BRAIN RESEARCH 1170 (2007) 90–96

available at www.sciencedirect.com

ScienceDirect

www.elsevier.com/locate/brainres

ELSEVIER

BRAIN RESEARCH

Research Report

Time perception deficit in children with ADHD

Binrang Yang[a,b], *Raymond C.K. Chan*[a,*], *Xiaobing Zou*[c], *Jin Jing*[d], *Jianning Mai*[e], *Jing Li*[f]

[a]*Neuropsychology and Applied Cognitive Neuroscience Laboratory, Department of Psychology, Sun Yat-Sen University, Guangzhou, China*
[b]*Shenzhen Children's Hospital, Shenzhen, China*
[c]*Child Developmental Behavior Center, the Third Affiliated Hospital, Sun Yat-Sen University, Guangzhou, China*
[d]*School of Public Health, Sun Yat-Sen University, Guangzhou, China*
[e]*Guangzhou Children's Hospital, Guangzhou, China*
[f]*Maternal and Child Health Hospital, Zhuhai, China*

ARTICLE INFO

Article history:
Accepted 11 July 2007
Available online 17 July 2007

Keywords:
ADHD
Time perception
Duration discrimination

ABSTRACT

Time perception deficit has been demonstrated in children with attention deficit hyperactivity disorder (ADHD) by using time production and time reproduction tasks. The impact of motor demand, however, has not yet been fully examined. The current study, which is reported herein, aimed to investigate the pure time perception of Chinese children with ADHD by using a duration discrimination task. A battery of tests that were specifically designed to measure time perception and other related abilities, such as inhibition, attention, and working memory, was administered to 40 children with ADHD and to 40 demographically matched healthy children. A repeated measure MANOVA indicated that children with ADHD showed significantly higher discrimination thresholds than did healthy controls, and there was an interaction effect between group and duration. Pairwise comparison indicated that children with ADHD were less accurate in discriminating duration at either target duration. Working memory (Corsi blocks task) was related to the discrimination threshold at a duration of 800 ms after controlling for full-scale IQ (FIQ) in the ADHD group, but this did not survive the Bonferroni correction. The results indicated that children with ADHD may have perceptual deficits in time discrimination. They needed a greater difference between the comparison and target intervals to discriminate the short, median, and long durations reliably. This study provides further support for the existence of a generic time perception deficit, which is probably due to the involvement of a dysfunctional fronto–striato–cerebellar network in this capacity, especially the presence of deficits in basic internal timing mechanisms.

1. Introduction

Time perception, which comprises multiple component processes, is an important function that facilitates the ability to predict, anticipate, and respond efficiently to coming events. Attention deficit hyperactivity disorder (ADHD) is one of the pervasive cognitive developmental disorders and is characterized by levels of inattention, hyperactivity, and impulsivity that are age-inappropriate. Time perception deficit has been hypothesized in models of ADHD. The most common model of behavioral inhibition argues that poor inhibition and interference control affect working memory, which consequently

* *Corresponding author.* Neuropsychology and Applied Cognitive Neuroscience Laboratory, Institute of Psychology, Chinese Academy of Sciences, 4A Datun Road, Beijing 100101, China.
E-mail addresses: rckchan@psych.ac.cn, rckchan2003@yahoo.com.hk (R.C.K. Chan).

0006-8993/$ – see front matter
doi:10.1016/j.brainres.2007.07.021

Table 1 – Summary of demographic characteristics and cognitive measures of the children with ADHD and controls

Measure	ADHD (N=40)		Controls (N=40)		F/X^2	p-values	Cohen's d
	Mean	SD	Mean	SD			
Demographic indexes							
Age (years)	8.46	1.63	8.63	1.37	0.233	NS	
Education (years)	2.75	1.48	2.63	1.28	0.164	NS	
Gender (male)	32	80%	34	85%	0.346	NS	
Handedness (right)	24	60%	21	52.5%	1.608 [a]	NS	
CPRS hyperactivity index	135	0.50	0.18	0.28	60.312	<0.001	2.89
CTRS hyperactivity index	1.38	0.66	0.27	0.38	41.923	<0.001	2.06
CBCL raw score	61.24	25.28	10.93	14.10	52.51	<0.001	2.46
Cognitive measures							
FIQ	99.32	12.1	108.3	11.94	10.89	0.001	0.75
Digit span backwards	3.15	0.98	3.95	1.2	10.74	0.002	0.73
Corsi block task (CBT)	3.7	0.91	4.6	0.81	21.79	<0.001	1.04
SART omission error	14.2	8.01	8.5	6.49	11.97	0.001	0.78
SART commission error	14.07	3.71	13.41	4.31	0.526	NS	0.16
SART Go-RT	405.46	113.56	362.5	82.97	3.67	NS	0.43
Response variability	0.55	0.16	0.53	0.3	0.188	NS	0.08

