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Evidence for cognitive involvement in discriminating speech in babble

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Abstract

Introduction: Speech in Background babble Discrimination (SIBD) is a recognized challenge. Stochastic Resonance (SR) is offered as the cognitive mechanism for speech discrimination. **Objective:** We hypothesize that SIBD has the hallmarks of SR processing because it is a non-linear transformation that includes frequency spreading and allows for brain processing without a priori knowledge of the incoming signal. **Materials and Methods:** To test the hypothesis we created two sets of HINT based, Hagerman style vocabulary, tests. The stochastic signal used is a recording of speech induced emission noise. The first set determines the SR transformation settings using a multi-dimensional optimum search. The second set measures the actual improvement in speech recognition for normally hearing and hearing impaired subjects. **Results:** The tests show an improvement of approximately 2 to 3 dB SNR of speech intelligibility. The improvement is much more significant for Hearing Impaired (HI) subjects. **Conclusion:** SR lowers the detection threshold of auditory signals by an order of magnitude. We show that these results, using emissions noise, show higher discrimination rate than reported results using non-matched noise. SR processing is a cognitive process as demonstrated by the sample sentences. OAE is suggested as the brain's mechanism of SR processing.

Keywords: hearing, nerve net, speech discrimination tests, speech perception, speech recognition software.

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INTRODUCTION

Speech In Background Babble Discrimination (SIBD) - The ‘cocktail party effect’ or the problem of selectively listening to specific sounds in a mixed sound situation, is a challenge for all hearing aid companies, so much so that the US National Institutes of Health (NIH) issued a consensus statement seeking a solution[1]. In principle there is no real physical difference between target and background speech and therefore, without additional information (preferably cognitive) to guide the separation process, this issue is unsolvable.

Stochastic Resonance (SR) has already been offered as a solution of choice for this problem. In this paper SR is defined and explained in the context of its use in adaptive signal augmentation. Oto-Acoustic Emissions (OAE) are proposed in this paper as the brain’s source of stochastic noise for SR. Signal augmentation in speech discrimination in background noise and in neural network connectivity is described.

PROBLEM STATEMENT

The spectral and temporal characteristics of the target speech and the background babble are very similar and yet our auditory system excels in addressing this issue. A Normally Hearing (NH) person can understand a sentence spoken in his native language immersed in background babble of the same language at a Sound to Noise Ratio (SNR) of approximately -13dB to -15dB. On the other hand the only effective solution that the assistive listening device industry can offer are directional microphones.

Any proposed solution should take into consideration the following:

1. A significant portion of HI people suffer from high frequency loss: a significant deterioration of sensitivity for frequencies above 3.5 to 4 kHz. This is counter-intuitive since speech frequencies do not exceed 2.5 to 3 kHz (including harmonics). This implies that the suggested transformation model should include a frequency shift or spread to higher frequencies.
2. The fact that sound amplification in the ear is a non-linear process was noted a long time ago. To mimic the operation of the ear, the suggested model should therefore include a non-linear transformation.
3. The sensory systems in general and the ear in particular deal with unknown incoming signals; the frequency contents of an unknown talker can be determined only after the target speech has passed the neural barrier. Therefore solutions that are based on resonance or positive feedback that are target frequency dependent cannot be accepted.
4. Neural Networks (NN) are the accepted mechanism for brain processing. Any proposed mechanism should show how the signal augmentation affects the operation of the NN.
5. The proposed mechanism should operate under the brain’s control. In principle there is no real physical difference between target and background speech; it should be available for complex signal processing (e.g. speech) only.
6. The cognitive system should be part of the proposed solution, namely the proposed mechanism should not do it all, it should only augment the incoming mixture in a fashion that will allow the cognitive system to perform. For example: Directional microphones - the listener’s head turns towards the talker of choice; this operation is under the control of the cognitive system.
7. This one is an auxiliary but not a necessary feature of the proposed mechanism: if we could show how a similar solution works for other animals that need target signal in noise processing, this will certainly strengthen our argument.

