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Listen to the noise: noise is beneficial for cognitive performance in ADHD

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Background: Noise is typically conceived of as being detrimental to cognitive performance. However, given the mechanism of stochastic resonance, a certain amount of noise can benefit performance. We investigate cognitive performance in noisy environments in relation to a neurocomputational model of attention deficit hyperactivity disorder (ADHD) and dopamine. The Moderate Brain Arousal model (MBA; Sikström & Söderlund, 2007) suggests that dopamine levels modulate how much noise is required for optimal cognitive performance. We experimentally examine how ADHD and control children respond to different encoding conditions, providing different levels of environmental stimulation. **Methods:** Participants carried out self-performed mini tasks (SPT), as a high memory performance task, and a verbal task (VT), as a low memory task. These tasks were performed in the presence, or absence, of auditory white noise. **Results:** Noise exerted a positive effect on cognitive performance for the ADHD group and deteriorated performance for the control group, indicating that ADHD subjects need more noise than controls for optimal cognitive performance. **Conclusions:** The positive effect of white noise is explained by the phenomenon of stochastic resonance (SR), i.e., the phenomenon that *moderate* noise facilitates cognitive performance. The MBA model suggests that noise in the environment, introduces internal noise into the neural system through the perceptual system. This noise induces SR in the neurotransmitter systems and makes this noise beneficial for cognitive performance. In particular, the peak of the SR curve depends on the dopamine level, so that participants with low dopamine levels (ADHD) require more noise for optimal cognitive performance compared to controls. **Keywords:** ADHD, stochastic resonance, dopamine, episodic memory, SPT, noise. **Abbreviations:** MBA: moderate brain arousal; SR: stochastic resonance; SPT: subject-performed task; VT: verbal task (VT).

Stochastic resonance is the counterintuitive phenomenon that an optimal amount of noise may under certain circumstances be beneficial for cognitive performance. The purpose of this study is to examine the effects of external auditive noise on performance in an episodic recall task in children with attention deficit hyperactivity disorder (ADHD). According to the Moderate Brain Arousal (MBA) model (Sikström & Söderlund, 2007), a neurocomputational model of cognitive performance in ADHD, noise in the environment introduces internal noise into the neural system through the perceptual system. This noise is proposed to compensate for the reduced neural background activity in ADHD and the hypofunctional dopamine system (Solanto, 2002). The MBA model predicts that noise enhances memory performance for ADHD and attenuates performance for controls. We will also argue for a link between the effects of noise, dopamine regulation, and cognitive performance.

ADHD is a developmental disorder characterized by behavioral impairments in three domains: inattention, impulsivity, and hyperactivity. ADHD is one of the most commonly diagnosed childhood psychiatric disorders, affecting approximately 3–7% (Castellanos & Tannock, 2002) of the childhood population. A vast literature shows that handling cognitive flexibility and rigidity during maintenance of goal-directed behavior is difficult to manage for ADHD children (Martinussen, Hayden, Hogg-Johnson, & Tannock, 2005).

It has long been known that cognitive processing is easily disturbed by noise and other distractors (Broadbent, 1958). The mechanism behind this effect, in general terms, is that the distractor removes attention from the target task. Research on this topic since 1958 has demonstrated this finding to hold across a wide variety of target tasks, distractors and participant populations. Consistent with this, ADHD children are regarded as more vulnerable to distraction compared to normal controls (Corbett & Stanczak, 1999) and several studies have demonstrated results supporting this notion (e.g., Geffner, Lucker, & Koch, 1996; Higginbotham & Bartling, 1993).

Two recent studies were, however, able to demonstrate the counterintuitive finding that under certain circumstances participants could benefit from noise and other task-irrelevant sounds presented concurrently with the target task. Abikoff, Courtney, Szeibel, and Koplewicz (1996) showed that children with ADHD were not distracted by background music, which can be considered as task-irrelevant noise. Surprisingly, the results further

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showed a noise-induced improvement in performance in the target (arithmetic) task. To the best of our knowledge Abikoff's finding has been replicated just once, by Gerjets, Graw, Heise, Westermann, and Rothenberger (2002), where noise was induced by music.