[a] Fisher's exact test.

affects temporal processing (Barkley, 1997). According to the delay aversion model, the primary deficit in ADHD is a preference for an immediate reward or an aversion to delay (Sonuga-Barke, 2003). The brain areas that are involved in time perception have consistently been implicated in the pathophysiology of ADHD (Castellanos et al., 2002; Durston et al., 2004; Giedd et al., 2001; Kim et al., 2002). Empirical evidence has shown that children with ADHD manifest deficits in time production (Van Meel et al., 2005), time reproduction (Barkley et al., 2001a,b; Kerns et al., 2001; Meaux and Chelonis, 2003; Smith et al., 2002; Sonuga-Barke et al., 1998; Toplak et al., 2003; West et al., 2000), and motor timing tasks (Rubia et al., 2003, 1999).

The impact of motor demands, however, is a critical variable in the study of time perception in ADHD. The organization of motor output is heavily dependent on the representation of time in the brain, and motor difficulties also characterize individuals with ADHD (Carte et al., 1996; Riordan et al., 1999). Time perception and motor coordination share the same underlying neural system, which is the predominantly right hemispheric fronto–striato–cerebellar network (Smith et al., 2003). Unlike time production and reproduction tasks, duration discrimination tasks can minimize the motor demands of timing performance and have no speeded responding. They are based on forced-choice judgments and are used to determine the idiosyncratic threshold at which intervals that differ by several milliseconds (ms) can be perceived as different. Few studies have explored time perception deficit in children with ADHD by using a duration discrimination task, and the results that have been obtained are inconsistent (Smith et al., 2002; Radonovich and Mostofsky, 2004; Rubia et al., 1999; Toplak et al., 2003; Toplak and Tannock, 2005). Some researchers have suggested that the processing of short intervals (less than 1 s) may be more related to an internal timing mechanism or cerebellar process, whereas that of longer intervals (1 s or greater) may be more related to the working memory process (Ivry, 1996; Mangels et al., 1998; Rammsayer, 1999). The attentional-gate model predicts that when intervals exceed the range that is relevant for typical sensory events, greater demands are placed on other cognitive functions such as sustained attention and working memory (Mangels and Ivry, 2001). The duration discrimination task, however, requires a comparison between two successive duration stimuli, and subjects have to maintain the presentation of the duration stimuli in the working memory to make a decision. Data on the variability of interval timing from a review by Gibbon et al. (1997) showed that coefficients of variation for a given task remain roughly constant between 0.1 s and 1.5 s. The aim of the study that is described here was to explore the relationship between neurocognitive functions, such as working memory, attention, inhibition, and time perception, and to extend the findings of time perception impairment in Chinese children with ADHD by using a duration discrimination task with 300, 800, and 1200 ms intervals to represent short, median, and long durations. Based on previous findings, we expected to find an association between working memory and time perception and group differences

Table 2 – Means, standardized deviations of discrimination thresholds, and results of repeated measures of MANOVAs

Duration (ms)	ADHD	Control	Effect sizes Cohen's d	MANOVA F (p-value)			Pairwise comparison	
	Mean±SD	Mean±SD		Group (G)	Duration (D)	G×D	F	p-value
300	58.27±21.17	45.05±19.23	0.65	53.268 (<0.001)	161.16 (<0.001)	7.575 (0.002)	8.552	0.005
800	134.93±40.17	105.94±35.61	0.76				11.663	0.001
1200	193.83±52.43	132.70±52.17	1.17				28.376	<0.001

Table 3 – Relationship between duration of discrimination thresholds and cognitive measures after controlling for FIQ

Groups	Target durations (ms)	Digit span backwards	Corsi blocks task	Omission errors of C-SART	Commission errors of C-SART
ADHD	300	−0.154	−0.053	0.084	0.122
	800	−0.158	−0.327 [a]	0.022	0.143
	1200	−0.16	−0.009	0.073	−0.118
Controls	300	0.179	−0.058	−0.035	−0.136
	800	0.119	−0.159	−0.063	−0.099
	1200	−0.108	0.17	0.052	0.157

[a] p-value<0.05; ms: millisecond.

between ADHD children and healthy controls on the duration discrimination task.

