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ORIGINAL CONTRIBUTION

Deficits in auditory sensory discrimination among children with attention-deficit/hyperactivity disorder

Yi-Min Tien[1,2] · **Vincent Chin-Hung Chen**[3,4] · **Tun-Shin Lo**[5,6] · **Chia-Fen Hsu**[1,2] · **Michael Gossop**[7] · **Kuo-You Huang**[5,6]

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Abstract

Research into children with attention-deficit/hyperactivity disorder (ADHD) has focused on complex cognitive dysfunction, but less attention has been paid to sensory perception processes underlying the symptoms of ADHD. Based on signal detection theory, the present study compared the sensory discrimination ability and decision bias of children with and without ADHD. It also investigated the differences between ADHD with predominantly inattentive (ADHDi) and combined presentations (ADHDc). The sample of 75 children and adolescents with ADHD (24 ADHDi, 51 ADHDc) (16 females and 59 males) and 22 typical developing controls (TD) (8 females and 14 males) completed an auditory signal detection task. Participants were asked to detect signals against levels of transient background noise (35, 45, 55, and 65 dB). The results showed that with the increase of noise levels, both the ADHD and TD groups demonstrated decreased sensory discrimination. Although both groups successfully detected signal against noise levels from 35 to 55 dB, the ADHD group showed lower discrimination ability than that of the TD group. For decision bias, no group difference was found. Further comparisons regarding the predominant symptom presentation of ADHD sub-groups showed no differences. Current research has suggested that the deficit in ADHD people's signal detection performance can be attributed to sensory discrimination rather than decision bias. We suggest that background noise should be taken into account when using auditory stimuli to investigate cognitive functions in people with ADHD.

Keywords ADHD · Signal detection theory · Auditory sensory discrimination · Decision bias

Introduction

Attention-deficit hyperactivity disorder (ADHD) is an early childhood developmental disorder that can seriously impair a child's cognitive, emotional, social, and academic performance, as well as their family life in multiple contexts, including school and home [2]. ADHD is one of the most common psychiatric disorders worldwide with estimated prevalence ranging from 3 to 12% [2, 21, 29]. It is usually diagnosed in childhood and may persist through adolescence and adulthood [5, 6]. ADHD is characterized by attentional problems and/or hyperactivity–impulsivity that interfere with functioning or development. These behaviors are differentially expressed in three types: primarily inattentive (ADHDi), primarily hyperactive/impulsive (ADHDh), and combined (ADHDc) [2].

Prior research on ADHD has focused mainly on executive dysfunctions involving prefrontal deficits [6]. Executive functions are a set of cognitive processes that control conscious and voluntary self-regulation and goal-directed

✉ Kuo-You Huang
kyhuang3317@gmail.com

[1] Department of Psychology, Chung Shan Medical University, Taichung, Taiwan

[2] Room of Clinical Psychology, Chung Shan Medical University Hospital, Taichung, Taiwan

[3] Department of Psychiatry, Chang Gung Memorial Hospital and University, Chiayi, Taiwan

[4] Graduate Institute of Clinical Medical Sciences, Chang Gung University, Taoyüan, Taiwan

[5] Department of Speech Language Pathology and Audiology, Chung Shan Medical University, No. 110, Sec. 1, Jianguo N. Rd, Taichung 40201, Taiwan

[6] Speech and Language Therapy Room, Chung Shan Medical University Hospital, Taichung, Taiwan

[7] National Addiction Centre, King's College, London, UK

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behavior, such as response inhibition, planning, abstract thinking, working memory, attention shifting, verbal fluency, and problem solving [28]. Barkley proposed the model of inhibitory control as the basis of executive dysfunction in ADHD. Various operations subsumed under the concept of executive dysfunctions are thought to be related to ADHD [5].

Difficulties in executive functions could have everyday implications for and influence on academic achievement and social competence [15, 19, 23]. However, less attention has been paid to sensory perception and subcortical functioning as alternative causes of ADHD difficulties [26]. Children with ADHD are likely to be at risk for auditory processing problems may be including hypersensitivity or defensiveness and hyposensitivity to sounds [12]. Children with hypersensitivity to sounds may be very sensitive to sounds that are unheard by others, and hence become distracted. On the other hand, children with hyposensitivity to sounds may often be unresponsive to oral commands or calls and seem to be puzzled about where the origin of a sound is.

Whether children with ADHD have auditory deficits is still a controversy. Pillsbury et al. [20] investigated basic binaural function in children with ADHD. They manipulated masking level and found no differences between children with ADHD and controls for the signal detection tasks, but for speech recognition tasks, ADHD children did not perform as well as the controls. However, recent studies have shown that children with ADHD have deviant auditory brain cortex response compared to controls [24], and ADHD children showed inefficient auditory processing on some tasks about auditory closure, binaural integration, and temporal ordering [17].