These studies, however, did not provide a satisfactory theoretical account for why noise was beneficial for performance. Here we suggest that the phenomenon known as stochastic resonance can be used to account for noise-induced improvement in cognitive performance. Stochastic resonance (SR) is the phenomenon that detection of a subthreshold signal is enhanced by addition of noise in a nonlinear system. SR occurs in any system where detection requires passing of a threshold, so that the added noise allows for the combined noise and signal to pass the threshold, permitting detection of the signal (Moss, Ward, & Sannita, 2004). This psychophysical phenomenon is present in biological sensory systems in animals and humans (Russell, Wilkens, & Moss, 1999). It has been found in several modalities; tactile, hearing, and vision (see Moss et al., 2004 for a review). The effect is not restricted to sensory processing. Stochastic resonance has been found in cognitive tasks where auditory noise improved the speed of arithmetic computations in a normal population (Usher & Feingold, 2000). Stochastic resonance is usually quantified by plotting detection, or cognitive performance, as a function of noise intensity. This relation exhibits an inverted U-curve, where performance peaks at a moderate noise level. That is, moderate noise is beneficial for performance whereas too little, or too much, noise attenuates performance (see Figure 1). After a review of noise and cognition studies (e.g., Baker & Holding, 1993) we suggest that, in order to induce the SR effect, noise has to be continuous (in order not to be attention-removing) and at a high energy level at all frequencies, as in white or pink noise.

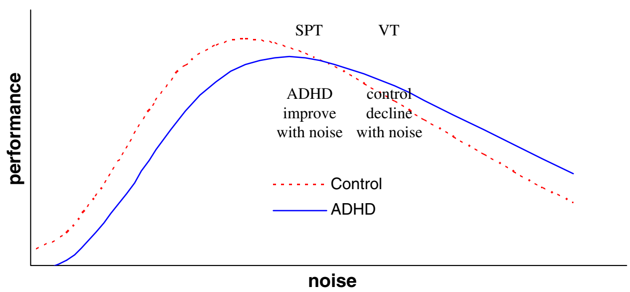

Figure 1 ADHD needs more noise for optimal performance compared to control. Note. The figure shows the stochastic resonance phenomena where performance on cognitive tests (y-axis) is optimal for moderate noise levels (x-axis), and attenuated for both too low and too high noise levels. More noise is required for optimal performance in low dopamine (ADHD) compared to high dopamine (control) neural systems, where dopamine modulates the gain in the sigmoid activation-function. SPT has a higher SNR ratio (left side of the figure) compared to VT (right side)

Stochastic resonance has been shown to be a ubiquitous natural phenomenon (Moss et al., 2004). In the brain, stochastic resonance plays an important role in dopamine signaling (Li, von Oertzen, & Lindenberger, 2006). Dopamine modulates neural responses and function by increasing the signal-to-noise ratio (SNR) through enhanced differentiation between background or efferent firing and afferent stimulation. Dopamine thus produces a suppressive influence on spontaneous activity, explaining its apparent inhibitory actions, and simultaneously causes an enhanced excitability in response to afferent-driven stimulation (J.D. Cohen, Braver, & Brown, 2002). It has been suggested that high activity of catecholamine neuromodulators in prefrontal neurons is associated with a high SNR of information processing (Kiefer, Ahlegian, & Spitzer, 2005). Thus, too low or too high neuromodulatory activity results in a low SNR and worse cognitive performance in such areas as working memory and inhibitory control. That is, the relation between cognitive performance and dopamine transmission shows an inverted U-shaped curve where either too high, or too low, levels attenuate performance (Goldman-Rakic, Muly, & Williams, 2000). Converging evidence indicates that hypo- or dysfunctioning catecholamine systems in the prefrontal cortex (PFC), among other areas, are a central neurobiological substrate of the cognitive and behavioral deficits associated with ADHD (Arnsten & Li, 2005). Based on neurocomputational modeling (Sikström & Söderlund, 2007), we suggest that dopamine-deprived neural systems, such as are thought to occur in ADHD (Solanto, 2002) or in aging (Erixon-Lindroth et al., 2005), require more noise to induce SR (see Figure 1).