2. Results

2.1. Demographic, clinical, and neurocognitive measure characteristics

As shown in Table 1, there were no significant group differences in age ($F[1,78]=0.233$, $p>0.05$), number of years of education ($F[1,78]=0.164$, $p>0.05$), sex distribution (chi-square=0.346, $p>0.05$), or handedness distribution (Fisher's exact test>0.05). Children with ADHD had lower full-scale IQs (FIQ) than did the healthy controls ($F[1,76]=10.89$, $p=0.001$). The scores on the Connors Parent and Teacher Rating Scales (CRS-R) and the Parent Report Form of Child Behavior Checklist (CBCL) scales for hyperactivity indexes in children with ADHD were significantly higher than those of the healthy controls ($p<0.001$). As for neurocognitive measures, children with ADHD had significantly lower scores on working memory on the backwards digit span test and the Corsi blocks test (CBT) than did the healthy controls ($F[1,78]=10.74$, $p=0.002$; $F[1,78]=21.79$, $p<0.001$, respectively) (Table 1). Furthermore, children with ADHD made more omission errors than did the healthy controls ($F[1,76]=11.97$, $p=0.001$). The two groups, however, did not differ significantly in commission errors or in the reaction time of the go trials (RT-Go) and their standard deviations (SD) in the sustained attention to response test for children (C-SART) with small to moderate effect sizes.

2.2. Time perception

The subsequent analysis used a repeated measures multivariate analysis of variance (MANOVA) on the target durations. Because Mauchly's test of sphericity was always significant for the repeated measures factor of the design, the Huynh–Feldt (HF) values for the F tests that involved the discrimination threshold are reported (Table 2). The results of a repeated measures MANOVA (2 [groups]×3 [discrimination thresholds]), with group as a between-subjects factor and thresholds as a within-subjects factor, show the main effect of duration (HF $F[1.576,122.961]=161.16$, $p<0.001$). This means that across groups, larger intervals were required to discriminate longer durations successfully. There was a significant main effect of group ($F[1,78]=53.268$, $p<0.001$) between the ADHD children and the controls, which indicates that the children with ADHD displayed significantly higher thresholds than did the healthy controls across all of the discrimination thresholds. The group by target duration interaction was significant (HF $F[1.576,122.961]=7.575$, $p=0.002$). Inspection of the discrimination thresholds indicated that children with ADHD needed disproportionately larger intervals to discriminate long durations such as 1200 ms. Pairwise comparison between the two groups at each target duration showed that children with ADHD had higher thresholds than did healthy controls, regardless of the duration (Table 2). The effect sizes were moderate to large, with the largest size obtained at a duration of 1200 ms. After co-varying for FIQ, a repeated measure MANOVA showed that the difference in the main effect of group and the interaction effect of group by target duration remained significant, whereas the main effect of duration disappeared.

2.3. Relationships between neurocognitive measures and discrimination thresholds

Table 3 shows that none of the cognitive measures were significantly related to the duration thresholds in the control group after partialing out FIQ. The score on the CBT (working memory), however, was inversely correlated with the discrimination threshold at a duration of 800 ms in the ADHD group ($r=-0.327$, $p=0.042$). The significant relationship disappeared after Bonferroni correction.

3. Discussion

The major findings of the study are summarized as follows.

1. A repeated measures MANOVA indicated that children with ADHD showed a significantly higher threshold than did the healthy controls at short, median, and long durations. The differences remained significant even after controlling for FIQ.
2. Working memory (CBT) was related to the discrimination threshold at a duration of 800 ms after controlling for FIQ in the ADHD group, but this did not survive the Bonferroni correction.