STOCHASTIC RESONANCE - OVERVIEW

SR theory was derived from chaos theory in order to describe systems with both periodic (coherent) and random forcing. SR posits that if a one-sided or two-sided energetic barrier limits the propagation of a signal, an increase in random noise can result in an improvement in the SNR. SR is found in the signal processing world, in antenna design and other engineering applications, as well as in biological systems[2]. Later on more examples from the animal kingdom will be presented.

Physicists[3] suggest that the joint effect of a weak periodic variation (the coherent target signal) and other random fluctuations will create a much stronger periodicity. While calling this mechanism Stochastic Resonance, they noted that it is not strictly a resonance in the sense of an increased response when a driving frequency is tuned to a “natural frequency” of the system. The analogy to resonance is still useful in that the SNR is maximized when some parameter, in this case the input noise, is tuned near a target frequency.

Three conditions are required for SR to occur:

1. An energetic activation barrier or, more generally, a form of threshold;
2. A weak coherent input (such as a periodic signal);
3. A source of noise that is inherent in the system or added to the coherent input.

These conditions are the hallmarks of SR. When these conditions are met, the target signal’s SNR is improved and it demonstrates non-linear amplification. As an example, consider this very simplified model (Figure 1):

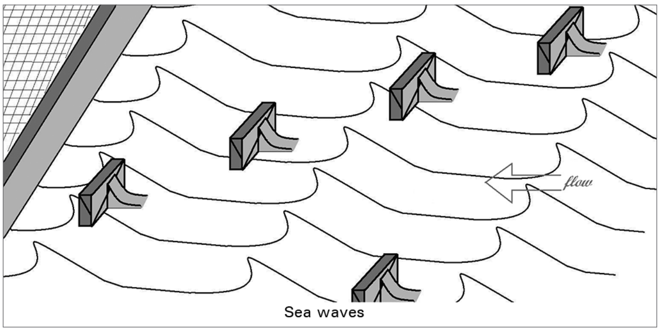

Figure 1. Stochastic Resonance model.

A series of sea waves (target signal) are hitting a jetty (one sided energetic barrier) at a constant frequency (coherence). The wave machines (in the picture) can be operated by an observer on the pier behind the jetty at any desired frequency. Sometimes the sea waves are too weak to cross the jetty and no effect is felt on the other side. The best procedure to help the sea waves cross the jetty is for the machines to push at the same frequency and phase of the waves (resonance). This procedure works only if the observer/controller has *a priori* knowledge of that frequency. However, SR predicts that activating the wave machines randomly (stochastic noise) approximately at the target frequency will allow the sea waves to cross. This solution comes at a cost because the amplification is not as good as resonance and the signal is distorted in a non-linear way. The non--linearity introduced by SR means that the target signal is accompanied by additional higher frequencies that are not harmonics of the original signal. The additional frequencies are higher because they are add-ons to the original frequency. Once some waves are allowed to pass, the target signal's frequency can be felt and one can control the wave machines to match the target signal more closely and, in effect, make an adaptive filter that selectively augments that specific target.

SR processing is realized through the concept of "augmentative filtering". SR is selectively augmenting specific information, not unlike the role of a filter. However, instead of forming a filter that attenuates unwanted signals, SR selectivity augments the signal of interest.

Applying the SR transformation provides the brain with a very powerful tool for:

1. Classification of unrecognized signals by spreading the frequencies over a much wider range for ease of recognition
2. Building an adapted augmenting filter around specific frequencies of interest
3. Storing filter templates for signals of interest (e.g., the voice of specific persons). Note that these templates offer a very compact form of recognition storage.

SIGNAL IN NOISE PROCESSING USING SR

Speech-in-Noise Discrimination has the hallmarks of SR processing. Consider the following: Three conditions are necessary for SR to occur: a coherent target signal, an energetic barrier, and a source of stochastic noise. To prove that SR can solve the problem of speech-in-noise discrimination, one needs to identify these elements:

1. The coherent target signal - which is the target speech that needs to be discriminated from background babble. The requirement for coherency means that we examine vowels (vowels have low frequency contents and contribute most of the speech acoustic energy).
2. The energetic barrier - which is the nerve's threshold. Below it a signal does not register.
3. Sources of stochastic noise - which we suggest (see below) are the Otoacoustic Emissions.