ADHD is believed to involve a hypofunctional dopamine system (Solanto, 2002). The MBA model assumes, consistent with earlier dopamine models (Li & Sikström, 2002; Servan-Schreiber, Printz, & Cohen, 1990), that the level of dopamine is modulated by the gain parameter in the sigmoid activation-function. A low dopamine level corresponds to a low gain, yielding a relatively more linear input–output relation in neural cells compared to high dopamine and high gain. The neural system is influenced by stochastic resonance as the signal plus noise passes a threshold during generation of action potentials. Neurocomputational simulations by Sikström and Söderlund (2007) showed that low dopamine levels in ADHD subjects shift performance on the stochastic resonance curve (inverted U-curve) to the right, so that ADHD subjects, for a given noise level, operate on the part of the curve where noise is beneficial for performance whereas under the same conditions controls operate on the part of the curve where performance declines (see Figure 1). Input parameters to the model are external noise and signal, which activate internal neural noise and signal. Through the SR phenomenon these provide an output measured by cognitive performance. Thus, these simulations provide a straightforward prediction of noise-induced improvement in cognitive performance for ADHD. The purpose of this paper is to explicitly set up an experiment to test this novel prediction.

Because we were interested in investigating performance for different signal and noise levels (mapping to different parts of the stochastic resonance curve), we used four different encoding conditions. The conditions were: external auditive noise vs. no noise and high vs. low memory performance tasks. Low memory performance is associated with a high internal noise level whereas high memory performance is associated with a low internal noise level. The external auditive noise activates the internal neural noise and the internal noise influences performance through the phenomenon of SR.

For the low noise, or high recall performance, we used a self-performed task. The self-performed task (SPT) paradigm is known to help focus attention by means of enactment. SPT yields an efficient encoding condition that requires few conscious strategies (R.L. Cohen, 1981). Participants are presented with verbal commands, simple verb–noun sentences such as 'roll the ball' or 'break the match'. While these commands are presented, participants are asked to perform the action indicated by each command. At the subsequent memory test, participants are instructed to remember as many of the verbal commands presented as possible. For the high noise, or low recall performance, we used a verbal task (VT) that includes the same type of verbal commands, and the same study time, as in the SPT condition except that they are presented to the participant without any instructions to perform any actions. Results from experiments using this paradigm are very stable; memory performance after enacted phrases (SPT) is consistently superior to the ones without enactment (VT) and is generally referred to as the *SPT effect* (see Nilsson, 2000, p. 137 for a review).

The MBA model predicts that cognitive performance in ADHD children benefits from noisy environments because the dopamine system modulates the SR phenomenon. It suggests that the stochastic resonance curve is right shifted in ADHD due to lower gain or lower dopamine. The MBA model predicts that for a given cognitive task ADHD children require more external noise or stimulation, compared to control children, in order to reach optimal (i.e., moderate) brain arousal level. However, in the high noise condition (VT task) performance will be near the peak for ADHD children whereas controls will operate on the part of the SR curve where there is too much noise for optimal performance. That is, noise will attenuate performance for controls but not for ADHD children. In the low noise condition (SPT task) ADHD children will operate on the part of the SR curve where noise is beneficial for performance, whereas controls operate near the peak. That is, in the SPT condition noise will increase performance for ADHD children but not for controls. Each participant is exposed to four conditions: white auditory noise and a control condition without noise during SPT and VT encoding.

Method

Participants

Forty-two children, aged 9.4–13.7 years, participated in the study. The ADHD group consisted of 21 boys and no girls. This group was diagnosed by pediatricians (in hospitals or local neuro-teams) according to the guidelines of DSM-IV (APA, 1994). Fifteen of the children were diagnosed ADHD-combined type (ADHD-C) and six as predominantly inattentive (ADHD-I). Diagnoses were given 1–4 years prior to the experiment and the children were 6–11 years old at the time of diagnosis (M = 8.1 yrs). An interview based on Conner's rating scale for teachers confirmed, in all cases, the diagnostic distinction between ADHD-C and ADHD-I at the time of the experiment.