Although the evidence from parental reports and laboratory investigations suggests deficits of auditory processing in ADHD, the methods adopted have failed to distinguish between sensory and decision factors. An important challenge is to determine how top–down attention modulation and bottom–up perceptual processing interact during auditory processing. Signal detection theory (SDT) is a theoretical framework used to differentiate sensory discrimination and response bias independently [14]. It can be used in tasks that require participants to categorize ambiguous stimuli, which can either be generated by a known process (i.e., signal) or be due to chance (i.e., noise). For example, a signal detection task involves signal trials and non-signal (noise) trials. Participants are asked to indicate whether a signal is present after each trial. On signal trials, yes responses are correct and termed hits, whereas on noise trials, yes responses are incorrect and termed false alarms. The hit and false alarm rates reflect two factors: "sensory discrimination" (the degree of overlap between the signal and noise distributions) and "response bias" (the general tendency to respond yes or no). A simple detection task tests both sensory and decision processes. SDT provides a framework for analyzing sensory discrimination ability and response bias separately.

In the current study, we used an auditory signal detection task in which participants were asked to detect a signal embedded in background noise to investigate: (1) whether children with ADHD have auditory deficits? (2) Which of the two mechanisms, "sensory discrimination", or "top–down attention modulation," contribute to the poor performance of children with ADHD. (3) If children with ADHD do have auditory deficits, we wanted to find out whether the deficit is specific to one of the ADHDi and ADHDc sub-groups. We hypothesized that both sensory discrimination ability and decision accuracy of children with ADHD were inferior to that of typically developing children. We also expected that the differences between these two groups would decrease as the background noise level increased.

Method

Participants

Seventy-five children and adolescents with a clinical diagnosis of ADHD (16 females and 59 males; mean age = 9.84, range 7–16 years) and 22 typically developing (TD) children and adolescents (8 females and 14 males; mean age = 10.64, range 7–15 years) were recruited as participants. Participants in ADHD group were recruited from the Chung Shan Medical University Hospital in Taiwan. They were all drug naive patients when participated in the current study. A child was eligible for the diagnosis of ADHD if he met the DSM-IV-TR criteria by a psychiatrist's interview [3]. The participants were recruited if they met the following criteria: (1) diagnosis of ADHD by a psychiatrist's interview, based on meeting the DSM-IV-TR criteria; (2) parental rating 1.5 SD above the normative mean on the Chinese version of the Swanson, Nolan, and Pelham Scale, used to measure behavioral characteristics of ADHD (SNAP-IV) [11, 18, 27]; and (3) estimated intelligence quotient (IQ) equal to or above 70. The exclusion criterion was the presence of other developmental or psychiatric or neurological disorders. The ADHD group was divided into two sub-groups: ADHDi (*n* = 24; 7 females and 17 males) and ADHDc (*n* = 51; 9 females and 42 males).

Table 1 shows the demographic information including the age, IQ score, and SNAP-IV rating score for the sub-groups of ADHD and the TD group. The test for mean differences using one-way ANOVA revealed no group difference in age and IQ. For the parental rating score using SNAP-IV, the results showed significant group differences for both inattentive and hyperactive/impulsive subscales. ADHDi and ADHDc showed higher IA and HI scores than TD. ADHDc

Table 1 Demographic information including the age, IQ score, and SNAP-IV rating score for each of the three groups

	ADHDi			ADHDc			TD			Test for mean difference		
	n	Mean	SD	*n*	Mean	SD	*n*	Mean	SD	*F*	*p*	η^2
Age	24	10.33	2.30	51	9.61	2.33	22	10.64	2.30	1.81	> 0.05	0.037
IQ	24	98.00	8.53	51	99.86	7.90	22	100.81	9.90	0.66	> 0.05	0.014
IA	24	17.88	7.44	51	17.70	5.07	22	6.86	2.62	34.95	< 0.001	0.429
HI	24	6.25	3.55	51	17.22	4.46	22	3.32	2.82	122.31	< 0.001	0.724

IQ denotes full-scale intelligent quotient measured by WISC III; IA, and HI denote parental rating score from inattentive and hyperactive/impulsive subscales of SNAP-IV, respectively

showed higher HI score than ADHDi, but there are no difference found in IA score.

Task and procedure

All participants accepted an auditory signal detection task and were asked to detect a signal embedded in transient background noise. The task consisted of 240 trials. For 120 of the trials a visual fixation cross was followed by a signal-plus-noise sound, and for the other 120 trials a visual fixation cross was followed by noise-only sound. Participants had to make a yes/no response about the presence of signal. The signal-plus-noise stimulus was a 100 ms sinusoid wave (60 dB) embedded in the middle of 300 ms of transient noise. There were four levels of noise: 35, 45, 55, 65 dB. Trials with and without signals, and different noise levels were all presented in random order. The experiments were conducted in a soundproof chamber to precisely manipulate the auditory signal and noise background and to avoid interference from outside the laboratory. Accuracy rate was calculated by the number of correct response over total trial number as the dependent variable.