SR processing meets some of the criteria listed above for an acceptable solution to the problem of SIBD:

High frequency spread and non-linearity (criteria 1 and 2) - as explained above, the non-linearity introduced by SR implies that the target signal is accompanied by additional higher frequencies that are not harmonics of the original signal. The additional frequencies are higher because they are add-ons to the original frequency.

No prior knowledge (criterion 3) - Sensory systems are the brain's windows and gate keepers to the world. Any incoming information falls under one of three categories:

1. Familiar - an expected piece of information that can be reduced or used to confirm what is already known.
2. Noise - considered irrelevant or even disturbing and should be ignored
3. New - and relevant, requires response and can be added to the learning data base.

This simple analysis implies that the treatment of input data is based on previously learned rules and is thus an evolving learning process. In other words: perception is an interaction of objective input and a pre-existing internal model of the world. As a first step though, one needs to apply a strategy like SR that can improve unknown inputs.

Neural Networks application (criterion 4) - Cognitive processes in the brain are usually associated with Neural Networks (NN). The simplest (Hebbian) model of NN operates in one of two modes: Learning mode and Computational mode. In the learning mode the different transformation possibilities are weighted by their ability to improve the solution. When a satisfactory solution is reached the NN switches to the computational mode. In this mode signals (new information) passing between the brain's network nodes are not amplified (or attenuated) in the "analog" sense of the word, namely, no energies are added (or reduced). Rather, the weights computed in the learning mode determine whether a given portion of the incoming signal will be used (pass through). In other words, a node is connected if the associated weight is large enough to cross the threshold, thus allowing the signal to pass through it.

The simplified NN model is not sufficient to explain how learning proceeds alongside usage of pre-existing knowledge in cognitive processes. In order to perform selective processing an optimal policy is adapted: a feedback mechanism that dynamically adjusts weights allows both existing knowledge and adaptation to modulate new information. This is consistent with models of Neural Networks adaptability: Adaptive Resonance Theory (ART)[4] or theories about Hebbian networks plasticity[5].

Evidence of stochastic signals playing a role in internal message transfer of organisms is abundant in the literature; noteworthy though is a recently published paper about the group behavior of social amoebae controlled by their generated stochastic signals[6]. The release of the neuro-transmitters at the synapse may also be affected by induced stochastic changes in membrane potential, which, in turn, will modulate the release of synaptic vesicles and neuro-transmitter.

In the last decade, researchers have suggested that SR plays a role in signal processing in sensory systems[7] and in other brain functions. Experiments with a neuronal network from a mammalian brain[8] demonstrated that weak signal delivery can be improved with the assistance of noise. More support for the contribution of SR to brain processing was supplied by showing reliability enhancement of neural response by SR[9] and by showing that under certain conditions neural SR exhibits error-free information transfer[10].

More specifically, the addition of white noise for assisting speech processing has been proposed by[11], using white noise as the stochastic signal and testing vowel recognition as the measured variable, confirm the predictions for non-matched noise (as opposed to noise with frequency contents similar to the target speech). As mentioned above, vowels are more coherent because of their low frequency contents as opposed to consonants; the theory predicts that SR is applicable to vowels as was confirmed.

In order for SR processing to qualify as a solution for the SIBD problem, it is necessary to show how the brain controls the stochastic signals (criterion 6 of the problem statement). Randomly generated white stochastic signals cannot serve as a control mechanism. In order to provide a complete solution, it is necessary to refer to Otoacoustic Emissions.

OTOACOUSTIC EMISSIONS (OAE)

SR is activated whenever any potentially unfamiliar signal is transmitted across neural networks by properly augmenting it. In this way, SR provides a connectivity control mechanism. In fact, connectivity control is the other aspect of signal augmentation.

In all of the previous reports, stochastic noise generation was attributed to external and internal naturally occurring sources. SR signal augmentation, in neural networks terminology, is an adjustment of the weights of selected inputs. Because of the importance of the stochastic signal, its generation cannot be arbitrary or uncontrolled, so a dedicated, controlled internal process is proposed.

