

7-2019

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Technical Report: UTEP-CS-19-63

Published in *Applied Mathematical Sciences*, 2019, Vol. 13, No. 14, pp. 677-680.

Recommended Citation

Acosta, Griselda; Smith, Eric; and Kreinovich, Vladik, "Why Pink Noise Is Best for Enhancing Sleep and Memory: System-Based Explanation" (2019). *Departmental Technical Reports (CS)*. 1340.

https://scholarworks.utep.edu/cs_techrep/1340

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Why Pink Noise Is Best for Enhancing Sleep and Memory: System-Based Explanation

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Abstract

Several researchers found out that acoustic stimulation during sleep enhances sleep and enhances memory. An interesting – and somewhat mysterious – part of this phenomenon is that out of all possible types of noise, the pink noise leads to the most efficient stimulation. In this paper, we use general system-based ideas to explain why in this phenomenon, pink noise works best.

1 Formulation of the Problem

Acoustic stimulation helps sleep and memory: a brief description of the observed phenomenon. Several researchers found out that acoustic stimulation during sleep help patients to sleep better and enhanced their memory; see, e.g., [4, 5, 6, 8].

Qualitative explanation of the phenomenon. While the level of enhancement was much higher than most researchers expected, the very fact that exercising some organ is good should be expected: it helps to exercise muscles, it helps to exercise brain activities, it helps to exercise visual activities, etc.

It is also understandable that a noise helps better than a signal emitted at a single frequency: just like exercising different muscles is better for a person's overall health than focusing on a single group of muscles, just like practicing different types of mental activities is better for a person's mental abilities than repeatedly performing tasks of the same type, it is reasonable to expect that processing components of different frequencies will work better than processing only one frequency.

Pink noise: why? The best stimulation results were obtained when the researchers applied *pink noise*, i.e., the noise in which the power spectral density $S(f)$ (i.e., energy per unit frequency) is inverse proportional to the frequency itself: $S(f) = \frac{c}{f}$ for some constant c .

From the biological viewpoint, this may not be that surprising, since the pink noise is the most common signal in biological systems; see, e.g., [7] (see also [2] and references therein). In particular, pink noise is a good description of signals corresponding to mental activities; see, e.g., [?]. Pink noise is also ubiquitous in nature in general: e.g., in describes the statistical structure of many natural images; see, e.g., [1].

However, from the scientific viewpoint, the efficiency of pink noise is still somewhat a mystery, since it is not clear why the use of the most biological signal would lead to a better enhancement than any other possible signals.

What we do in this paper. In this paper, we provide a system-based explanation of why pink noise is the most efficient one.

2 Our Explanation

Main idea. As we have mentioned earlier, the best results are usually achieved when different organs, different parts of the organs are all involved. With respect to frequencies, this means that the biological acoustic sensors corresponding to all the frequencies should be involved.

Of course, if on one of the frequencies, we have a very weak signal, this means that the sensor corresponding to this frequency is practically not exercised at all. So, to make sure that the exercise leads to the largest possible effect, it is reasonable to require that each of these sensors is exercised similarly, i.e., in precise terms, that the energy of the part of the signal affecting each sensor will be the same for all sensors.

To describe this idea in precise terms, we need to recall which part of the signal is affecting each of these sensors.

Acoustic perception: a particular case of the general Weber's law.

In general, our perception – be it visual or acoustic or any other – follows the *Weber's law*, according to which, for each perceived quantity x , the just noticeable difference Δ_x is proportional to the actual value of this quantity, i.e., $\Delta_x = \delta \cdot x$ for some $\delta > 0$; see, e.g., [3].

In particular, for the frequency, this means that for each frequency f , the just noticeable difference in frequency $\Delta_f(f)$ should be proportional to the frequency itself, i.e., we should have $\Delta_f(f) = \delta \cdot f$, for some value $\delta > 0$. In other words, each biological acoustic sensor corresponding to a certain frequency f actually takes in all the frequencies from f to $f + \Delta_f(f) = f + \delta \cdot f$.

What will happen if we have a signal with power spectral density $S(f)$? By definition, the power spectral density is the energy per unit frequency. Thus, to get the overall energy $E(f)$ affecting this sensor, we need to multiply the

power spectral density $S(f)$ by the width $\Delta_f(f)$ of the corresponding frequency interval $[f, f + \Delta_f(f)]$. As a result, we get the value

$$E(f) = S(f) \cdot \Delta_f(f) = S(f) \cdot \delta \cdot f.$$

As we have mentioned, the best effect is expected when each sensor gets the exact same amount of energy, i.e., when $E(f) = \text{const}$. For the above expression $E(f) = S(f) \cdot \delta \cdot f$, the requirement $E(f) = \text{const}$ means that, to achieve the best effect, we should use the power spectral density $S(f) = \frac{\text{const}}{\delta \cdot f}$. This is exactly the pink noise, with $c = \frac{\text{const}}{\delta}$. Thus, we have indeed explained why, out of all possible types of acoustic noises, the pink noise leads to the most efficient stimulation of sleep and memory.

Acknowledgments

This work was supported in part by the National Science Foundation via grants 1623190 (A Model of Change for Preparing a New Generation for Professional Practice in Computer Science) and HRD-1242122 (Cyber-ShARE Center of Excellence).

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