Data analysis

To investigate whether the ADHD group performed differently than the TD group on the auditory signal detection task, we conducted statistical analyses of both accuracy rate and indices based on signal detection theory (SDT) [14]. SDT is used to analyze data from experiments, where the task is to categorize ambiguous stimuli that can be generated either by a known process (called signal) or obtained by chance (called noise). The goal of SDT is to estimate two main parameters from the experimental data. The first parameter, called d', indicates the sensory discrimination ability of the perceiver (signal relative to the noise). The second parameter, called β, indicates the decision bias (i.e., the response tendency) of the participant. According to SDT, sensory discrimination (d') and decision bias (β) are mutually independent mechanisms. Sensory discrimination (d') is derived from the Z scores of the hit rate and the false alarm rate ($d' = Z_{\mathrm{FA}} - Z_{\mathrm{Hit}}$). Decision bias ($\beta$) is the relative likelihood of observing the threshold value if the signal is present to observing the threshold value if the signal is not present. Regarding the signal detection theory and psychophysics, please refer to the classical work of Green and Swets [14]. In research with small numbers of trial (less than 100 per condition), Brown and White [8] suggest adoption of log-transformed d' and β indices to increase reliability.

The auditory signal detection task used in the current study required participants to perform a simple yes–no response for each trial. In the terminology of signal detection theory [14], according to the signal present or absent and participant's yes–no response, the response can be assigned to the four cells of a signal detection matrix: hits (Hit), misses (Miss), false alarms (FA), and correct rejections (CR).

The accuracy rate can be calculated as Eq. (1):

$$\text{Accuracy rate (AR)} \; = (\text{Hit} + \text{CR})/(\text{Hit} + \text{CR} + \text{FA} + \text{Miss}). \tag{1}$$

Before calculating sensory discrimination and decision bias indices, we calculated the following rates (Eqs. 2a–2d). To avoid response count of 0, we adopted the correction to add a constant 0.25 to all response counts as Brown and White [7] suggested:

$$\text{Hit rate (HR)} = \text{Hit}/(\text{Hit} + \text{Miss}), \tag{2a}$$

$$\text{Miss rate (MR)} = \text{Miss}/(\text{Hit} + \text{Miss}), \tag{2b}$$

$$\text{Correct reject rate (CRR)} = \text{CR}/(\text{CR} + \text{FA}), \tag{2c}$$

$$\text{False alarm rate (FAR)} = \text{FA}/(\text{CR} + \text{FA}). \tag{2d}$$

Finally, we adopted log-transformed d' and β indices [7] using Eqs. (3a) and (3b):

$$\log d' = 1/2 \times \log 10((\text{Hit}/\text{Miss}) \times (\text{CR}/\text{FA})), \tag{3a}$$

$$\log \beta = 1/2 \times \log 10((\text{Hit}/\text{Miss}) \times (\text{FA}/\text{CR})). \tag{3b}$$

Design and statistics

A mixed design was employed, with (participant) group as the between-subjects variable and level of noise as the within-subjects variable. The responses were measured and then converted into the dependent variables (accuracy rate and the other indices). One-sample t tests were conducted for each group and for each noise level to test whether the accuracy rates and logd' were significantly greater than the chance level. Two-way ANOVAs were used to assess the differences in accuracy rate, reaction time, logd', and logβ, with noise level (NL35, NL45, NL55, and NL65) as the within-subjects factor and group (TD vs. ADHD; ADHDi vs. ADHDc) as the between-subjects factor. Independent t tests will be conducted as planned comparisons to test the group differences at each noise level.

Results

Group differences between children with and without ADHD

Accuracy rate

As shown in Fig. 1a, both the ADHD and TD groups showed the same trend: accuracy rate decreased as the noise level increased. One-sample t tests were conducted for each group and for each noise level to test whether the accuracy rates were significantly greater than the chance value of 0.5. The results revealed both ADHD and TD group performed above chance for all noise levels except NL65 (ADHD: $t_{(74)} > 11.32$, $p < 0.001$; TD: $t_{(21)} > 8.66$, $p < 0.001$). Based on the finding, the following statistic analysis only included three noise levels (NL35, NL45, and NL55).

The two-way ANOVA showed significant main effects for noise level [$F_{(2,190)} = 28.50$, $p < 0.001$, $\eta^2 = 0.231$] and for group [$F_{(1,95)} = 5.70$, $p < 0.05$, $\eta^2 = 0.057$]. The noise level by group interaction failed to reach significance [$F_{(2,190)} = 1.10$, $p > 0.05$, $\eta^2 = 0.110$]. The main effect for group suggested that accuracy rate for TD is higher than ADHD group. Post hoc LSD analyses for accuracy rate as a function of noise level showed NL35 > NL45 > NL55 ($p < 0.05$).

We conducted independent t test as planned comparisons to test the differences between the ADHD and TD groups at each noise level. The results showed that accuracy for the TD group was significantly higher than for the ADHD group at NL35 [$t_{(95)} = -3.95$, $p < 0.001$] and NL45 [$t_{(95)} = -3.19$, $p < 0.01$], but no difference was found at NL55 and NL65 (both $t_{(95)} > -0.54$, $p > 0.05$). Although both groups could successfully detect signals at NL55, the group difference declined for noise levels greater than 55 dB.