Otoacoustic Emissions (OAE) is the noisy mechanical output of the Outer Hair Cells (OHC) on the outer side of the cochlear basilar membrane. The sound emitted by the OHC is stochastic, but not white and the frequencies generated by the outer hair cells are around the input audio signal frequencies[12]. Because of the close proximity of the inner and the outer hair cells, the OHC mechanical output affects the sensitivity of the Inner Hair Cells (IHC), but the precise mechanism is disputed. A popular theory among audiologists suggests that it is a resonance or a positive feedback effect[12]. This explanation is countered by empirical evidence[13] and by theory: in order for any one of these mechanisms to operate, the amplifying signal (OHC output) must follow the amplified signal very closely, i.e., exactly the same frequency at exactly the same phase. OAEs cannot accomplish such temporal proximity because no *a priori* knowledge of the target signal is available and a mechanical delay between sound and OAEs is inevitable.

Possible explanations for the role of OAE in speech-in-noise discrimination may be found in two areas:

1. Pathology - In some severe cases of vertigo, patients undergo a neurectomy which also severs the Olivo-Cochlear bundle[14]. This efferent nerve bundle includes fibers that control OHCs and OAE. Follow-up studies revealed two side effects: 1) Decreased ability to discriminate vowels in a noisy situation, 2) Vocal attention shift delays.
2. Chaos Theory - Physicists have associated SR with speech as discussed at length before. White noise was selected as the source of stochastic noise[15], while for the coherent target signal vowels with their low frequency contents were selected. They simulated a neuron with threshold and showed that the coherent vowel-like signal is augmented by applying the white noise.

Understanding the role of noise in sound processing[16] leads to the use of added noise in cochlear implants[17]. OAE is an example of signal augmentation:

frequency selectivity of neural activity is increased by narrowing the mechanical tuning curves.

The question may arise about what else ties OAE with SR in addition to pathology. SR theory predicts that the stochastic signal should have a frequency content that is similar to the target signal. Figure 2 below shows a comparison between standard Speech Shaped Noise (SSN) (bottom) and the average output of OAE at the same frequency range (top) (source: Madsen OAE measurement instrument.

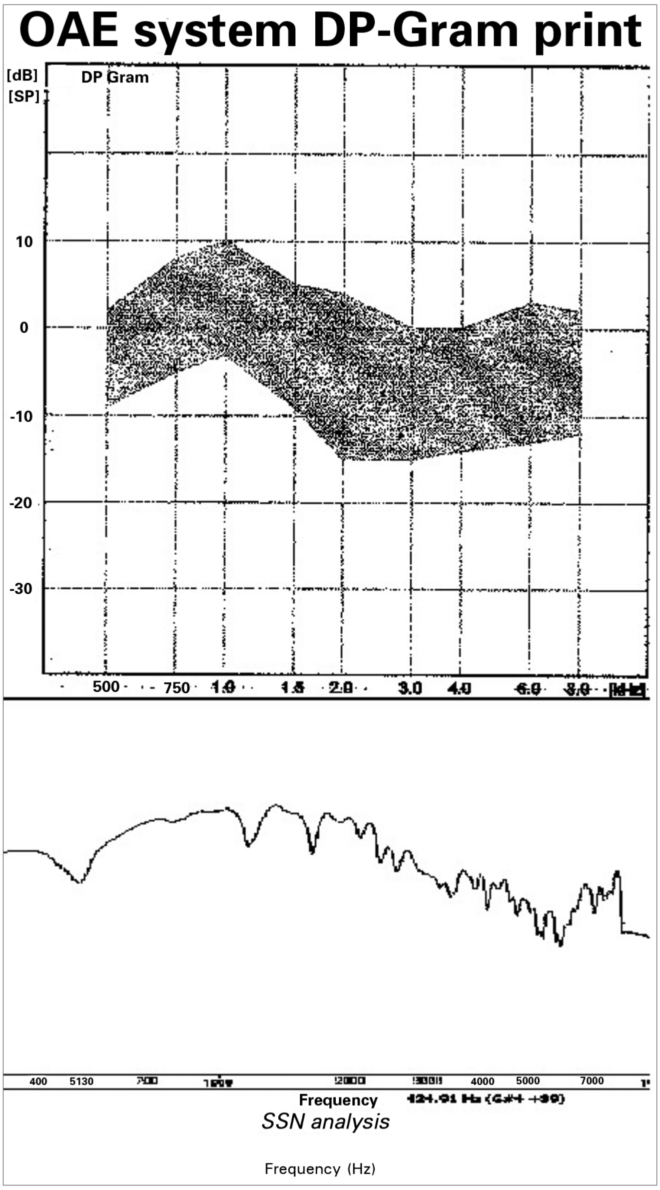

Figure 2. SSN vs DPOAE output.