Although most of the participants (14) did not use medication, a smaller group (7) of the ADHD children used methylphenidate, supplied for one month or longer (see Table 1). The medicated children comprised the ADHD-C group in six cases; only one child in the ADHD-I group was given medication. The medication was administered in the morning; three of the children also got an additional dose during the day. For ethical and practical reasons, the medicated children remained on medication and the test was conducted in the morning during a normal school day. The participants used no other types of medication. To control for possible confounding effects, the medicated and non-medicated groups were analyzed separately. We focus on the non-medicated participants. Further co-diagnoses such as conduct disorder and mental retardation were used as exclusion criteria. The ADHD children attended either regular school in small separate groups (10 children) or schools for children with special needs (11 children).

The control group was matched to the ADHD group on the basis of four inclusion criteria; district (controls were chosen from the same area as the experimental

Table 1 Participant characteristics

				School performance	
	Medicated	N	Age (SD)	(1) (2) (3)	(M)
ADHD (no med.)	–	14	11.2 (1.2)	2 9 3	(2.1)
ADHD (tot)	7	21	11.2 (1.1)	3 13 5	(2.1)
Control	–	21	11.2 (1.1)	3 12 6	(2.1)

Note. Only boys were tested. School performance was judged by teachers as: 1 = below average, 2 = average, or 3 = above average. Medication was Methylphenidate or equivalent.

group), gender (boys), age (months), and school performance (teacher ratings). Teachers made a judgment of school performance on three levels; average, above average and below average, based on what is expected for the age according to the curriculum (see Table 1). Teachers' school performance ratings corresponded well with the earlier WISC scores obtained at the time of the ADHD diagnosis. IQs below 80 were excluded. Teacher interviews confirmed that all control children were well within the normal range on the Conner rating scale and intelligence was within a normal range. The study was conducted at participants' schools following permission from parents, headmasters, and approval of the local ethics committee at the Department of Psychology, Stockholm University.

Design

The design was a $2 \times 2 \times 2$, where type of encoding (subject performed task vs. verbal task) and noise (no noise versus noise) were the within-subject manipulations and the between-group variable was ADHD versus Control.

Materials

The to-be-remembered (TBR) items consisted of 96 sentences divided into 8 separate lists with 12 verb–noun sentences in each list. Each sentence consisted of a unique verb and a unique noun (e.g., 'roll the ball'). The sentences were placed in random order. All to-be-remembered sentences were recorded on a CD. In the no noise conditions the sentences were read in silence and in the noise conditions they were read in the presence of white noise. The equivalent continuous sound level of the white noise and the speech signal was 81 and 80 dB (A), respectively. Thus, the signal-to-noise ratio was −1 dB. The noise level was set in accordance with earlier studies where an effect of SR on cognition (arithmetic) was obtained for a normal population (Usher & Feingold, 2000) and on working memory for Alzheimer patients (Belleville, Rouleau, Van der Linden, & Collette, 2003). Recordings were made in a sound studio.

Procedure

Participants were tested individually before lunch. The experiment lasted for about 45 minutes. First, two training sentences were presented. There were 4 conditions; SPT, SPT + noise, VT, and VT + noise. SPT/VT conditions comprised every second list and noise or no noise was used during every second SPT/VT encoding condition. The encoding conditions (SPT/VT, no noise/+noise) were counterbalanced across participants so that each list was present in every condition equally many times. List-order (1–8) and condition-order (SPT/VT and no noise/+noise) were also counterbalanced. Participants sat at a table screened off from a part of the table where the to-be-remembered objects were placed. The items in the SPT conditions required one or two physical objects. These objects were given to participants at the time of presentation of the sentence (spoken as commands to the participants) and were then hidden behind a screen after the actions had been performed. The rate of presentation was the same for all conditions and controlled by the recording on the CD. A new sentence was read every 9th second. Time taken to present each list of 12 sentences was approximately 1 minute and 40 seconds. Directly after presentation of the last item in a list, participants performed a free-recall test in which they spoke out loud as many sentences as possible, in any order. Recall time was measured and the maximum allowed time was 2 minutes.

