

Sensory white noise in clinical ADHD: Who benefits from noise, and who performs worse?

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Abstract

Background: Experimental research has shown the benefits of auditory white noise on cognitive performance in children with attention problems. However, little is currently known about individual differences in noise response amongst children with a clinical diagnosis of attention deficit hyperactivity disorder (ADHD). In addition, no research has so far tested the effects of visual white noise on children with ADHD.

Objectives: The present work aimed at testing the effect of visual and auditory white noise on cognitive performance in children diagnosed with ADHD.

Method: Forty-three children with ADHD diagnosis performed a visuo-spatial working memory test with experimentally controlled auditory and visual white noise. Symptomatic and demographic data were collected.

Results: Surprisingly, results did not show significant effects of noise across the full sample of ADHD children. However, responses to noise appeared to affect subgroups of ADHD children differently: Those with relatively more inattentive traits responded positively on noise exposure whereas those with relatively more hyperactive/impulsive traits performed worse during noise exposure. Individual differences in noise response in the auditory and visual modalities were strongly correlated.

Conclusions: It is important to consider individual differences in response to noise exposure, and to take into account the specific ADHD symptom profile (inattentive vs. hyperactive/impulsive) in applying noise to support cognitive performance in children with ADHD.

Keywords: ADHD; auditory white noise; visual white pixel noise; cognitive performance

Introduction

Attention-deficit/hyperactivity disorder (ADHD) is a common neurodevelopmental disorder that is associated with a range of troublesome outcomes in social, academic, and work-life contexts (1). An ADHD diagnosis requires the presence of inappropriate levels hyperactive-impulsive and/or inattentive symptoms for at least 6 months, occurring in two different settings, typically at home and in school, and causing significant impairments in everyday life (1). Meta-analyses indicate that symptoms related to inattention are more strongly

associated with lower school achievements and poor adaptive functioning, whereas hyperactive-impulsive symptoms are associated with peer conflicts, high-risk behaviors, and propensity to accidents (2).

ADHD is usually treated with stimulant drugs (3). Non-pharmacological treatments have also been found helpful. For children, these approaches commonly involve caregivers, in the form of psychoeducation, and assistance in establishing positive parenting practices and everyday routines (4). In addition, there is compelling experimental evidence for the instant benefits of auditory white

noise on cognitive performance in children with attention problems and/or an ADHD diagnosis (5-9). Additionally, recent developments of visual white noise applications have been promising (10, 11), but their use in clinical ADHD has not been investigated yet.

Auditory white noise is a random and meaningless signal that contains all frequencies within the range of human hearing (20 Hz-20 kHz). It includes a flat power spectrum, i.e., the same amplitude over the entire frequency band. White visual noise, in analogy, contains all visible light frequencies. White noise has been found to lower sensory detection thresholds within modalities but also cross modally (12).

A recent meta-analysis including thirteen white noise studies in children with attention deficits found promising results, with white noise exposure showing small to medium effects sizes on cognitive performance (13). White noise interventions are simple, fast-acting, free, and have no known side effects.

The exact mechanisms behind white noise benefits, regardless of the modality, are not yet fully understood. Our research has been guided by the Moderate Brain Arousal (MBA) hypothesis, that takes the phenomenon of stochastic resonance (SR) into account (MBA; 14). According to this model, white noise improves the signal-to-noise ratio where the noise interacts and reinforces weak signals pushing them over the detection threshold (15). The SR effect appears highly sensitive to both the intensity of the signal and the noise level; this relationship is presumed to follow an inverted U-curve function, where performance peaks at moderate white noise levels. This means that a moderate level of white noise is beneficial for performance (14). However, different brains may require different amounts of white noise to work optimally; a noise level that is good for children with ADHD might, according to the MBA hypothesis, be detrimental for typically developing children (16).