The short duration of the temporal discrimination tasks meant that the confounding impacts of working memory, sustained attention, delayed aversion, and inhibitory controls (Sonuga-Barke, 2003) may have been reduced to a minimum. For this reason, time discrimination tasks have been considered to be more suitable tests of pure time estimation than are other temporal tasks (Rubia et al., 1999). Using a forced-choice response procedure and removing the requirement for a speeded response in the discrimination task, the influence of motor control or timing is minimized in the study of ADHD (Carte et al., 1996; Riordan et al., 1999). In the current study, impairment in time perception was further confirmed in children with ADHD by using this task with target durations that extended from 300 ms to 1200 ms. Specifically, children with ADHD needed a greater difference between comparison and target durations to discriminate the item reliably. The pairwise comparison analyses confirmed that the differences were significant at short, median, and long durations. The findings are consistent with certain previous studies (Smith et al., 2002; Toplak et al., 2003; Toplak and Tannock, 2005), although negative findings were reported in other studies (Radonovich and Mostofsky, 2004; Rubia et al., 1999). In the current study, the effect size increased with an increase in the target duration, which is consistent with previous studies. The effect size of 0.65 at a duration of 300 ms was close to the 0.61 that was reported by Toplak and Tannock (2005) at a duration of 200 ms and less than the 0.89 that was estimated at a duration of 400 ms by Toplak et al. (2003). At a duration of 800 ms, the effect size of 0.76 was close to the 0.85 that was reported by Smith et al. (2002) and Toplak and Tannock (2005) at a duration of 1000 ms. At a duration of 1200 ms, the effect size was more than that reported by Smith et al. (2002) and Toplak and Tannock (2005) at a duration of 1000 ms. Evidence from neuro-imaging studies has also provided preliminary findings on the dysfunction of duration discrimination in children with ADHD. Duration discrimination tasks involve the cerebellar, prefrontal cortex, and basal ganglia regions (Mathiak et al., 2004; Pouthas et al., 2005; Smith et al., 2003), which have been consistently implicated in the pathophysiology of ADHD (Castellanos et al., 2001, 2002; Durston et al., 2004; Giedd et al., 2001; Kim et al., 2002; Semrud-Clikeman et al., 2000).

Some studies have reported a relationship between working memory and discrimination threshold in children with ADHD (Toplak et al., 2003; Toplak and Tannock, 2005). These results were interpreted as indicative of the need for individuals with ADHD to draw on additional cognitive processes to discriminate durations. Some researchers, however, have suggested that the processing of short intervals (less than 1 s) may be more related to an internal timing mechanism or basal ganglia (Harrington et al., 1998) and cerebellum (Mangels et al., 1998; Ivry, 1996) processes, whereas that of longer intervals (1 s or greater) may be more related to working memory processes or frontal cortical processes (Mangels et al., 1998). No significant relationships between the discrimination threshold and neurocognitive functions were found in the current study, perhaps because the shortness of the task minimized the impact of confounding neuropsychological functions, such as working memory, sustained attention, and inhibitory control. Furthermore, as the duration discrimination task used a forced-choice response procedure without the need for a speeded response, the influence of motor control is minimized in the study of ADHD. Also, differences in the methodology of neurocognitive measures could account for a small part of the variance in the current study.

A one-way analysis of variance (ANOVA) on the number of sustained attention to response test (SART) omission errors revealed the main effect of group ($F[1,78]=11.97$, $p<0.001$), which is similar to the results that were obtained by Bellgrove et al. (2005), O'Connell et al. (2004), and Shallice et al. (2002) and partly consistent with those that were obtained by Johnson et al. (in press). There was no effect of group on commission errors ($F[1,78]=0.526$, $p>0.05$). These results are consistent with those that were obtained by Bellgrove et al. (2005) and Johnson et al. (in press), but inconsistent with those that were obtained by Shallice et al. (2002) and O'Connell et al. (2004). The children with ADHD, however, did not differ from the healthy controls in Go-RT or response variability, despite the approximate median effect size of the Go-RT. This is inconsistent with the findings of Bellgrove et al. (2005), O'Connell et al. (2004), and Shallice et al. (2002). The different results may stem from the difference in the SART methodology and the heterogeneity of the participants. In contrast to the study by Shallice et al. (2002), the participants in the studies by Bellgrove et al. (2005), O'Connell et al. (2004), and Johnson et al. (in press) were given a SART with a fixed sequence that required them to withhold a response to a rare digit (for example, a 3) that occurred in the context of a digit stream (1–9). The proportion of ADHD subtypes and comorbidities in the current study was also different from that in previous studies.