Reaction time (RT)

Only the RT for correct responses was included for analysis. Mean RT for ADHD and TD groups were shown in Fig. 1b. Since the accuracy rates fall into chance level at NL65 condition for both ADHD and TD groups, only 3 noise levels (NL35, NL45, NL55) were included for further analysis.

The two-way ANOVA showed significant main effects for noise level [$F_{(2,190)} = 3.78$, $p < 0.05$, $\eta^2 = 0.038$]. There were no significant effect for group [$F_{(1,95)} = 1.46$, $p > 0.05$, $\eta^2 = 0.015$] and noise level by group interaction [$F_{(2,190)} = 1.55$, $p > 0.05$, $\eta^2 = 0.160$]. It suggested there are no response speed difference between ADHD and TD groups. Post hoc LSD analyses showed that RT at NL55 was significantly longer than at NL45 ($p < 0.01$).

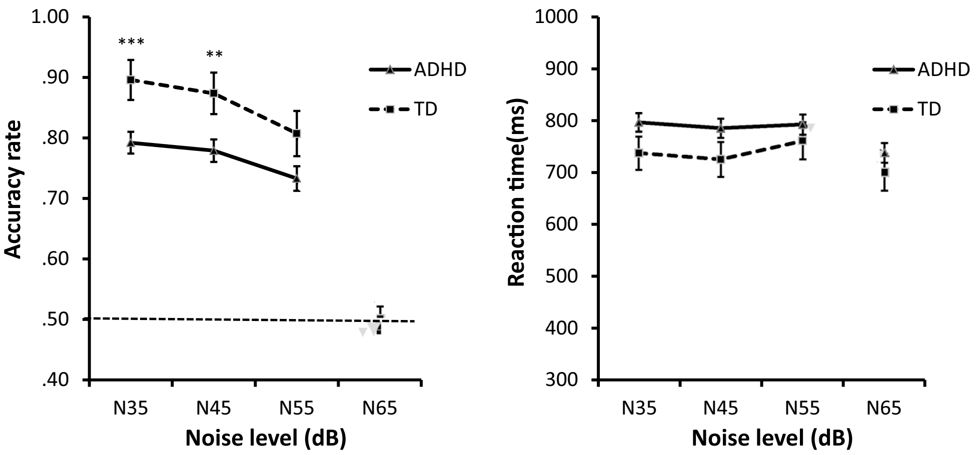

Fig. 1 Group means for a, accuracy rate and b, reaction time of auditory signal detection at different levels of background noise for the ADHD ($n = 75$) and TD ($n = 22$) groups. Error bars represent the standard error of the mean

Behavioral analysis according to signal detection theory

Sensory discrimination

As shown in Fig. 2a, for both the ADHD and TD groups log*d*′ decreased as noise level increased. We investigated whether log*d*′s were significantly different from chance (test value = 0). Results showed that both groups could discriminate signal from noise when the noise level was below 55 dB (ADHD: $t_{(74)} > 10.89$, $p < 0.001$; TD: $t_{(21)} > 7.28$, $p < 0.001$) but neither group could discriminate signal from noise when the noise level was at 65 dB ($p > 0.05$). Based on the finding, the following statistic analysis only included 3 noise levels (NL35, NL45, NL55).

The two-way ANOVA showed significant main effects for noise level [$F_{(2,190)} = 17.40$, $p < 0.001$, $\eta^2 = 0.155$] and for group [$F_{(1,95)} = 4.71$, $p < 0.05$, $\eta^2 = 0.047$]. The noise level by group interaction was not significant [$F_{(2,190)} = 1.29$, $p > 0.05$, $\eta^2 = 0.130$]. The main effect for group suggested log*d*′ for TD is larger than ADHD group. Post hoc LSD analyses for accuracy rate as a function of noise level showed NL35 = NL45 > NL55 (all significant $p < 0.05$).

We conducted independent *t* tests as planned comparisons to test the differences between the ADHD and TD groups at each noise level. The results showed that log*d*′s were significantly higher for the TD group than for the ADHD group at NL35 [$t_{(95)} = -2.61$, $p < 0.05$] and NL45 [$t_{(95)} = -2.06$, $p < 0.05$], while no difference was found at NL55 and NL65 (both $t_{(95)} > -1.00$, $p > 0.05$). The results suggest that although both groups can successfully detect signals at NL55, the group difference was diminished when the noise level was larger than 55 dB.

Decision bias

As shown in Fig. 2b, logβ for both the ADHD and TD groups showed the same trend, that the value was close to 0 when the noise level was at 35–55 dB but sharply dropped at 65 dB. The two-way ANOVA showed a significant main effect of noise level [$F_{(2,190)} = 9.72$, $p < 0.001$, $\eta^2 = 0.093$]. The group main effect [$F_{(1,95)} = 0.10$, $p > 0.05$, $\eta^2 = 0.001$] and interaction [$F_{(2,190)} = 0.94$, $p > 0.05$, $\eta^2 = 0.010$] failed to reach statistical significance. Post hoc pairwise comparisons using LSD showed that logβ decreased as noise level increased (NL35 = NL45 > NL55, all significant $p < 0.01$).