It is well recognized that ADHD is associated with lower physiological arousal levels, as evident in lowered resting state skin conductance (16, 17) and in electroencephalography (EEG) patterns characterized by an excess of slow theta and alpha wave activity, and an atypical theta/ beta ratio ((18) but see also Ogrim, Kropotov (19)). This physiological hypoarousal is linked with state regulation deficits, and Geissler, Romanos (20) propose that EEG-defined low vigilance status is a biomarker of ADHD. They also suggest that in ADHD, hyperactivity and sensation seeking could be an autoregulatory response to create a more stimulating environment, thus increasing arousal and possibly improving vigilance. In summary, while underarousal and unstable vigilance produces

inattention in ADHD, hyperactivity might not a disorder of its own, but should perhaps be seen as an autoregulatory response, that may or may not be present in ADHD (21). Indeed, there are findings showing that heightened activity can be an asset and help to focus during high working memory demands, thus improving performance in challenging cognitive tasks (22).

There have been attempts to translate research findings on white noise benefits into clinical applications (23). Relatively little is known in terms of individual differences in ADHD, and it is possible that a subgroup of children with ADHD may be particularly responsive to white noise during cognitive performance, whereas others are not. Learning more about predictors of response to white noise exposure is a crucial step to develop recommendations for clinical applications.

Our overarching hypothesis is that white noise, either through an increase of arousal and/or through stochastic resonance, can improve vigilance and support inattentive children. The present study aims to investigate whether hyperactivity and inattention, measured by SNAP scores (24), contribute differently to performance in cognitive tests, and if stimulation with external sensory random noise has differential effects on hyperactivity and inattention among participants, addressing several gaps in current knowledge regarding white noise benefits.

Our study comprised three aims, addressing several gaps in current knowledge of noise benefits.

First, we compared the effects of auditory white noise and those of visual white noise on a visual working memory task, in a relatively large sample of children with an ADHD diagnosis recruited from a child psychiatry unit. Based on prior findings from non-clinical samples with attention problems, we expected a small positive effect of both auditory and visual white noise on performance.

Second, we explored whether white noise benefit is modality independent, and if the individuals who show a benefit from auditory white noise also show it in the visual modality. Since the mechanisms underlying white noise benefits on cognitive performance are suggested to be modality independent (5, 25), we hypothesized that individual differences in the magnitude of benefit from auditory and visual white noise would be correlated.

Third, we explored what constitutes the predictors of individual differences in white noise benefit, in terms of symptom load of inattentive and hyperactive traits. Because ADHD and autism spectrum disorder (ASD) can overlap to a large degree, we also examined whether ASD was also present or not in our sample.

To rule out age effects, we controlled for age in our analyses. We expected a stronger association between

noise benefit and inattention symptom severity than with hyperactivity/impulsivity

Methods

Participants

Participants were recruited by healthcare staff at the Child and Adolescent Psychiatric unit (CAP) in Helsingborg, a city of 112'000 inhabitants in the south of Sweden. To be included, in addition to having received an ADHD diagnosis, participants needed to have undergone a complete neuropsychiatric/neurodevelopmental assessment. All ADHD diagnoses were verified by a senior consultant in child and adolescent psychiatry with over 10 years of experience in the field. All participants spoke fluent Swedish. Exclusion criteria were illiteracy, intellectual disability, ongoing problematic home conditions such as abuse and post-traumatic stress disorder. Initially, 47 participants (36 boys, 11 girls) with an ADHD diagnosis, mean age 14.3 (range 9-18 yrs), were recruited. Parents were asked to fill out the SNAP screening questionnaire before the testing to achieve a dimensional score for each of the two ADHD dimensions (24). Four participants were excluded from the final sample due to missing data on the SNAP ($n = 2$), technical errors during testing ($n = 2$), leaving a total of 43 participants included in the analysis. Medicated children were asked to hold up medication 24 hours ahead of testing. For more information about participants see table 1. All children were within normal range of IQ (> 70). Other comorbidities were reading disability ($n=3$), language disability ($n=4$). Thirteen of the children wore corrective glasses. According to parent reports one child had slight hearing problems and the rest had a normal hearing. All comorbid ASD diagnoses were established at the Child and Adolescent Psychiatric unit at the same time as the ADHD diagnosis.

Ethical approval was obtained from the Ethical Review Board in Lund (EPN 2021-04444). Written consent was obtained from parents of participating children and all participating children gave oral assent.