In short, the current study demonstrates the time perception deficit in children with ADHD by using duration discrimination tasks at short durations and excluding the effects of deficient motor control. In accordance with the neuro-imaging results, this study provides further support for a generic time perception deficit, which is probably due to the involvement of a dysfunctional fronto–striato–cerebellar network in this capacity, especially the presence of deficits in basic internal timing mechanisms (Ivry, 1996).

4. Experimental procedures

4.1. *Participants*

The initial sample pool consisted of 15 children with ADHD in the clinical group and 18 healthy children in the comparison group. Additional samples involved 25 children with ADHD and 22 healthy children. The final sample consisted of 40 children with ADHD and a matched healthy control group.

There were 32 boys and 8 girls in the ADHD group (mean age, 8.46 years, SD = 1.63). The mean estimated FIQ was 99.32 (SD = 12.1). Sixty-five percent of the ADHD participants had a diagnosis of ADHD combined type (ADHD-CT), and 35% were of the ADHD inattentive type (ADHD-IT). Twenty percent of the children with ADHD suffered from the comorbidities of a learning disability or oppositional defiant or conduct disorders. The children's parents and teachers completed the ADHD checklist, which consists of the 18 ADHD behaviors that are listed in DSM-IV, the CRS-R (Conners, 1989; Chinese version, Wang et al., 1999), and the CBCL (Achenbach, 1978; Chinese version, Wang et al., 1999), which also covers the DSM-IV symptoms for ADHD. Inclusion in the study required a diagnosis of ADHD that was based on clinical semi-structured parent and child interviews with an expert consultant pediatrician. The ADHD children had to meet the following criteria: (1) there had been parent and/or teacher complaints of inattention, poor impulse control, and over-activity; (2) they had at least 6 of the 18 inattention or hyperactivity-impulsive symptoms on the ADHD checklist or scores by either informant at or above the clinical cutoff on the CRS or the CBCL; (3) they met all of the DSM-IV criteria for ADHD during the semi-structured clinical interview; and (4) they had never received psychoactive medication. All of the ADHD children were recruited from consecutive referrals to three child behavioral clinics that serve large urban populations in Guangdong Province, China. Handedness was assessed by means of the Annett Hand Preference Questionnaire (Annett, 1970).

Another 40 healthy children (34 boys and 6 girls) were recruited from a primary school in Guangdong Province as the healthy controls. Their mean age and estimated FIQ were 8.63 years (SD=1.37) and 108.3 (SD=11.9), respectively (see Table 1). Based on annual screening by the school and reports by parents, the healthy children had no identified problems, and they had no comorbid behavioral disorders as defined by evaluations of other CRS-R scales. None of them had any record of problems from previous screening procedures, and there was no indication of difficulties on any of their school reports. The children were nominated by their teachers and were selected by their similarity to the ADHD group in age (within one year), sex, and handedness. Participants were excluded if they had a history of neurological, psychiatric, pervasive developmental, or any other serious medical condition or an estimated IQ below 75.

4.2. Tests

4.2.1. *Test battery of neurocognitive functions*

IQ was assessed by the short form of the Chinese version of the Wechsler Intelligence Scale for Children-Revised (C-WISC, Gong and Cai, 1993). Items included block design, picture completion, information, and vocabulary. These four subtests were combined because previous studies have demonstrated that they correlate 0.95 with a child's FIQ (Goh, 1980).

Sustained attention and inhibition were tested by a random sequence version of the visual C-SART, which consisted of two parts, one for practice and another for the test. In each part, two boy figures were presented on a computer screen in a random sequence. If there was one boy (go trials), then the children had to press the "space" key. If there was another boy (no-go trials), then they did not need to press any key. The target rate was 90% in the test block, which implied that subjects had to press the "space" key nine times as often as they pressed no key. Recorded dependent measures included omission errors (that is, failures to respond to the go trials), commission errors (that is, failure to withhold in the no-go trials), and mean Go-RT. Response variability was calculated from the SD of the Go-RT and the mean Go-RT (defined as the SD Go-RT/mean Go-RT).