We also investigated whether logβ significantly deviated from the unbiased value (test value = 0). The ADHD group showed a bias tendency at all noise levels [log$\beta < -0.124$, all $t_{(74)} > 4.17$, $p < 0.001$]. The TD group adopted unbiased criteria at noise levels 35 and 45 dB [log$\beta > -0.914$, $t_{(21)} < -1.70$, $p > 0.05$], but adopted a biased criterion when the noise level was 55 or 65 dB [log$\beta < -0.336$, $t_{(21)} > 5.25$, $p < 0.001$]. The independent *t* tests for logβ between ADHD and TD groups did not show significant differences at each noise level. It suggested that ADHD and TD did not adopt different decision criterion.

Differences between ADHD Presentation Sub-groups

Accuracy rate

As shown in Fig. 3, both the ADHDi and ADHDc subgroups showed the same trend that accuracy rate decreased as noise level increased. A two-way ANOVA was conducted with group (2; ADHDi vs. ADHDc) and noise level (3; NL35, NL45, NL55) as independent variables. The results showed significant main effects for noise level [$F_{(2,146)} = 14.47$, $p < 0.001$, $\eta^2 = 0.165$] but not for group [$F_{(1,73)} = 1.74$, $p > 0.05$, $\eta^2 = 0.023$]. The noise level by group interaction was also significant [$F_{(2,146)} = 3.14$, $p < 0.05$, $\eta^2 = 0.041$].

A one-way ANOVA for groups was conducted to examine the effects of noise. The accuracy rate for the ADHDi group was not significantly related to noise level [$F_{(2,46)} = 1.50$, $p > 0.05$, $\eta^2 = 0.061$] and the accuracy rate for the ADHDc group was significantly related to noise

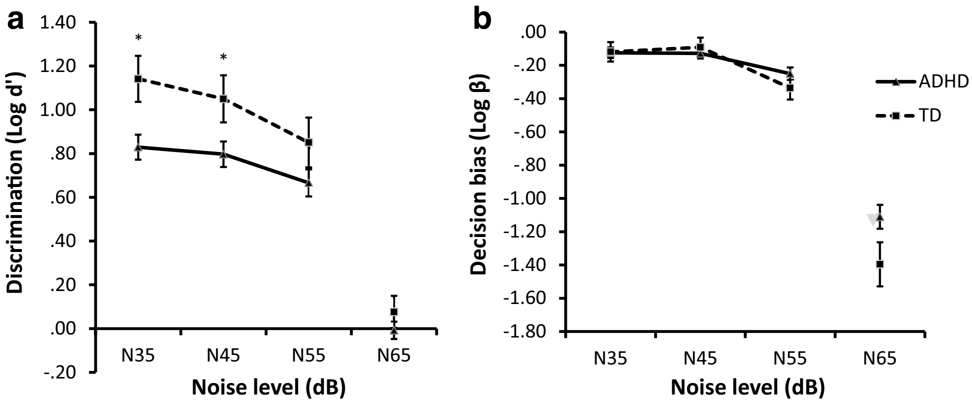

Fig. 2 Group means for a, discrimination (log*d*′) and b, decision bias (logβ) of auditory signal detection at various levels of background noise for the ADHD ($n = 75$) and TD ($n = 22$) groups. Error bars represent the standard error of the mean. Note that the TD group showed better discrimination at 35 and 45 dB than the ADHD group. No group differences were found for decision bias

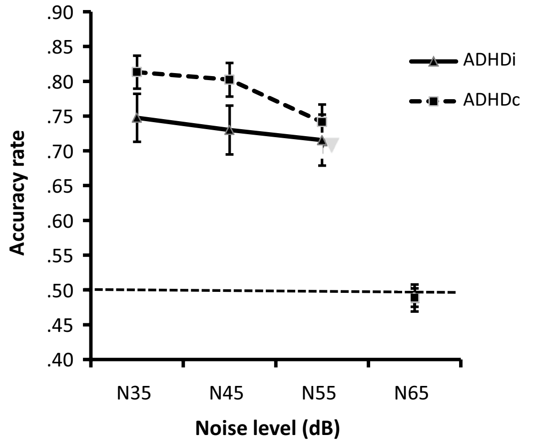

Fig. 3 Group means for accuracy rate of auditory signal detection at various levels of background noise for the ADHD sub-groups (ADHDi, $n = 24$ and ADHDc, $n = 51$). Note that no significant group difference was found between the two sub-groups. Error bars represent the standard error of the mean

level [$F_{(2,100)} = 26.89$, $p < 0.001$, $\eta^2 = 0.350$]. Post hoc LSD analyses for accuracy rate as a function of noise level showed NL35 = NL45 > NL55 (all significant $p < 0.001$).