TABLE 1. Participant characteristics

Characteristics	N	Mean	SD	Range
Total	43			
Boys	32			
Girls	11			
Age	43	14.3	2.5	8.8 – 18.4
SNAP* inattention	43	16.0	6.3	4 - 27
SNAP* hyperactivity	43	11.9	6.5	1 - 27
ADHD diagnosis		<i>light</i>	<i>medium</i>	<i>severe</i>
severity**	43	8	27	8
ASD comorbidity	12			

Note: *SNAP score (21), parent ratings, ** severity, child psychiatrist ratings

Design

A within-subjects (1 x 3) experimental design was used, in which visuo-spatial working memory recall was compared in three noise conditions: no/ambient noise, auditory white noise, visual white pixel noise. The three conditions were presented once in random order.

Procedure and test battery

All testing were conducted individually at the Child Psychiatry unit. A 15.6' laptop, 60 Hz Dell Precision 7550 (Dell, 2020) was used to administer the tests, together with a HP x500 Optical Wired USB Mouse (Hewlett-Packard Company, 2018). During the no noise and the auditory white noise conditions, the background on the computer screen consistently kept a gray color (gray value 128 where 0 represents black and 255 represents white). Working memory was tested with the computerized visuo-spatial test, Spanboard, presented using the software Psychopy (Spanboard; 5). Participants were asked to remember the location and the order of dots appearing one-by-one in a randomized order on a 4 x 4 grid on the screen, and after the presentation of all dots, indicate the visuo-spatial sequence using the computer mouse to click the correct grid locations. In the first trial, the array started with 2 dots and increased with one more dot in each subsequent trial, until the participant made an error in two consecutive trials. The dots were shown for 2250 ms, followed by a 750 ms pause, and the inter-stimulus interval was 3s. A complete trial lasted for approximately 5 min in each noise condition. The dependent variable was the total number of correctly recalled dots in each noise condition. Other tasks were also conducted during the test session (word reading, word recall, and non-word reading), and these data will be reported elsewhere.

Noise conditions

Auditory white noise. Based on findings from earlier studies, the noise level was set to approximately 80 dB. The noise was delivered binaurally through noise canceling headphones covering the ears JBL live 650BT (JBL, 2019). Noise levels were measured with UT351/352 sound level meter (UNI-T's, 2018).

Visual white pixel noise was embedded on a laptop computer screen. The participants were seated approximately 40 cm away from the screen (1920 x 1080 pixels; 19.0 x 30.0 cm). Visual white noise was added to the stimulus image by blending it with a PsychoPy texture where each pixel had values from a uniform distribution $U[0, 255]$. Black was represented by $RGB = 0$ and white was represented by the value 255. The image (I) and the noise texture (N) were blended together by a weighting function, such that the stimulus $S = a*I + (1-a)*N$.

Consequently, different values of the parameter ‘a’ gave rise to different noise levels in the stimulus; $a=1$ adds no noise whereas $a=0$ produces a stimulus containing only noise. For this study, a uniform visual noise at level alpha 50 was used and the value of parameter “a” equaled 0.5 (i.e. 50 percent noise, range 0 – 100% white pixel noise).

No noise/ ambient noise, participants sat alone in a soundproof room that only contained a table and two chairs, to keep distractions minimal.

