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Why Noise Improves Memory in ADHD Children

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Abstract

Noise is typically conceived as being detrimental for cognitive performance. Contrary to this notion recent studies have found that auditory noise may in some cases improve cognition. Recent data and theories suggest that this beneficial effect of noise depends on several factors including the type of task being performed and noise levels. More importantly, whereas some groups of children increase performance during noise other groups declines. From our point of view these findings can be accounted for in a neurocomputational theory where noise interacts with dopamine, environmental factors, and individual levels of dopamine, where well controlled levels of noise may be beneficial for cognitive performance.

Introduction to noise induced enhancements of cognitive performance

Noise is typically considered to be deleterious for cognitive functioning. Under most circumstances cognitive processing is easily disturbed by noise from the environment and non-task distractors, an effect that has been known for a long time (Broadbent, 1954, 1957, 1958a, 1958b). The effect of distraction is believed to be due to competition for attentional resources between the target stimuli and the distractor i.e., the distractor removes attention from the target task. Repeated research on this topic has demonstrated this finding to hold across a wide variety of target tasks, distractors and participant populations (Belleville et al., 2003; Boman et al., 2005; Hygge et al., 2003; Rouleau & Belleville, 1996; Shidara & Richmond, 2005). Most experiments since Broadbent's days have dealt with the negative effects of noise and distraction. However recently, in contrast to the main body of evidence regarding distractors and noise, the opposite has been shown. Two studies were able to demonstrate that under certain circumstances ADHD participants could benefit from auditory, task irrelevant noise presented concurrently with the target task (Abikoff et al., 1996; Gerjets et al., 2002). This finding is particularly surprising because persons with attentional problems, for example attention deficit hyperactivity disorder (ADHD) children are known to be more vulnerable to distraction compared to normal control children (Blakeman, 2000; Brodeur & Pond, 2001; Higginbotham & Bartling, 1993). These studies did not, however, provide a satisfactory theoretical account for why noise was beneficial for cognitive performance. Our research has recently extended these findings and suggested a theoretical framework for understanding these apparently contradictory results. We showed that auditory stimulation effect had different effects on the memory performance of children with ADHD and control children (Söderlund et al., 2007). These effects were replicated in two studies for children with sub-clinical attentional problems (Söderlund et al., in progress). In this chapter we review our findings that the noise induced improvements in cognitive performance can be accounted for by a statistical phenomenon that occurs in threshold-based system called stochastic resonance. We suggest that auditory noise can, under certain prescribed circumstances, improve attention and cognitive performance in inattentive children. We review a model and findings that shows a link between noise stimulation and cognitive performance. This is accomplished in the Moderate Brain Arousal (MBA) model (Sikström

& Söderlund, 2007), which suggests a link between attention, dopamine transmission, and external auditory noise (white noise) stimulation.

The Moderate Brain Arousal Mode

Stochastic resonance (SR) is the counterintuitive phenomenon by which weak signals that cannot be detected because they are presented under detection threshold, become detectable when additional random (stochastic) noise is added (Moss et al., 2004). SR may be conceived as that noise adds additional energy to the signal and pushes it above the threshold for detection. However, it should be noted that beneficial effect of SR is found also when the threshold is lower than the signal.

SR, although a paradoxical phenomenon, is well established across a range of settings; it exists in any threshold-based system with noise and signal that requires the passing of a threshold for the registering of a signal. Figure 1 is a representation of this phenomenon.

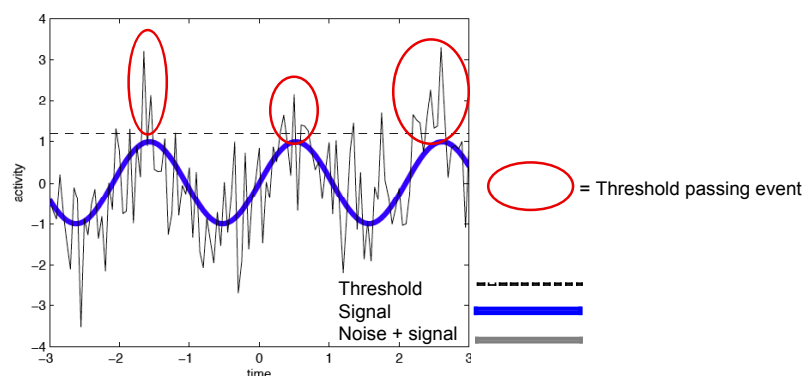


Figure 1: Stochastic resonance where a weak sinusoidal signal goes undetected as it does not bring the neuron over its activation threshold. With added noise, the same signal results in action potentials.