The spectral contents of Speech Induced Emission Noise (SIEN) as recorded by commercially available OAE instruments and SSN are very similar and for testing purposes one can replace the other.

In order to demonstrate the cognitive aspect of SR processing of speech we created a simple five-sentence demonstration[18]:

1. An English five words sentence "immersed" in background babble. The babble is 6dB louder than the target speech (SNR = -6). Deciphering the target speech is very difficult (File: 01 Clean_with_Babble.wav).
2. The clean target sentence without noise. The sentence is meaningless but the syntax is correct (File: 02 Clean.wav).
3. Sentence (1) after application of an SR transformation: stochastic noise was added and signals above threshold were shifted upwards and added to the basic mix. Note that the target speech is more understandable. The improvement is equivalent to about 3 dB (File: 03 Transformed.wav).
4. A different sentence that underwent the exact same transformation as sentence (3) yet its intelligibility is worse and the background babble is more distinctive (File: 04 Also_Transformed.wav) (alternate between (3) and (4) to hear the difference).
5. The clean target sentence from (4): underscores the role of cognitive intervention (understanding the language) without which the babble is overwhelming. This clearly explains why one cannot understand this sentence (File: 05 Also_Transformed.wav).

The potential for improvement of speech recognition with a non-matched stochastic signal was also demonstrated by computer simulations[19] showing that stochastic fluctuations enhance the encoding of low level acoustic signals. More specifically, stochastic resonance lowers the detection threshold of auditory signals by an order of magnitude. None of these simulations identified OAE as the source of stochastic noise. Rather, Brownian motion and other physiological activities were considered sources of the noise.

TESTING PROCEDURE

Testing was performed to support this hypothesis. Initially the addition of SIEN was tested[20]. This test was based on selected syllables. Encouraging results prompted advancement to the next step.

Two HINT based tests were created: one to set the optimal conditions for this SR application and another to measure the improvement. Words selected for both tests were mostly from the standard spondee list. The words were arranged in accordance with Hagerman's[21] methodology.

The SR transformation, namely adding Speech Induced Emission Noise (SIEN) and performing a non-linear upward shift, is the hypothesized method. Therefore, the first test used a direct multi-variable optimum search method[22] to determine the values of the transformation (filter) parameters:

1. The ratio of SIEN mixed to the target Speech/Babble mix
2. Stochastic Resonance (SR) transformation is a threshold phenomenon, therefore the threshold level around which the transformation occurs.
3. Even around the threshold only a portion of the mix is transformed; the fraction (%) of the incoming signal untransformed.

The second/main test was a HINT test with Hagerman sentences with a varying SNR between target speech and background babble. Each 20-sentence set had 10 sentences which were SR transformed and 10 without it (control). The order of the sentences was set at random by the computer program to create a double blind test.

First, we tested a group of NH subjects. With the transformation parameters determined in the first test, we performed the second double blind test with each subject being his own control. 80 sentences divided into 4 tests of 20 sentences each were presented to the subjects binaurally in an adaptive procedure to find the SNR threshold. The subjects were divided into 3 groups as follows:

1. NH 50% - consisted of 8 normally hearing subjects whose SNR threshold was set at the point where they could repeat 50% of the words in the sentences.

2. HI - a group of 9 hearing impaired subjects whose SNR threshold was set at the point where they could repeat 50% of the words in the sentences.

3. NH 70% - Assuming that SNR scores at the first NH group might reach a ceiling, another group consisting of 10 normally hearing subjects was tested and their SNR threshold was set at the point where they could repeat 70% of the words in the sentences.

The population tested includes 9 HI and 8 NH. The age range is 23 to 90.

RESULTS

The optimum point was found in the first test to be: 25dB of added SIEN and 17% mix of the non-linear transformation. Table 1 presents the results for the NH subjects.