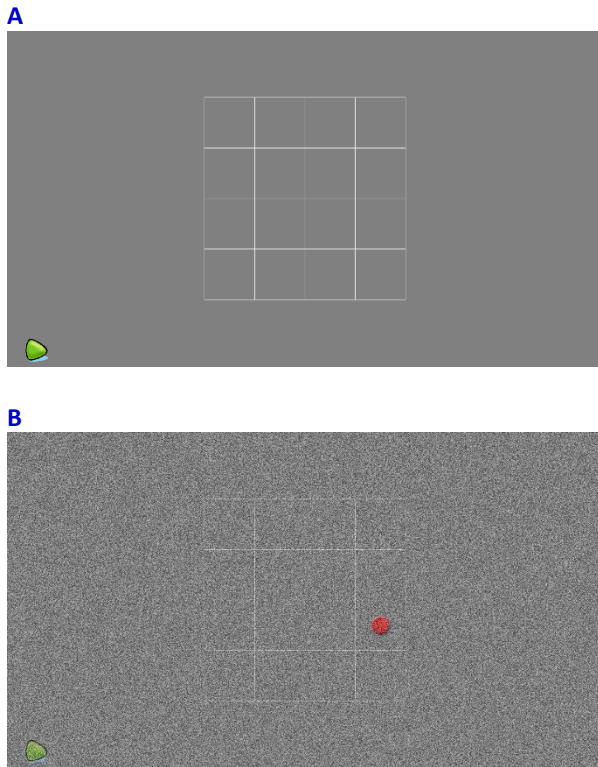


FIGURE 1. Illustrates the two visual white pixel noise levels, no noise, alpha 0 (A) and 50% noise, alpha 50 (B).

Analytical strategy and statistics

To evaluate the effect of white noise exposure (aim 1), we performed a repeated measures one-way ANOVA with noise conditions (3 x 1: no noise vs. auditory vs. visual noise) as the within individual factor. Next, planned post-hoc paired samples t-test were performed. To address aim 2, we first calculated one delta score for each noise type by subtracting performance in the noise conditions from performance in the no noise condition. Pearson correlation analyses were performed to explore whether the same individuals benefitted from noise, regardless of modality. For aim 3, two linear regressions were performed, where the outcome variable was either the delta value of the auditory noise benefit or of the delta values of the visual noise benefit. As independent predictors, we used attention scores and hyperactivity scores from SNAP. To probe specificity, we also considered two possible confounders in the regression model,

namely comorbid ASD diagnosis and chronological age. The reason why we considered ASD is that ASD and ADHD tend to overlap, and ASD is commonly associated with hypersensitivity to sensory stimulation (26). All predictors were entered simultaneously, and the variables with the largest p-values were systematically removed stepwise until the model included only uniquely significant predictors. Since we had a priori predictions or performed multivariate analyses, we did not use Bonferroni corrections. The significance level was thus set at $p < 0.05$. A final consideration made was whether there was any evidence of order effect in our experiment. In the supplementary online material (SOM) we address this issue through follow up analyses.

Results

A repeated measures one-way ANOVA with noise condition as the within individual factor showed no main effect of noise ($F(2,84) = 1.90$, $p = .155$, $n = 43$) when the entire group of participants was included. Planned post-hoc paired samples t-test examining for the auditory noise condition indicated a trend in the expected direction ($M = 33.3$, $SD = 15.7$ vs. $M = 38.8$, $SD = 19.9$; $t(42) = 1.54$, $p = .066$, one-tailed), whereas the visual noise condition contrast ($M = 33.3$ vs. $M = 34.1$, $SD = 17.0$) was not close to being significant ($t(42) = 0.29$, $p = .385$, one-tailed).

Moving on to aim 2, we explored whether “noise benefitters” improved under both types of noise conditions. We found a strong positive correlation between auditory and visual noise delta scores ($r = .64$, $p < .001$), meaning that those who benefitted from auditory noise also benefitted from visual noise. The delta scores also indicated that there was a substantial minority of participants who did not improve, or even performed worse in the white noise conditions.

To further explore the factors that predicted noise benefit, we ran two linear regression analyses in a backward fashion. The final model for visual noise benefit was statistically significant, whereas the model with auditory noise benefit was only borderline significant ($p = .055$), and results for the auditory manipulation should therefore be interpreted with caution. Results showed that in both modalities, only the attention and hyperactivity scores predicted noise benefit. Both symptom scores significantly predicted noise benefit, yet in opposite directions: a high inattention score predicted noise benefit, whereas a high hyperactivity score was associated with a negative effect of noise exposure. The final regression models are reported in Tables 2 and 3 for visual and auditory noise benefit, respectively. Neither age nor a comorbid ASD diagnosis predicted noise benefits in any direction,

TABLE 2. Linear regression, auditory noise benefit with attention and hyperactivity scores as predictors.