SR has been identified in a number of naturally occurring phenomena and the concept has been used to explain climate changes (Benzi et al., 1982); bistable optical systems (Gammaitoni et al., 1998); mechanoreceptors of the crayfish (Douglass et al., 1993); and the feeding behavior in the paddlefish

(Russell et al., 1999). In particular SR has been found in neural systems and in behavioral data. Threshold phenomena in neural systems are linked to the all-or-none nature of action potentials and they can be modeled by a non-linear activation function, the sigmoid function, that estimates the probability that a neural cell will fire (Servan-Schreiber et al., 1990). This firing probability or gain parameter modifies how responsive a neural cell is to stimulation; the higher gain (less random response) the better performance. In humans SR has been found in the different modalities, including audition (Zeng et al., 2000), vision (Simonotto et al., 1999), and touch (Wells et al., 2005) etc., where moderate noise improves sensory discriminability. In fMRI scans a moderate noise level increased neural cortical activity in visual cortex (Simonotto et al., 1999).

Interestingly, the SR effect is not restricted to sensory processing; SR has been found an enhancing effect in higher cognitive functions as well. Auditory noise improved the speed of arithmetic computations in a normal population (Usher & Feingold, 2000). The amount of noise to induce an SR-effect on higher functions is much higher as compared to the ones used in signal detection experiments. In Usher et al's. (2000) experiment noise levels ranged between 50-90dB and performance, as measured by reaction times, were fastest at 77dB noise level. Moreover, SR can be transferred to other modalities as e.g. auditory noise improves visual detection (Manjarrez et al., 2007) and has a role in the motor system as well (Martinez et al., 2007). SR may also play a role in patients with neuro degenerative disease suggesting that SR may also improve central processing (Yamamoto et al., 2005). Tactile stochastic stimulation provided by vibrating insoles improved balance control in elderly (Priplata et al., 2003), in stroke and diabetes patients (Priplata et al., 2006), and also improved gait i.e. speed, stride length and variability in Parkinson patients' (Novak & Novak, 2006).

Inattention, dopamine and Stochastic Resonance

Noise induced cognitive enhancement is of particular interest in ADHD children that normally are viewed as having severe problem with attention. There are several types of attentional problems, and these problems are also depending on the subtype of ADHD (Nigg, 2005). Paradigms involving attention deficits include; delay aversion, deficit in arousal/activation regulation, and executive function/inhibitory deficits (Castellanos & Tannock, 2002). Delay aversion is the phenomena that characterized by intolerance for

waiting and is believed to be related to difficulty in sustaining attention on long and boring tasks (Sonuga-Barke, 2002). Poor regulation of activation or arousal are also connected with inattention (Castellanos & Tannock, 2002) and hyperactivity may be regarded as a form of self-stimulation to achieve a higher arousal level. Executive deficits are predominantly linked to impairments in working memory and effortful attentional control shown in the difficulty to stop an ongoing response and response shift (Casey et al., 1997).

The MBA model suggests that attentional problem adheres from too strong reactions from environmental stimuli that are caused by too low levels of extracellular dopamine. Dopamine signaling comes in two different forms. One form is stimulus independent, more or less continuous and is called tonic firing. This form determines the amount of dopamine in the extracellular fluid. The second form is fast and stimulus dependent, and is called phasic dopamine release. The tonic form modulates the phasic form via a pre-synaptic auto feedback mechanism. Autoreceptors in the pre-synaptic cell are activated when the tonic level is too high and suppresses spike-dependent phasic dopamine release. However, when the tonic levels are low the phasic releases increases (Grace, 1995). Too much tonic firing inhibits phasic release and is, according to the MBA model, associated with cognitive rigidity. Low tonic levels, in contrast, cause neuronal instability and boosted phasic responses (Grace et al., 2007). Excessive phasic transmission could cause instability in the neuronal network activation and is related to symptoms of failure to sustain attention, distractibility and excessive flexibility that are common in ADHD. It is known that ADHD has low tonic dopamine levels (Volkow et al., 2002) and from the MBA perspective this leads to an abundance of phasic dopamine release and behavioral problems. In this context we prefer to view ADHD not as a discrete category, rather we believe that children could be more or less more likely to have the symptoms that are typical of ADHD and it should be viewed as a continuous dimension. From this view ADHD like symptoms are spread in the populations and can explain inattention and hyperactivity seen in normal populations as well. A major insight gained from the MBA model is that individual differences in the level of background noise within the neural system (linked to differences in dopamine signaling) will be reflected in different effects of environmental noise on performance.