We conducted independent *t* tests to test the differences between the ADHDi and ADHDc groups at each noise level. The results showed that there was no group difference for accuracy rates at each noise level (all $t_{(73)} > -0.59$, $p > 0.05$)

Behavioral analysis according to signal detection theory

Sensory discrimination

As shown in Fig. 4, both the ADHDi and ADHDc sub-groups showed the same trend that log*d*′ decreased as noise level increased. The two-way ANOVA showed significant main effects for noise level [$F_{(2,146)} = 7.08$, $p < 0.01$, $\eta^2 = 0.088$]. The group main effect [$F_{(1,73)} = 0.31$, $p > 0.05$, $\eta^2 = 0.004$] and group by noise-level interaction [$F_{(2,146)} = 1.22$, $p > 0.05$, $\eta^2 = 0.016$] failed to reach statistical significance. Post hoc pairwise comparisons using LSD showed that log*d*′ decreased as noise level increased (NL35 = NL45 > NL55, all significant $p < 0.01$).

Decision bias

As shown in Fig. 4b, both the ADHDi and ADHDc sub-groups showed the same trend that log*β* was close to the unbiased value of 0 at 35–55 dB but sharply deviated from 0 at 65 dB. The two-way ANOVA showed significant main effects for noise level [$F_{(2,146)} = 4.19$, $p < 0.05$, $\eta^2 = 0.054$]. The group main effect [$F_{(1,73)} = 0.58$, $p > 0.05$, $\eta^2 = 0.008$] and group by -level interaction [$F_{(2,146)} = 1.28$, $p > 0.05$, $\eta^2 = 0.017$] failed to reach statistical significance. Post hoc pairwise comparisons using LSD showed that log*β* decreased as noise level increased (NL35 = NL45 > NL55, all significant $p < 0.01$).

Discussion

In this study, we gave an auditory signal detection task to ADHD and TD groups. The main findings were: (1) the accuracy rate decreased with background noise level increased for both ADHD and TD groups, and accuracy rate of ADHD group was significant inferior to TD group in NL35 and NL45 dB. (2) Reaction times were not different between two groups. (3) TD group performed better than ADHD group only in log*d*′, not in log*β*, and it means the deficit of sensory discrimination, not decision bias, for ADHD children. (4) There were no any differences in accuracy rate, log*d*′ and log*β* between ADHDi and ADHDc sub-groups. These results showed that the accuracy rate decreased as the noise level increased for ADHD and TD groups. Both groups successfully detected signals embedded in background noise when the noise level was less than 55 dB. There was a clear group difference for noise levels of 35 dB and 45 dB, but

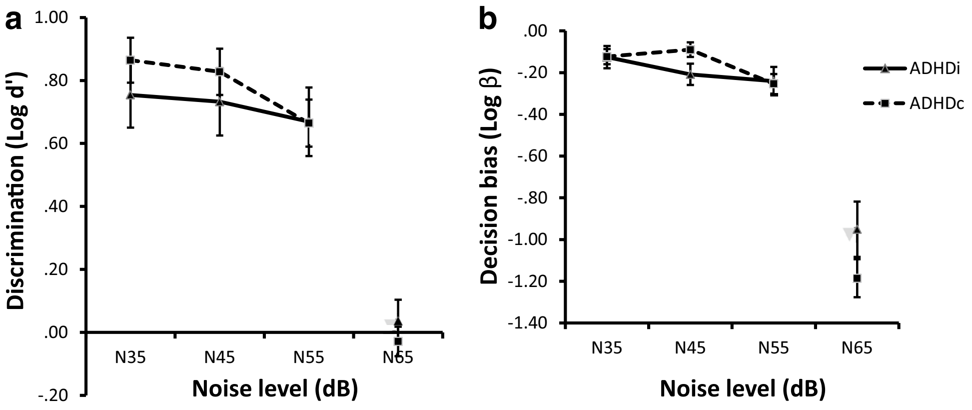

Fig. 4 Group means for a, discrimination (log*d*′) and b, decision bias (log*β*) of auditory signal detection under various levels of background noise for the ADHD sub-groups (ADHDi, $n = 24$ and ADHDc, $n = 51$). Note that no significant group differences were found between the two sub-groups. Error bars represent the standard error of the mean

no difference was found at 55 dB or above. Using SDT analysis, we found a similar trend with group differences for sensory discrimination but not for decision bias, suggesting that the performance difference between the ADHD and TD groups can be attributed to sensory discrimination rather than decision bias. Regarding performance, no differences were found between the ADHD sub-groups on accuracy rate, sensory discrimination, and decision bias. In this study, we confirmed the hypothesis that the ADHD group showed lower sensory discrimination ability but not for decision bias. Besides, the between-group differences declined as background noise level increased.

In the current study, an auditory signal detection task was used to investigate participants' perceptual discrimination and decision bias. Compared to other cognitive tasks, signal detection tasks require less cognitive loading and processes than other tasks used to assess attention or executive function. Results showed ADHDi and ADHDc sub-groups had consistent attention deficits, which could be one of the most important reasons for their poor performance compared to the normally developed children. In addition to attention deficits, performances of decision bias between ADHD and TD groups, and between ADHDi and ADHDc sub-groups were not different. In general, the ADHDc group should show more hyperactivity/impulsive symptoms than TD children and ADHDi group. The lack of performance differences in decision bias between the ADHDi and ADHDc sub-groups suggests that hyperactivity/impulsive symptoms may not be the causes of performance differences on auditory signal detection task. Or, another possibility is that simple pure tone detection task may appear ceiling effect easily; therefore, the difference between the two groups cannot be revealed. Gray et al. proposed that children with ADHD are more impulsive than normal children at lower levels of information uncertainty. Response biases in children with ADHD may diverge from normal only in situations, where distracting external stimuli have an intermediate level of predictability [13]. In our current study, predictability was kept constant across levels of noise, which may have lessened impulsive behavior caused by uncertainty. Therefore, we suggest that further research could try to add cognitive loading or increase the uncertainty of stimuli to clarify this question.

