seesaw effect that we found in experiments 1 and

Subject 1
Subject 4
Subject 7
Subject 10
Subject 5
Subject 11
Subject 3
Subject 6
Subject 9
Subject 12

Mean D' per bin

Fig. 12. A: values of D' for lowest-intensity pulses vs. the normalized noise power bins (5 bins of equidistant amplitude zones, noise applied to the index finger) for all 12 subjects. Subjects 1–7 as well as subject 12 exhibited clear stochastic resonance (SR) behavior: as the intensity of the input electrical noise increased, D' increased to a significant peak and then decreased again. In subjects 8 and 9, detection was maximal for the highest noise level. Perhaps, in this case, the applied noise amplitude ranges included only the “ascending half” of the SR curve, i.e., the range of noise amplitudes was not wide enough to cover fully the SR effect. Subjects 10 and 11 showed no clear effect. B: the grand average of all 12 subjects reveals the classic SR inverse U-shape curve.
2 may be described as dithering. The term SR is usually used when
aiming at a general detection enhancement of near-threshold signals that is driven by (an optimal) noise power (McDonnell and Abbott 2009; Wannamaker et al. 2000) as shown by an inverse U-shape relationship between noise power and signal detection. Hence, the results of experiment 5, in which at certain powers of (fast!) noise the detection of near-threshold pulses is generally enhanced, most clearly meet that terminology. Nevertheless, the underlying mechanisms may be similar if not the same for dithering and SR, namely, signal addition at quantization or detection thresholds, respectively. Therefore, one may generally speak of “noise-induced threshold crossings” (Gammaitoni 1995). The aim of SR in its more narrow definition may best be achieved if noise has the features used in experiment 5 (fast compared with the target signal). Thus the SR approach followed in this study (hypothesis; McDonnell and Abbott 2009) acknowledges that the terms SR and dithering are not mutually exclusive, but rather refer to different situations of using noise to influence signal detection.

When (low-pass) noise signal was applied to the adjacent finger (experiments 3 and 4), subjects became significantly worse in detecting single pulses of the highest intensity. The detection rates of the two less-intense near-threshold pulses (at threshold, 10% below threshold) remained unaffected (experiment 3). In principle, the same pattern was seen in experiment 4, in which pulse trains were used instead of single pulses. This pattern seems not consistent with SR; rather, lateral inhibition may play an important role here (Hsieh et al. 1995; Taskin et al. 2008). Lateral inhibition is a well-known phenomenon in sensory systems. There is an extensive overlap of adjacent finger representations in primary somatosensory cortex (SI), and ample evidence in literature suggests that principal neurons in humans and other primates have receptive fields that spread out to more than one finger, causing substantial overlapping finger representations (Iwamura et al. 1993; Schroeder et al. 1995; Smits et al. 1991). The overlap is more extensive for neurons located in the caudal subarea of SI. The overlap is particularly noticeable when it comes to the representation of the human middle and the human index finger (Krause et al. 2001). A functional feature caused by this overlap is the sharpening of stimulus representation in space by inhibiting input from “neighboring” body parts (lateral inhibition). The presence of such lateral inhibition effects has been shown in both animal as well as human studies (Greek et al. 2003; Hsieh et al. 1995).

Whereas in these experiments no clear indication of SR effects of noise to an adjacent finger was found, experiment 5 gives new evidence for a facilitatory effect of applying noise to the adjacent finger: the total detection rates became distinctly higher, i.e., there was a significant enhancement of the general ability of subjects to detect near-threshold trials. This finding strongly suggests a central component of SR in the CNS. Overall, the influence of ENS on an adjacent finger seems to be mediated by at least two opposing effects, i.e., lateral inhibition and SR. It seems that these effects differ with respect to their dependence on the strength of the target pulse and/or the precise temporal relationship between target pulses and noise. For example, the SR effect occurred mainly on the two lower intensities, whereas the inhibitory effect was seen at the highest intensity.

When the target stimuli are pulse trains instead of single pulses, the enhancement effect of ENS seems to be drastically stronger. Each single pulse corresponded to the shortest segment of signal that the implemented equipment could possibly generate (200 μs). Two positive segments employed simultaneously create a stronger stimulus that is more likely to be detected than each single stimulus applied separately. Therefore, the enhancement effect of subliminal noise is drastically stronger when using pulse trains for which the probability of two signal segments of positive voltage value coinciding in time is proportional to the extent of stochastic capability of the resonating system (Papoulis and Pillai 2001; Wio et al. 2012). Notably, there may also be an influence of periodicity within the pulse train stimulus. Periodically stimulated sensory neurons typically exhibit a statistical phase-locking to the stimulus (Dolnik et al. 1992; Longtin 1992). Periodic stimuli favor firing of neurons at a preferred phase of the stimulus cycle with peaks centered at integer multiples of the driving periods. The phase-locked effect has been shown to take place specifically for neurons involved in transducing electrical fields (Longtin 2002). Periodicity of the stimuli also has an impact on signal processing in the CNS since it can induce neural synchronization. Both intra- and interregional synchronization of neural activity induced by periodic input have been shown to be facilitated by the addition of moderate amounts of random noise (Ward et al. 2010). To disentangle the two effects (SR only vs. SR and effect of periodic stimulation), studies will have to be performed in which pulse trains are presented at irregular intervals.

In conclusion, this study shows that subliminal ENS stimulation can be used to improve perception of near-threshold electrical stimuli. Enhancement of detectability was achieved either for all near-threshold intensities (experiments 4 and 5) or selectively (experiments 1–3) by tuning the respective frequency content of the interacting signals. In the case of selective enhancement, there is a tradeoff between attenuation of pulses above threshold and facilitation of pulses under threshold; hence, ENS can serve as a transfer function modulator. Potential applications are numerous, including fine-tuning of brain-computer interfaces, control of surgical instruments, and implants such as cortical microarrays, real-time calibration of microcontrollers, pain modulation, informational feedback for monitoring and sensor devices, as well as haptic/sensory rehabilitation and sensorimotor adaptation.

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AUTHOR CONTRIBUTIONS
F.I., T.N., and A.V. conception and design of research; F.I. performed experiments; F.I. and T.N. analyzed data; F.I., T.N., and A.V. interpreted results of experiments; F.I. prepared figures; F.I. and A.V. drafted manuscript; F.I., T.N., and A.V. edited and revised manuscript; F.I., T.N., and A.V. approved final version of manuscript.

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