Simulation of dopamine in neural cells shows that a neural system with low dopamine levels requires more noise for an optimal performance. This modeling has been contacted in the MBA model where dopamine is

manipulated by the gain parameter. This modeling shows that children with low levels of dopamine (ADHD and inattentive) require more noise than attentive children to perform well in cognitive tasks. Attentive children are believed to have enough internal noise for performing well. Therefore, neural systems with low levels of noise, as in inattention, require more external noise for the facilitating effect of SR to be observed. Accordingly, systems with high internal noise levels require less external noise. In this sense the individual levels of neural noise, and the individual SR curve, influence the external noise and performance differently. The effect of noise on performance follows an inverted U-shaped curve. A moderate noise is beneficial for performance whereas too little and too much noise diminish performance. Levels of noise that enhance performance of children with low internal noise attenuate performance for children with higher levels of internal noise. The MBA model takes as an input an external noise and a signal that in turn activates internal neural noise and signal. Through the SR phenomenon these provide an output measured by cognitive performance. Thus, this provides a straightforward prediction of noise-induced improvement in cognitive performance in ADHD and inattentive children.

To conclude, the MBA model predicts that the dopamine system modulates the SR phenomenon leading to that cognitive performance in ADHD and inattentive children benefits from noisy environments. The stochastic resonance curve is right shifted in ADHD due to lower dopamine. The MBA model predicts that for a given cognitive task ADHD children and inattentive children require more external noise or stimulation, compared to control children, in order to reach optimal (i.e. moderate) brain arousal level. This prediction is tested in three studies that are reviewed below.

Experimental support of the MBA model The affirmed predictions of the MBA model have been experimentally tested in three studies consisting of an episodic memory task where participants are learning word pairs. The main manipulations were auditory noise and grouping of children based on ADHD and other behavioral testing. Participants are presented with verbal commands, simple verb – noun sentences such as “roll the ball” or “break the match” (Nilsson, 2000). At the subsequent memory test, participants are instructed to remember as many of the verbal commands presented as possible. Results from the studies are summarized in figures 2 to 4 below. For a more extensive description of study 1 see Söderlund et al. (2007), study 2 and 3 see Söderlund, Sikström and Loftesnes (in preparation).

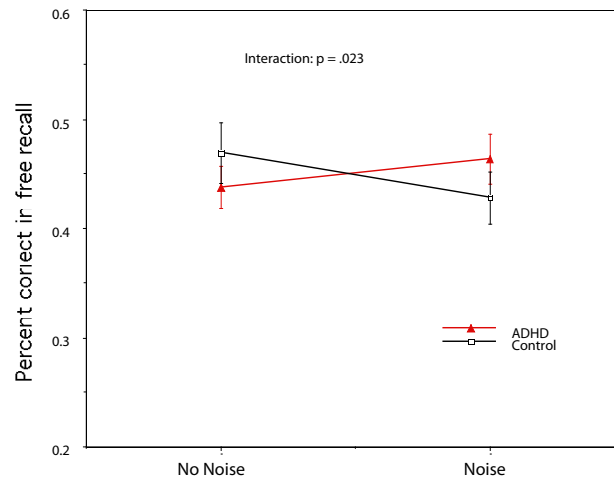


Figure 2. Study 1; Percentage correct recall as a function of noise and group (ADHD vs. Control)

In study 1 (Söderlund et al. 2007), ADHD and normal children participated in a word pair learning task followed by a free recall task, which was conducted either during noise exposure or a silent control condition. The results showed an interaction between noise and group when medicated children were excluded while medication could be a possible confound. ($F(1,33) = 5.73$, $p = .023$, $\eta^2 = .15$) (see Figure 2). When the medicated group was included, to see if noise effect was present in this group too, in the assessment the interaction between noise and group became stronger ($F(1,40) = 8.41$, $p = 0.006$, $\eta^2 = .17$).