As reported in Söderlund and Jobs [26], children with ADHD seem to have a listening problem and they need auditory information to be repeated. Moreover, children with ADHD also display significant deficits in verbal– and visual–spatial working memory, and executive functions [1, 10, 28]. The ability to keep verbally given instructions in mind and follow them is important for schoolwork, and ADHD is, therefore, commonly associated with school failure and academic under-achievement [6, 25]. Group differences in auditory perception between ADHD and TD participants have been reported in a small number of studies [12, 17]. However, Pillsbury et al. [20] found no deficits in signal detection per se in their ADHD group, but they found reduced processing efficiency in speech recognition, particularly in noisy environments. The hyposensitivity of ADHD shown in our results indicated that ADHD children have deficits in auditory signal perception, and it may have caused inefficient encoding in working memory.

The results of this study suggested some kind of auditory processing deficits in ADHD. Is this deficit different from APD? It is another issue worthy of further study, and it is also a limitation that the current study cannot clarify. Auditory processing disorder (APD) refers to auditory perceptual difficulties that are not related to peripheral hearing deficits or language and cognitive impairments [4, 8, 22]. Children with APD may have difficulty hearing in noisy environments and cannot understanding instructions [16], poor reading and spelling, as well as poor concentration and impaired memory [9]. The challenge is how to determine whether auditory processing problems stem from deficiencies in the auditory processing mechanism (APD) or from attention deficit (ADHD). Our evidence suggests that children with ADHD have a hyposensitivity to sounds rather than hypersensitive. It may be important to rule out APD problem prior to considering testing for ADHD, because auditory processing deficits can affect performance on tests of ADHD. Therefore, differentiating ADHD and APD requires joint cooperation of the physician/psychologist and audiologist. A limitation of this study is that it did not include an APD group. Future research is needed to directly compare performance on signal detection tasks among ADHD, APD, and TD groups. In addition, the use of visual tasks to detect the sensory discrimination and decision bias of ADHD may be an interesting way to investigate the deficits of ADHD in the future.

Strength and limitations

The main strength of this study is applied signal detection theory (SDT) to identify whether children with ADHD having sensory discrimination problem or decision bias difficult that cause auditory processing deficits, and attempts to discriminate differences between ADHDi and ADHDc children. However, there are also several limitations. First, sample size is slightly lower, especially ADHDi group. However, it is not an easy work to recruit appropriate participants at outpatient. Second, although we control the ages and IQ, we could not rule out the possible influence of other confounding variables not assessed and adjusted for, such as family history of ADHD, educational level of parents, and income of family. Third, participants in our study did not recruit children with auditory processing disorder (APD), and therefore, we could not clarify the differences in the performance of auditory signal detection task between ADHD and APD in this study.

Conclusions

ADHD is one of the most common psychiatric disorders in children. Results of this study lead us to infer that the deficit of auditory processing in children with ADHD is primary due to the poor sensory discrimination rather than decision bias. Clinicians and therapists should advise parents and teachers trying to reduce the interference of noise in learning environment, to promote ADHD children's cognitive performance and academic learning.

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Author contributions Y-MT contributed to the study design and statistical analysis and drafted the initial manuscript; VC-HC carried out the participants interview and diagnosis, interpreted the data, revised the manuscript, and contributed equally to Y-MT; T-SL contributed to the task design and reviewed the manuscript; C-FH and MG critically reviewed the manuscript; and K-YH conceptualized the study, finalized the manuscript, and took responsibility for the integrity of the data. All authors have read and approved the final manuscript as submitted.

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Compliance with ethical standards

Conflict of interest All authors have no financial relationships relevant to this article and conflicts of interest to disclose.