Working memory was assessed by the backwards digit span subtest of the C-WISC (Gong and Cai, 1993) to capture verbal working memory performance and the CBT (Vandierendonck et al., 2004) to capture visual working memory performance. For the CBT, nine identical blocks were positioned irregularly on a wooden board, and an experimenter pointed to a series of blocks at a rate of one block per second. The children were then required to point to the blocks in the same order that they had been presented. The difficulty level was progressively raised by increasing by one the number of squares that were replaced. Participants were presented with two trials at each difficulty level, which ranged from two to nine squares. The dependent variable is defined as the difficulty level for which a child was able to finish at least two trials successfully.

4.2.2. *Time perception*

Time perception was tested by a duration discrimination task that was similar to that in the study by Toplak and Tannock (2005). Participants were presented with three intervals of 50 ms. They were shown a visual image of a 100×100-pixel square at the beginning and end of each interval, which were also separated by a choice response window that appeared until the participant had made a choice response. The target interval refers to the consistently presented stimulus (either 300, 800, or 1200 ms), and the comparison interval refers to the interval that was adapted to a participant's performance. Each target interval was presented in a separate session. For the 300 ms target session, increments of the target duration were adjusted up or down by 10 ms (the first comparison duration was 360 ms), depending on the accuracy of the participant's responses. For the 800 ms target session, the increments changed by 20 ms (the first comparison duration was 950 ms), and for the 1200 ms target session, the increments changed by 30 ms (the first comparison duration was 1400 ms). After presentation of the two intervals, a question – "which interval lasted the longest, the first or the second?" – appeared on the screen together with a cue that indicated which key represented which interval. The subjects then responded accordingly by pressing the left (first) or right (second) key. The target interval was randomly presented as either the first or second duration, and the comparison interval was always longer than the target interval.

An up–down transformed-response adaptive procedure was used to estimate the threshold at which a participant could accurately discriminate the target duration from the comparison duration with 80% accuracy. Each time that an error in judgment was made, the comparison duration was increased, thus increasing the difference between the two durations that were to be compared. Conversely, when a correct response was given, the comparison duration was decreased, thus reducing the difference between the two durations that were to be compared. The procedure stopped after six reversals of direction. The last five reversal values were averaged to produce an estimate of threshold duration discrimination. The primary dependent measure for the discrimination tasks was the participant's duration threshold minus the target interval. The threshold was defined as the difference between the target duration and the shortest comparison duration that participants could reliably discriminate with 80% accuracy.

All of the tasks were presented in similar two-alternative forced-choice trials using a mouse for response input. There were four practice trials for each task to help participants to understand the task demands. The practice trials used 1000 ms as the target duration and 500 ms as the comparison duration. Longer comparison durations were used during the practice trials to help ease the participants into the task. They were told that they would see two pairs of squares, that each set would be separated by a short gap, and that one gap would be longer than the other. Furthermore, they were told that their task was to decide which of the two gaps were the longest and to press the corresponding button. No feedback about errors was provided during the task. Participants used their dominant hand to respond.

4.3. *Procedure*

Written consent was provided by the guardians of both the children with ADHD and the healthy controls. Each child received a battery of cognitive tests, including the duration discrimination task, in a standardized order to minimize boredom. Each child was seated comfortably in front of a laptop computer in a quiet room, and the control children were tested at their school.

4.4. *Data analysis*

The results were analyzed using SPSS version 12. Demographic characteristics and neurocognitive function variable differences between the two groups were tested using ANOVA, with group membership as the independent variable. Effect sizes on the post hoc analyses were calculated using Cohen's *d*. Chi-square analyses were used for comparisons on dichotomous variables. To examine all of our variables of interest on the duration discrimination task, including group and duration, we conducted a repeated MANOVA, with group as a between-subject factor and duration as a within-subject factor. Following the MANOVA, correlational analyses were conducted to examine whether any of the other neurocognitive measures were significantly correlated with the duration discrimination thresholds.

Acknowledgments

The authors would like to thank Dr. Tom Manly for providing the children version of the Sustained Attention to Response Task to be used in this study. This study was supported partially by the 100-Scholar Fund of the Sun Yat-Sen University to Raymond Chan.