The mixed procedure was used to analyze the results. We found a main effect of filter (F = 16.49, $p < 0.0001$ (DF = 1)). Using the Wilks' Lambda test we found a main effect of filter for the first and third tests (Wilks' Lambda = 0.348, $p < 0.0001$and Wilks' Lambda = 0.73, $p = 0.0067$, correspondingly).

A main effect of group was found as well (F = 16.84, $p < 0.0001$ (DF = 2)).The group effect was found for each of the tests (F = 15.06, $p < 0.0001$ (DF = 2), F = 15.90, $p < 0.0001$ (DF = 2), F = 11.3, $p = 0.0003$ (DF = 2) and F = 6.86, $p = 0.0061$ (DF = 2) for tests 1-4, correspondingly).

We did not find a significant interaction between group and filter. An interaction between group and filter was found only for the first (Wilks' Lambda = 0.768, $p = 0.0421$) and second (Wilks' Lambda = 0.73, $p = 0.0251$) tests.

Figure 3 presents the results of each group for the 4 tests. The tests show an improvement of about 2 to 3 dB SNR of speech intelligibility. The improvement is much more significant for Hearing Impaired (HI) subjects when comparing the 50% groups. These results were implemented in a hearing aid add-on patent[23] which improves the separation between target speech and background babble by about 3dB.

SPEECH IN BABBLE DISCRIMINATION MODEL

We propose a Speech-in-Background-Babble Discrimination (SIBD) model based on SR. In this model the SIBD process is a four-step operation:

1. When the speech signal arrives at the inner ear, the Outer Hair Cells (OHC) generate a general speech spectrum stochastic signal which is added to the incoming signal to create a non--linear (non-harmonic) frequency expansion of the input signal, spreading the signal frequencies over a wider range. This non-linear spread (the SR spread) of frequencies is in effect a pre-processing or adaptive step. For example, imagine a pile of coins that needs to be sorted. As a first step what we usually do is spread the coins over a larger area so we can appreciate the diversity of coins present. This step is called an expansion step. Expansion allows the brain to acquire some information about the target signal in relation to the noise so that it can create a new filter or apply an appropriate filter (adaptation phase). As the input progresses, more and more information about the target signal is known and the filter is adapted to better match the target signal and allow the sensory system to augment it above noise.
2. The cognitive system picks out the speaker of interest and initiates signal augmentation.
3. The brain stem in turn modulates the OHC to generate a narrow spectrum stochastic signal to form a filter that matches the speaker. This would be a narrow frequency range as opposed to the wide frequency speech shaped noise that was used in the expansion of step 1.
4. When attention is shifted to another speaker the process is repeated.

This model allows for the inclusion of guidance from the cognitive system as required by an effective solution. In addition, storing a frequency profile for easier discrimination later is applicable here, as it is easier to identify a voice that we have heard before.

Table 1. SR transformation - parameters determination.

		SIEN added in dB						
		20	25	30	35	40	45	50
Transformation mix (%)	0	2.08	2.87	2.13	2.83	1.83		1.63
	3			0.50				
	7			0.33				
	10	1.63	2.92	2.13	2.85	0.75		2.25
	13	2.00	3.00	1.90	3.15	2.50		
	17	1.63	2.58	2.20	2.75	1.50		3.25
	20	2.19	2.83	1.85	2.55	2.13		2.25
	23	2.88	2.67	2.20	2.45	1.50		2.25
	27	2.83	2.83	1.65	2.30	2.00		1.25
	30	2.63	2.63	1.28	2.20	1.75		1.25
	33	0.88	2.58	1.81	1.80	2.00		1.50
	37	1.50	2.83	1.44	1.50	1.50		
	40	1.13	2.42	1.38	1.90	1.00		0.50