References

1. Alderson RM, Kasper LJ, Patros CH, Hudec KL, Tarle SJ, Lea SE (2015) Working memory deficits in boys with attention deficit/hyperactivity disorder (ADHD): an examination of orthographic coding and episodic buffer processes. Child Neuropsychol 21:509–530
2. American Psychiatric Association (2013) Diagnostic and statistical manual of mental disorders, 5th edn. American Psychiatric Publishing, Arlington
3. American Psychiatric Association (2000) Diagnostic and statistical manual of mental disorders, 4th edn. American Psychiatric Publishing, Washington
4. Bamiou DE, Musiek FE, Luxon LM (2001) Aetiology and clinical presentations of auditory processing disorders—a review. Arch Dis Child 85:361–365
5. Barkley RA (1997) ADHD and the nature of self-control. Guilford Press, New York
6. Barkley RA, Fischer M, Smallish L, Fletcher K (2006) Young adult outcome of hyperactive children: adaptive functioning in major life activities. J Am Acad Child Adolesc Psychiatry 45:192–202
7. Brown GS, White KG (2005) The optimal correction for estimating extreme discriminability. Behav Res Methods 37:436–449
8. Chermak GD, Tucker E, Seikel JA (2002) Behavioral characteristics of auditory processing disorder and attention-deficit hyperactivity disorder: predominately inattentive type. J Am Acad Audiol 13:332–338
9. Dawes P, Bishop DVM, Sirimanna T, Bamiou DE (2008) Profile and aetiology of children diagnosed with auditory processing disorder (APD). Int J Pediatr Otorhinolaryngol 72:483–489
10. Gau SS, Chiang HL (2013) Association between early attention-deficit/hyperactivity symptoms and current verbal and visuo-spatial short-term memory. Res Dev Disabil 34:710–720
11. Gau SS, Shang CY, Liu SK, Lin CH, Swanson JM, LiuYC TuCL (2008) Psychometric properties of the Chinese version of the Swanson, Nolan, and Pelham, version IV scale-parent form. Int J Methods Psychiatr Res 17:35–44
12. Ghanizadeh A (2009) Screening signs of auditory processing problem: does it distinguish attention deficit hyperactivity disorder subtypes in a clinical sample of children? Int J Pediatr Otorhinolaryngol 73:81–87
13. Gray LC, Breier JI, Foorman BR, Fletcher JM (2002) Continuum of impulsiveness caused by auditory masking. Int J Pediatr Otorhinolaryngol 66:265–272
14. Green DM, Swets JA (1966) Signal detection theory and psychophysics. Wiley, New York
15. Hale JB, Reddy LA, Semrud-Clikeman M, Hain LA, Whitaker J, Morley J, Lawrence K, Smith A, Jones N (2011) Executive impairment determines ADHD medication response: implications for academic achievement. J Learn Disabil 44:196–212
16. Jerger J, Musiek F (2000) Report of the consensus conference on the diagnosis of auditory processing disorders in school-aged children. J Am Acad Audiol 11:467–474
17. Lanzetta-Valdo BP, Oliveira GA, Ferreira JTC, Palacios EMN (2017) Auditory processing assessment in children with attention deficit hyperactivity disorder: an open study examining methylphenidate effects. Int Arch Otorhinolaryngol 21:72–78
18. Liu YC, Liu SK, Shang CY, Lin CH, Tu C, Gau SS (2006) Norm of the Chinese version of the Swanson, Nolan and Pelham, Version IV scale for ADHD. Taiwan J Psychiatry 20:290–304
19. Massetti GM, Lahey BB, Pelham WE, Loney J, Ehrhardt A, Lee SS, Kipp H (2008) Academic achievement over 8 years among children who met modified criteria for attention-deficit/hyperactivity disorder at 4–6 years of age. J Abnorm Child Psychol 36:399–410
20. Pillsbury HC, Grose JH, Coleman WL, Conners CK, Hall JW (1995) Binaural function in children with attention-deficit hyperactivity disorder. Arch Otolaryngol Head Neck Surg 121:1345–1350
21. Polanczyk GV, Willcutt EG, Salum GA, Kieling C, Rohde LA (2014) ADHD prevalence estimates across three decades: an updated systematic review and meta-regression analysis. Int J Epidemiol 43:434–442
22. Riccio CA, Hynd GW, Cohen MJ, Hall J, Molt L (1994) Comorbidity of central auditory processing disorder and attention-deficit hyperactivity disorder. J Am Acad Child Adolesc Psychiatry 33:849–857
23. Rogers M, Hwang H, Toplak M, Weiss M, Tannock R (2011) Inattention, working memory, and academic achievement in adolescents referred for attention deficit/hyperactivity disorder (ADHD). Child Neuropsychol 17:444–458

24. Seither-Preisler A, Parncutt R, Schneider P (2014) Size and synchronization of auditory cortex promotes musical, literacy, and attentional skills in children. J Neurosci 34:10937–10949
25. Serra-Pinheiro MA, Mattos P, Regalla MA, Souza I, Paixão C (2008) Inattention, hyperactivity, oppositional-defiant symtoms and school failure. Arq Neuropsiquiatria 66:828–831
26. Söderlund GBW, Jobs EN (2016) Differences in speech recognition between children with attention deficits and typically developed children disappear when exposed to 65 dB of auditory noise. Front Psychol. https://doi.org/10.3389/fpsyg.2016.00034
27. The MTA Cooperative Group (1999) A 14-month randomized clinical trial of treatment strategies for attention-deficit/hyperactivity disorder. Arch Gen Psychiatry 56:1073–1086
28. Trannel D, Anderson SW, Benton A (1994) Development of the concept of "executive function" and its relationship to the frontal lobes. In: Boller F, Grafman J (eds) Handbook of neuropsychology. Elsevier Science, Amsterdam, pp 125–148
29. Willcutt EG (2012) The prevalence of DSM-IV attention-deficit/hyperactivity disorder: a meta-analytic review. Neurotherapeutics 9:490–499