REFERENCES

Achenbach, T.M., 1978. The child behavior profile, I. Boys aged 6–11. J. Consult. Clin. Psychol. 46, 478–488.
Annett, M., 1970. A classification of hand preference by association analysis. Br. J. Psychol. 61, 303–321.
Barkley, R.A., 1997. Behavioral inhibition, sustained attention, and executive functions, constructing a unifying theory of ADHD. Psychol. Bull. 121, 65–94.
Barkley, R.A., Edwards, G., Laneri, M., Fletcher, K., Metevia, L., 2001a. Executive functioning, temporal discounting, and sense of time in adolescents with attention deficit hyperactivity disorder (ADHD) and oppositional defiant disorder (ODD). J. Abnorm. Child Psychol. 26, 541–556.
Barkley, R.A., Murphy, K.R., Bush, T., 2001b. Time perception and reproduction in young adults with attention deficit hyperactivity disorder. Neuropsychology 15, 351–360.
Bellgrove, M.A., Hawi, Z., Kirley, A., Gill, M., Robertson, I.H., 2005. Dissecting the attention deficit hyperactivity disorder (ADHD) phenotype: sustained attention, response variability and spatial attentional asymmetries in relation to dopamine transporter (DAT1) genotype. Neuropsychologia 43, 1847–1857.
Carte, E.T., Nigg, J.T., Hinshaw, S.P., 1996. Neuropsychological functioning, motor speed and language processing in boys with and without ADHD. J. Abnorm. Child Psychol. 24, 481–498.
Castellanos, F.X., Giedd, J.N., Berquin, P.C., Walter, J.M., Sharp, W., Tran, T., Vaituzis, A.C., Blumenthal, J.D., Nelson, J.M., Bastain, T.M., Zijdenbos, A., Evans, A.C., Rapoport, J., 2001. Quantitative brain magnetic resonance imaging in girls with attention-deficit/hyperactivity disorder. Arch. Gen. Psychiatry 58, 289–295.
Castellanos, F.X., Lee, P.P., Sharp, W., Jeffries, N.O., Greenstein, D.K., Clasen, L., Blumenthal, J.D., James, R.S., Ebens, C.L., Walter, J.M., Zijdenbos, A., Evans, A.C., Giedd, J.N., Rapoport, J.L., 2002. Developmental trajectories of brain volume abnormalities in children and adolescents with attention deficit/hyperactivity disorder. JAMA 288, 1740–1748.
Conners, C.K., 1989. Conners' Rating Scales Manual. Multi-Health Systems, North Tonawanda, NY.
Durston, S., Hulshoff, P.H., Schnack, H.G., Buitelaar, J.K., Steenhuis, M.P., Minderaa, R.B., Kahn, R.S., van engeland, H., 2004. Magnetic resonance imaging of boys with attention deficit/ hyperactivity disorder and their unaffected siblings. J. Am. Acad. Child Adolesc. Psych. 43, 332–340.
Gibbon, J., Malapani, C.L., Dale, C.L., Gallistel, C.R., 1997. Toward a neurobiology of temporal cognition, advances and challenges. Curr. Opin. Neurobiol. 7, 170–184.
Giedd, J.N., Blumenthal, J., Molloy, E., Castellanos, F.X., 2001. Brain imaging of attention deficit/hyperactivity disorder. Ann. N. Y. Acad. Sci. 931, 33–49.
Goh, D.S., 1980. Note on selection of WISC-R short forms for different uses. J. Clin. Psychol. 36, 319–321.
Gong, Y.X., Cai, T.S., 1993. Chinese Version of the Wechsler Intelligence Scale for Children (C-WISC III). Hunan map press, Changsha.
Harrington, D.L., Haaland, K.Y., Hermanowicz, N., 1998. Temporal processing in the basal ganglia. Neuropsychology 12, 1–10.
Ivry, R.B., 1996. The representation of temporal information in perception and motor control. Curr. Opin. Neurobiol. 6, 851–857.
Johnson, K.A., Kelly, S.P., Bellgrove, M.A., Barry, E., Cox, M., Gill, M., Robertson, I.H., in press. Response variability in attention deficit hyperactivity disorder: evidence for neuropsychological heterogeneity. Neuropsychologia.
Kerns, K.A., McInerney, R.J., Wilde, N., 2001. Time reproduction, working memory, and behavioral inhibition in children with ADHD. Child Neuropsychol. 7, 21–31.
Kim, B.N., Lee, J.S., Shin, M.S., Cho, S.C., Lee, D.S., 2002. Regional cerebral perfusion abnormalities in attention deficit/hyperactivity disorder. Statistical parametric mapping analysis. Eur. Arch. Psychiatry Clin. Neurosci. 252, 219–225.
Mangels, J.A., Ivry, R.B., 2001. Time perception. In: Rapp, B. (Ed.), The Handbook of Cognitive Neuropsychology: What Deficits Reveal About the Human Mind. Psychology Press, PA, USA.
Mangels, J.A., Ivry, R.B., Shimizu, N., 1998. Dissociable contributions of the prefrontal and neocerebellar cortex to time perception. Cogn. Brain Res. 7, 15–39.
Mathiak, K., Hertrich, I., Grodd, W., Ackermann, H., 2004. Discrimination of temporal information at the cerebellum, functional magnetic resonance imaging of nonverbal auditory memory. Neuroimage 21, 154–162.
Meaux, J.B., Chelonis, J.J., 2003. Time perception differences in children with and without ADHD. J. Pediatr. Health Care 17, 64–71.
O'Connell, R.G., Bellgrove, M.A., Dockree1, P.M., Robertson1, I.H., 2004. Reduced electrodermal response to errors predicts poor sustained attention performance in attention deficit hyperactivity disorder. NeuroReport 15, 2535–2538.
Pouthas, V., George, N., Poline, J.B., Pfeuty, M., Vande Moorteele, P.F., Hugueville, L., Ferrandez, A.M., Lehericy, S., Lebihan, D., Renault, B., 2005. Neural network involved in time perception: an fMRI