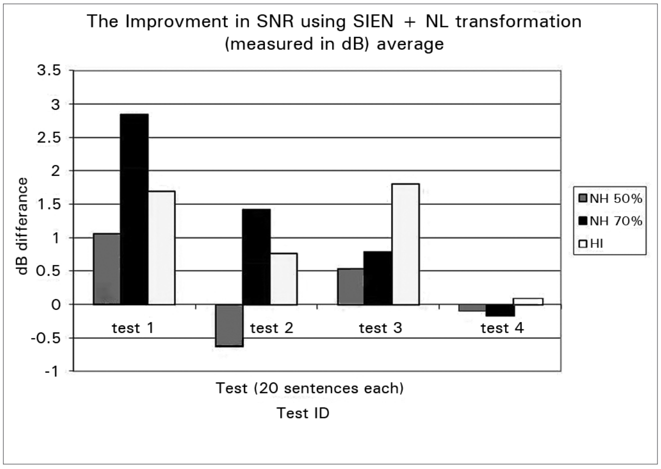

Figure 3. Test results Summary.

Another insight gained by this model is that although Speech in Noise Discrimination is a cognitive process, the actual separation is performed at the early sensory level, with selectivity of the process modulated by cognition.

The Auditory Brainstem Response (ABR) to click stimuli allows electrophysiological assessment of the auditory pathway function, providing information on integrity and timing of neural activity in the brainstem. Speech-evoked ABRs provides a frequency following response of phase-locked neural activity in the brainstem. The response to the properly presented syllable (e.g.,/da/) is enhanced compared to backward presentation of the same syllable. This would suggest that cognition is involved in modulating brainstem activation, which supports Step[2].

RELEVANCE TO OTHER SENSES

The principles governing neural function in hearing are not unlike any other part of the nervous system and may therefore be also applicable to other sensory systems and to brain processing in general. Therefore, SR rules can be generalized to other brain functions in addition to other senses besides hearing. SR may play a role in other aspects of brain function.

A review of SR in sensory information processing[7] examined the possibility of stochastic neural activity initiated by the outer hair cells (OAE) influencing computations in other brain sites. The neural activity associated with audible sound frequencies implies that the influence of cells located in the inner ear is widespread. Thus, Lugo et al. have “demonstrated that the same auditory noise can enhance the sensitivity of tactile, visual, and propioceptive system responses to weak signals. Specifically, we show that the effective auditory noise significantly increased tactile sensations of the finger, decreased luminance and contrast visual thresholds and significantly changed EMG recordings of the leg muscles during posture maintenance”[24]. In addition, other sites that generate stochastic signals have been identified in the brain.

CONCLUSION

SR predicts that the enhancement of signals in the ear is non-linear with a threshold effect process. The stochastic signal frequency contents are not completely random, and can be shaped to match the target signal’s frequency as the name resonance implies. An exact frequency match, as in resonance, is not necessarily sought for because a close enough match will allow crossing neural threshold. Thus, neural activity is enhanced by narrowing the mechanical tuning curves. We show that our results, using emission noise, show a higher discrimination rate than results reported using non-matched noise such as white noise.

The contribution of SR to brain processing is therefore highly dependent on its ability to mix the crafted noise with the target signal and thus facilitate its transmission through the brain's network. It should be emphasized that the SIBD model proposed is a cognitive process which heavily relies on previous knowledge.

Our test results provide evidence supporting the hypothesis. SR action provides an augmentative filter which preprocesses the information for the brain to do the actual separation.