Results

Recall performance

A $2 \times 2 \times 2$ mixed ANOVA was conducted with one between-subject factor, Group (ADHD vs. Control) and two within-subjects factors, encoding condition (SPT vs. VT) and noise (no noise vs. +noise). Consistent with earlier SPT studies, strict scoring was used for the nouns (exact matches were required) and lenient scoring was used for the verbs (exact matches not required).

There was a main effect of encoding, where SPT outperformed VT (F (1,33) = 45.85, p = .000, eta^2 = .58). The interaction between group and noise was also significant (see Figure 2, F (1,33) = 5.73, p = .023, eta^2 = .15). No other main effects or interactions were found. When medicated children were included in the assessment the interaction between group and noise became stronger (F (1,40) = 8.41, p = .006, eta^2 = .17).

Table 2 shows means and standard deviations for the proportion of correctly recalled items divided into group, medication, noise level, and encoding condition. Consistent with our hypothesis, noise enhanced performance for the ADHD group (M = .44 vs. .46) and impaired performance for the control group (M = .47 vs. .43). Paired-sample t-tests were conducted to test the predictions of SNR within tasks. In the SPT conditions, consistent with the prediction ADHD participants performed better with, compared to without, noise, when all ADHD parti-

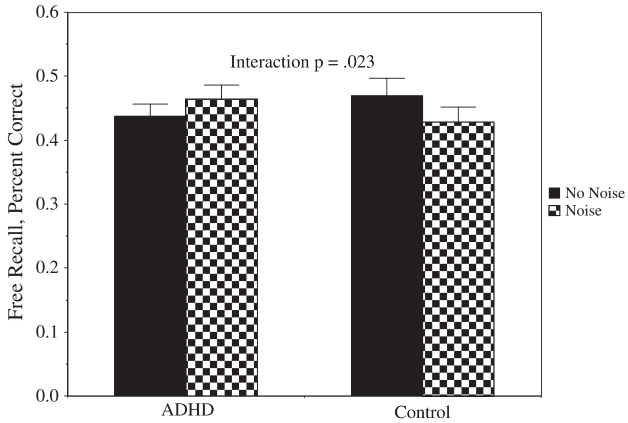

Figure 2 Percentage correct answers in free recall as a function of noise and group

Table 2 Proportion of items correctly recalled across encoding conditions and groups (SPT–VT, Noise–No noise, ADHD–Control, Medicated–Non-medicated)

		Type of encoding			
Group	N	SPT (SD)	SPT+noise (SD)	VT (SD)	VT+noise (SD)
ADHD	21	.47 (.12)	.52 (.12)	.40 (.12)	.41 (.10)
ADHD-non-medicated	14	.47 (.11)	.50 (.11)	.40 (.15)	.42 (.11)
ADHD-medicated	7	.49 (.14)	.55 (.13)	.39 (.06)	.39 (.06)
Control	21	.52 (.14)	.50 (.13)	.42 (14)	.35 (.13)

cipants were included in the analysis (t (20) = 2.56, p = .01, one-tailed); however, when only the non-medicated children were included the result did not reach significance but indicated a trend (t (13) = 1.59, p = .07, one tailed). In the control group, noise did not significantly influence SPT performance. However, consistent with the prediction, the control group performed significantly lower in VT + noise compared to the VT condition (t (20) = −2.47, p = .01, one-tailed) whereas noise did not influence the ADHD group in the VT noise condition. In summary, the tests of our directed hypotheses were significant. These tests are more precise tests of our predictions than the three-way interaction between group, noise, and encoding which was not significant (F (1,33) = .49, p = .49, eta^2 = .02).