Study 2 (Söderlund, Sikström and Loftesnes, in preparation) comprised of a normal population of school children where children were divided into groups depending on cognitive performance. Cognitive performance was measured by teacher's judgment of general scholastic skills in three levels: average, above and below average. While the below group only consisted of four participants the below and average groups were merged together. Figure 3A shows that the interaction between noise and group is significant ($F(1,30) = 5.92$, $p = 0.021$, $\eta^2 = .14$). The significant difference between groups in the no noise condition ($t(30) = 3.67$, $p = .001$) disappears in the noise condition (Figure 3A).

Study 3 (Söderlund, Sikström & Loftesnes, in preparation) were an extension and replication of study 2, which also consisted of a normal population of school children. The children were grouped according to (1) teachers' judgments of general school performance, (2) teacher judgments of inattention/hyperactivity, and (3) the score on a Raven test. The results are presented in figures 3B, 4A, and 4B (below), note that group sizes differ between the figures

In Study 3, there was a significant interaction effect between noise and below/above groups, however, there was no interaction effect involving the middle group (Figure 3B). Note that the memory performance level was significantly lower for the below group as compared to the average and above groups ($F(2,48) = 8.51, p = .001$).

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Figure 3A

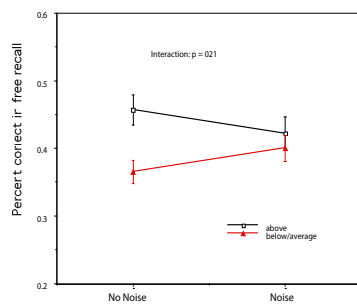


Figure 3A. Recall performance as a function of noise and school performance in two groups (teachers judgments: above $N = 12$, below/average $N = 20$).

Figure 3B

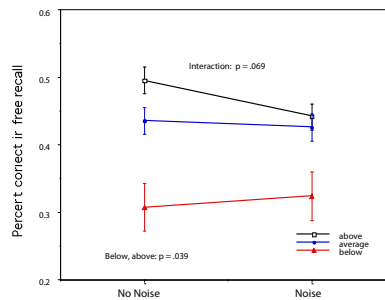


Figure 3B. Study 3: Recall performance as a function of noise and school performance (teachers judgments in three groups: above $N = 22$; average $N = 22$; below $N = 7$).

In Study 3, the interaction between noise and Raven score was significant ($F(2,48) = 3.35$, $p = .044$, $\eta^2 = .12$) (Figure 4B). Note that the difference in memory performance between below and high performing groups disappeared with noise exposure when t-tested separately. Figure 4A shows the lowest p-value in the interaction between attention and noise ($F(2,48) = 4.99$, $p = .011$, $\eta^2 = .17$). Inattentive children did benefit most from noise and there was no main effect on performance of group, all groups performed at the same level ($F(2,48) = 1.28$, $p = .288$).

Conclusions

Traditionally, noise has been conceived as being detrimental for cognitive performance. Recent results from our laboratory shows that this picture has to be revised. Several independent datasets are now showing that noise may actually be beneficial for cognition. However, this beneficial effect only occurs in well defined circumstances. First of all the volume of the noise has to be well tuned for the task. Our data (see also Usher, 2000) shows beneficial effect during noise levels within 70-80 decibel, where lower levels show weaker or absent effects, and higher volumes are detrimental for performance. The aforementioned noise levels apply to cognitive testing and are much larger than the noise levels showing benefits in perceptual auditive tests, where most of stochastic resonance studies have been conducted. More importantly, our studies shows that the benefit of noise differ depending on the groups of participants, where some groups show benefits in cognitive performance by noise, whereas for other groups a decline in performance is found for the same noise levels. Groups that show benefits in performance are ADHD children and children with low cognitive skills, whereas normal controls and particularly high achieving children show decline in performance. The decline in performance for some of the groups should not be interpreted as that noise always is bad for these groups. In contrast the MBA framework suggests that these participants may benefit of noise at other noise levels, or in other task. This framework further suggests that moderate amount of noise may increase the neural activity to optimal levels, and function as a substitute for insufficient dopamine levels. Further studies from our group will focus on directly measure how noise influence dopamine levels and the neural activity. This line of research may potential lead to possibilities of tuning our neural systems to optimal levels. In the future, this environmental therapy may be an alternative to classical pharmacological therapies.

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