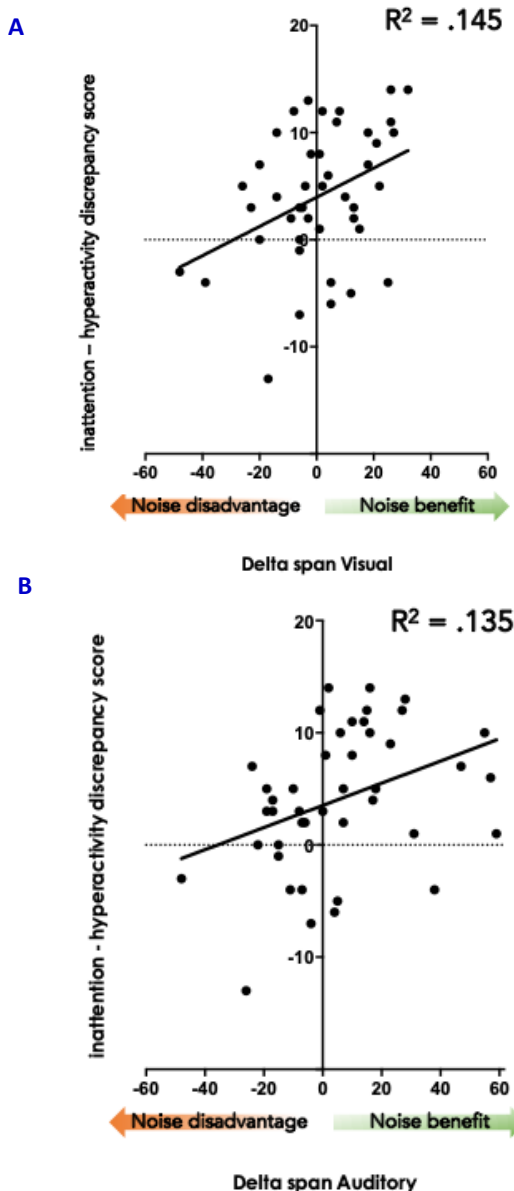
Model 1	R	R ²	df	F value	p-values
Auditory noise benefit	.367	.135	40	3.114	.055
	<i>Beta unstd</i>	<i>Beta std</i>		<i>t-values</i>	
Attention score*	1.369	0.369	40	2.152	.038
Hyperactivity score*	-1.359	-0.376	40	-2.190	.034

Note. *Parent rated attention and hyperactivity scores after the SNAP instrument (21).

TABLE 3. Linear regression, visual noise benefit with attention and hyperactivity scores as predictors.

Model 2	R	R ²	df	F value	p-values
Visual noise benefit	.382	.146	40	3.407	.043
	<i>Beta unstd</i>	<i>Beta std</i>		<i>t-value</i>	
Attention score*	1.105	0.396	40	2.327	.025
Hyperactivity score*	-1.024	-0.377	40	-2.211	.033

Note. *Parent rated attention and hyperactivity scores after the SNAP instrument (21)

**FIGURE 2.** Noise benefit in a visuo-spatial working memory task in visual (A) and auditory modalities (B) as a function of discrepancy score between hyperactivity and inattention assessed by the SNAP score.

see supplementary material tables S1 and S2 for more details.

We finally examined whether the magnitude of the difference between scores of inattention and hyperactivity was associated with differences in noise benefit. We found that a relatively high inattention score vis-à-vis hyperactivity/impulsivity symptom profile is predictive of noise benefit, and that this was the case for both modalities (see figures 2A and B).

Discussion

This is the first study to explore the effects of visual and auditory white noise in a group of pediatric clinical patients with ADHD diagnosis. There were three main findings in our study.

First, we found no main effect of white noise in this clinical ADHD population, when considered as a whole. Our data also revealed the presence of a rather large subgroup (about one third of the participants) who exhibited a negative noise effect, performing worse in both noise modalities. This was in contrast with earlier studies, in which we had found that a large majority of participants with attention problems benefitted from noise, while a small group did not show any effect of noise at all (e.g. 5, 7, 9). Samples in our prior research consisted mainly of children who had been screened for inattentive traits by their teachers in general classes; thus, we suspect that the lack of an effect in the current sample could be related to more severe neuropsychiatric symptoms, and perhaps in particular to the high level of hyperactivity displayed in this more affected participant group. The pronounced negative effect of noise for children that scored high on hyperactivity may corroborate the hypothesis that motor hyperactivity is an autoregulatory response to underarousal in ADHD (20, 22). This could potentially be understood in the light of the MBA model and the inverted U-hypothesis where hyperactivity in combination with external noise exposure may bring children over the

top for optimal arousal for cognitive performance and thus be detrimental for results (14).