Discussion

The most intriguing result in the present study is the positive effect of white noise on performance for the ADHD children. This noise effect was present in both the non-medicated and medicated children. This supports the MBA (Moderate Brain Arousal) model (Sikström & Söderlund, 2007), suggesting that the endogenous (neural) noise level in children with ADHD is sub-optimal. MBA accounts for the noise-enhancing phenomenon by stochastic resonance (SR). The model suggests that noise in the environment introduces internal noise into the neural system through the perceptual system. Of particular importance, the MBA model suggests that the peak of the SR curve depends on the dopamine level, so that participants with low dopamine levels (ADHD) require more noise for optimal cognitive performance compared to controls.

Three ADHD models – cognitive-energetic (Sergeant, 2000), delay aversion (Sonuga-Barke, 2002b), and optimal stimulation (Zentall & Zentall, 1983) – argue that state factors have to be taken into account when explaining deficits seen in ADHD. These state factors could be conceptualized as arousal and activation regulation and deficiencies that lead to impairments in allocation of cognitive resources. However, in contrast to MBA, none of these models use stochastic resonance modulated by dopamine as an explanatory framework to account for cognitive performance in ADHD.

The cognitive-energetic model focuses on energetic levels. For example, ISIs have been found to alter the participants' energetic state, where both over- and under-arousal could be induced by the applied event rate (Sergeant, 2000, 2005). As confirmatory evidence, methylphenidate has been found to have the same effect as an increased event rate, where both are seen as state-regulating factors (van der Meere, Gunning, & Stemerdink, 1999). Furthermore, ADHD children show reduced P300 amplitudes to cues and distractors (Banaschewski et al., 2003). Energetic level can also be manipulated through cognitive load, signal intensity and novelty (Sergeant, 2005). The MBA model is consistent with this but also points out the possibility of increasing energetic level irrespective of task and improving cognitive performance by the use of noise.

The optimal stimulation model (Zentall & Zentall, 1983) is a homeostatic model, suggesting that there is an optimal level of stimulation toward which organisms strive. It is argued that hyperactivity stems from low levels of arousal and serves to maintain an optimal arousal level. Hyperactivity, impulsivity, and a short attention span should be seen as a form of self-stimulation to achieve an optimal arousal level. Behaviors supporting this view are reward-seeking and stimulation-seeking behaviors often seen in ADHD (Zentall & Zentall, 1983). More recent research has found that in the presence of highly appealing toys ADHD children spent half as much time attending to, and recalled less of, the content in TV programs (Lorch et al., 2000). The MBA model is consistent with the proposed need of external stimulation in ADHD but elaborates on the conditions when this stimulation will be beneficial.

In the delay aversion model attention is allocated toward environmental stimulation that speeds up the perceived passage of time. Intolerance of waiting is manifested as a tendency to select an immediate reward rather than a larger delayed reward (Sonuga-Barke, 2002b). Altered reward processes in ADHD (Sonuga-Barke, 2003) could be explained as a ceiling effect due to an excessive phasic DA response to novel stimuli. Delay aversion is found in over-sensitivity to inter-stimulus intervals (Sonuga-Barke, 2002a), an increase in activity and inattention during delay periods (van der Meere et al., 1999), and avoidance of delay. This over-sensitivity to external stimulation is suggested to be caused by an overactive alerting system in ADHD that makes behavioral responses maladaptive to external demands (Nigg & Casey, 2005). This view is complementary to the MBA model, where prolonged ISIs produce insufficient phasic responses generating too little dopamine, and resulting in a dysfunctional arousal state (Sikström & Söderlund, 2007).

The beneficial effects of noise in cognitive performance for ADHD have not been considered earlier, nor have these effects been systematically tested, in the literature. Surprisingly few experiments have explored the possibilities of stimulating participants with noise and there are no theories about positive effects of noise in the literature apart from SR experiments referred to in the introduction. Most experiments since Broadbent's days deal with the negative effects of noise and distraction. We know of only two ADHD studies using noise stimulation; however, neither of these invoked the concept of stochastic resonance as an explanatory framework nor are they theory driven, rather they refer to general appeal or arousal. Abikoff et al. (1996) attributed the enhancing effect to increased level of general appeal counteracting boredom, and Gerjets and colleagues (Gerjets et al., 2002) to optimal stimulation in line with the early optimal stimulation theory (Zentall & Zentall, 1983).