REFERENCES

1. Microphone problem statements. In: Bauer, Stephen, editor. Stakeholder Forum on Hearing Enhancement [Internet]; 2000 June 9-10; New York, NY. Buffalo, NY: Rehabilitation Engineering Research Center on Technology Transfer; 2000; [cited 2011 Apr 1]. Available from: http://t2rerc.buffalo.edu/pubs/forums/hearing/hearing.pdf
2. Wiesenfeld K, Moss F. Stochastic resonance and the benefits of noise. From ice ages to crayfish and squids. Nature. 1995;373(6509):33-6.
3. Gammaitoni L, Hänggi P, Jung P, Marchesoni F. Stochastic resonance. Rev Mod Phys. 1998;70(1):223-87.
4. Carpenter GA, Grossberg S. Adaptive resonance theory In: Arbib MA, editor. The handbook of brain theory and neural networks. 2nd ed. Cambridge, MA: MIT Press; 2003; p. 87-97.
5. Song S, Miller KD, Abbott L. Competitive hebbian learning through spike-timing-dependent synaptic plasticity. Nat Neurosci. 2000;3(9):919-26.
6. Prindle A, Hasty J. Stochastic emergence of groupthink. Science. 2010;328(5981):987.
7. Moss F, Ward LM, Sannita WG. Stochastic resonance and sensory information processing: A tutorial and review of application. Clin Neurophysiol. 2004;115(2):267-81.
8. Gluckman BJ, Netoff TI, Neel EJ, Ditto WL, Spano ML, Schiff SJ. Stochastic resonance in a neuronal network from mammalian brain. Phys Rev Lett. 1996;77(19):4098-101.
9. Schreiber S, Samengo I, Herz AVM. Two distinct mechanisms shape the reliability of neural responses. J Neurophysiol. 2009 May 1;101(5):2239-51.
10. Yasuda H, Miyaoka T, Horiguchi J, Yasuda A, Hanggi P, Yamamoto Y. Novel class of neural stochastic resonance and error-free information transfer. Phys Rev Lett. 2008;100(11):118103.
11. Moskowitz MT. Stochastic resonance in speech recognition: A neural-mediated role for additive Gaussian noise on the peripheral level [dissertation]. [Princeton, NJ]: Princeton University; 2001. 79p.
12. Kemp DT. Stimulated acoustic emissions from within the human auditory system. J Acoust Soc Am. 1978;64(5):1386-91.
13. Karavitaki KD. Experimental evidence does not support feed-forward outer hair cell forces. 1999. 84p.
14. Zeng FG, Martino KM, Linthicum FH, Soli SD. Auditory perception in vestibular neurectomy subjects. Hear Res. 2000;142(1-2):102-12.
15. Hohn N, Burkitt AN. Modelling the Neural Response to Speech: Stochastic Resonance and Coding Vowel-like Stimuli. In: Proceeding of the IEEE Engineering in Medicine and Biology Society (EMBS) Conference [Internet]; 2001 February 19, Melbourne, Australia. Melbourne, Australia: The Bionic Ear Institute, 2001. p.21-4 [updated Feb 2001; cited 2011 Apr 1]. Available from: http://nicolas.hohn.googlepages.com/Hohn_Burkitt_EMBS_2001.pdf
16. Jaramillo F, Wiesenfeld K. Mechanoelectrical transduction assisted by brownian motion: A role for noise in the auditory system. Nat Neurosci. 1998;1(5):384.
17. Zeng FG, Fu QJ, Morse R. Human hearing enhanced by noise. Brain research. 2000;869(1-2):251-5.
18. Rembrand R. A successful application of SR transformation to solve a cognitive problem in understanding speech masked by background babble. [Internet]. Haifa, Israel: Evoked Potential Laboratory, Technion IIT [updated 2011 Mar 1; cited 2011 Apr 1]. Available from: http://www.technion.ac.il/eplab/stimuli%20demonstration/rafi%20rembrandt/speech%20masked%20by%20background%20bable.htm
19. Svrcek-Seiler WA, Gebeshuber IC, Rattay F, Biro TS, Markum H. Micromechanical models for the brownian motion of hair cell stereocilia. J Theor Biol. 1998;193(4):623-30.
20. Kishon-Rabin L, Gam S, Shiff T, Rembrand R, Roth DA. Speech perception enhanced by noise in listeners with normal hearing. J Basic Clin Physiol Pharmacol. 2008;19(3-4):237-48.
21. Hagerman B. Sentences for testing speech intelligibility in noise. Scand Audiol. 1982;11(2):79-87.
22. Press, WH, Teukolsky, SA, Vetterling, WT, Flannery, BP. Numerical recipes in C: the art of scientific computing. 2nd ed. Cambridge: Cambridge University Press; 1992.
23. Rembrand R, Aboody Y, inventors; NEAT Ideas NV., assignee. Hearing Aid. United States patent US 20,040,234,089. 2003 July 20.
24. Lugo E, Doti R, Faubert J. Ubiquitous crossmodal stochastic resonance in humans: Auditory noise facilitates tactile, visual and proprioceptive sensations. PLoS ONE [Internet]. 2008 [cited 2009 Jan 3];3(8):e2860. Available from: http://www.plosone.org/article/info:doi%2F10.1371%2Fjournal.pone.0002860