Second, from an individual difference perspective, parallel effects (whether negative, nil, or positive) of white noise were present for both the auditory and visual modality conditions. In this first study exploring visual noise benefit on higher cognition in a clinical ADHD group, we show that, at least regarding performance on this visual working memory test, there seems to be important individual differences among children with ADHD in terms of noise benefit that are consistent across modalities.

Third, we showed, for the first time, that there were differential associations between the effect of white noise on cognitive performance and each of the two dimensions in ADHD. Our results indicated the presence of a negative association between hyperactivity scores and noise benefit, and of a positive association between inattention scores and noise benefit in the multivariate analyses. While earlier studies indicated a strong correlation between teacher- or parent-rated attention ability and noise benefit, the unique associations between traits of inattention and hyperactivity have never been explored in a regression model where the overlap between them is statistically controlled. Of course, the current findings need to be replicated in a larger sample, but our data give weight to the argument that the hyperactive/impulsive and inattentive dimensions of ADHD exert different effects on cognitive performance (27-29).

The relationship between inattention and hyperactivity in ADHD is complex and not completely understood, and not all individuals with ADHD exhibit both inattention and hyperactivity: some individuals may exhibit predominantly inattentive symptoms (formerly called ADD), while others may exhibit predominantly hyperactive-impulsive symptoms. Some studies suggest that inattention and hyperactivity may be separate constructs that have different underlying causes (27, 30, 31), while others suggest that they may share a common underlying mechanism (32) along a continuum of symptom severity (33). For example, some models conceptualize that excess motor activity could be a compensatory mechanism that facilitates neurocognitive functioning (34).

Limitations

This is a small study ($n = 43$) and findings need to be replicated in larger group, more balanced in terms of sex and age. In the present study, more than two-thirds of participants were boys, who tend to be more affected by hyperactivity (35). It would therefore be of large interest to confirm, in a larger sample, if the profile of inattention versus hyperactivity is equally predictive of white noise benefit status in boys and in

girls. Moreover, we lack data on participants IQ scores, although we know that they all scored above 70, i.e. the cut off for intellectual disability. Furthermore, the age span in the present study is rather large (8-18 yrs) and it is since long known that symptoms of ADHD tend to decrease with age (36). In a larger sample with a broad age range the effect of age could be studied separately. Finally, the regression model for auditory noise benefit was not significant ($p = .055$) making further analyses tentative.

Conclusions and clinical significance

Here we show, in a multivariate model, that white noise, regardless of its modality, is beneficial in a visual working memory task for those ADHD-children who show high levels of inattention relative to hyperactivity. However, for ADHD children with predominantly hyperactivity symptoms, noise is detrimental to performance. Therefore, we propose that noise benefiterers are ADHD children who are mostly inattentive, and who do not show high levels of hyperactivity/impulsivity. By contrast, inattentive children who have high levels of hyperactivity/impulsivity may instead get distracted by sensory noise and perform worse.

We propose that children that are dominantly inattentive, without hyperactivity, are more dependent on external stimulation to reach a sufficient level of brain arousal in order to improve their cognitive performance (14). Our findings indicate that inattention and hyperactivity, the two cardinal symptoms of ADHD, may in fact be separate constructs, and that the therapeutic approach should be tailored to the individual profile of each child.

Conflict of interests

None of the contributing authors have any conflicts of interest to report.

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Data sharing

Data available on request from corresponding author Göran Söderlund, email: goran.soderlund@hvl.no

Author contributions

GS, and JÄJ conceived and designed the experiment and wrote the first draft. SES recruited participants, performed the experiment, and collected data. GS, JÄJ and MT analyzed data and made tables. MT made supplementary tests and made the tables. NH revised the manuscript and made the figures. EMC and PG validated diagnoses, read the manuscript, and gave valuable input.

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