However, research has shown enhancing effects of white noise on non-clinical groups (90 dB) on simpler, short-term memory tasks such as anagrams (Baker & Holding, 1993) whereas speech noise was detrimental. These noise effects also interacted with other variables such as gender and time of the day (Holding & Baker, 1987), which makes these results equivocal. In simple addition tasks white noise (80 dB) improved performance, in both elderly and younger participants, as compared to a no-noise condition (Harrison & Kelly, 1989). More recent experiments providing white noise found no effect on cognition in digit-span recall in comparison with irrelevant speech, which attenuated performance (Belleville et al., 2003; Rouleau & Belleville, 1996). In Belleville et al.'s (2003) experiment a small, but non-significant, increment was seen among older and Alzheimer patients as compared with young participants using white noise (75 dB). Furthermore, extra noise required in old age to induce SR was modeled by Li and colleagues (2006). White noise also improved performance in monkeys in a delayed task experiment, whereas Mozart's piano music was found detrimental (Carlson, Rama, Artchakov, & Linnankoski, 1997). In experiments were ecologically relevant noise was studied, effects on episodic and semantic memory showed that both road traffic noise (62 dB followed by 78 dB sequences) and meaningful irrelevant speech were detrimental for memory performance. Episodic memory was found particularly vulnerable to noise and irrelevant speech was most detrimental for memory performance. Under some conditions road traffic noise did not interfere with memory recall at all (Boman, Enmarker, & Hygge, 2005). For example, in Zentall and Shaw's (1980) experiment high levels of speech noise (69 dB) were detrimental for ADHD whereas low levels (64 dB) were beneficial for cognitive performance. However, fan noise where the main energy is below 1000 Hz did not have a positive effect on ADHD children. Noise and signal levels were also lower as in the present experiment (50dBHL, SNR +10 dB) (Geffner et al., 1996). Stimulus levels in the present experiment were placed according to earlier studies that have found SR in cognitive tests (Usher & Feingold, 2000).

In summary, the literature review above suggests that noise has to be continuous (i.e., not attention-removing) and at a high energy level at all frequencies, for example white or pink noise, to induce the SR effect. Furthermore, beneficial noise levels may vary between groups, i.e., ADHD subjects, the elderly and people with Alzheimer's require more noise to induce SR. In a follow-up experiment we will manipulate noise levels under the hypothesis that they have to be estimated on an individual basis, see arguments below.

As the first paper studying the stochastic resonance phenomenon in ADHD, there are limitations in the current study that should be investigated in future studies. For example, our study investigated only two noise levels and two encoding conditions, thus it would be interesting to include more levels so that the entire stochastic resonance curve can be mapped out. Further studies should also measure individual dopamine levels, and study how these levels correlate to symptom severity, intellectual capacity and the required noise level. Medicated participants responded as strongly to noise as non-medicated participants. However, medication is a confounding variable, and it would be interesting to look for interaction between noise and medication during noise exposure.

There are several clinical implications of the MBA model. For example, it can be used to understand shortcomings in cognitive functioning for patient groups where changes in the dopamine system have been identified. While noise affects children selectively, it can be used as a complement or as an alternative to medication in ADHD. Moreover, reinforced cognitive processing by noise could have applied implications for clinical groups, as well as for normal populations. The MBA model may be used to create appropriate and adaptive environments for ADHD children, especially in school settings. White noise can be replaced with more pleasant auditive stimulation such as music or other pleasant sounds.

Klingberg and colleagues have attained remarkable results with Robomemo, a computer game that trains working memory (Klingberg et al., 2005). In this context, the MBA model can serve as a tool for tailoring individually adapted treatments for ADHD children. Computerized training programs are particularly interesting because crucial variables can be manipulated easily and precisely. This provides us with the hope of creating long-term changes as an alternative to short-term medications. Further research will exploit the effect of white noise and stochastic resonance in the context of learning and ADHD.

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