study comparing long and short interval estimation. Hum. Brain Mapp. 25, 433–441.
Radonovich, K.J., Mostofsky, S.H., 2004. Duration judgments in children with ADHD suggest deficient utilization of temporal information rather than general impairment in timing. Child Neuropsychol. 10, 162–172.
Rammsayer, T.H., 1999. Neuropharmacological evidence for different timing mechanisms in humans. Q. J. Exp. Psychol., B 52B, 273–286.
Riordan, H.J., Flashman, L.A., Saykin, A.J., Frutiger, S.A., Carroll, K.E., Huey, L., 1999. Neuropsychological correlates of methylphenidate treatment in adult ADHD with and without depression. Arch. Clin. Neuropsychol. 14, 217–233.
Rubia, K., Taylor, A., Taylor, E., Sergeant, J.A., 1999. Synchronization, anticipation, and consistency of motor timing in dimensionally defined children with attention deficit hyperactivity disorder. Percept. Mot. Skills 89, 1237–1258.
Rubia, K., Noorloos, J., Smith, A., Gunning, B., Sergeant, J., 2003. Motor timing deficits in community and clinical boys with hyperactive behavior: the effect of methylphenidate on motor timing. J. Abnorm. Child Psychol. 31, 301–313.
Semrud-Clikeman, M., Steingard, R.J., Filipek, P., Biederman, J., Bekken, K., Renshaw, P.F., 2000. Using MRI to examine brain–behavior relationships in males with attention deficit disorder with hyperactivity. J. Am. Acad. Child Adolesc. Psych. 39, 477–484.
Shallice, T., Marzocchi, G.M., Coser, S., Del Savio, M., Meuter, R.F., Rumiati, R.I., 2002. Executive function profile of children with attention deficit hyperactivity disorder. Dev. Neuropsychol. 21, 43–71.
Smith, A., Taylor, E., Rogers, J.W., Newman, S., Rubia, K., 2002. Evidence for a pure time perception deficit in children with ADHD. J. Child Psychol. Psychiatry 43, 529–542.
Smith, A., Taylor, E., Lidzba, K., Rubia, K., 2003. A right hemispheric fronto-cerebellar network for time discrimination of several hundreds of milliseconds. Neuroimage 20, 344–350.
Sonuga-Barke, E.J.S., 2003. The dual pathway model of AD/HD, an elaboration of neuro-developmental characteristics. Neurosci. Biobehav. Rev. 27, 593–604.
Sonuga-Barke, E.J.S., Saxton, T., Hall, M., 1998. The role of interval underestimation in hyperactive children's failure to suppress responses over time. Behav. Brain Res. 94, 45–50.
Toplak, M.E., Tannock, R., 2005. Time perception, modality and duration effects in attention-deficit/hyperactivity disorder (ADHD). J. Abnorm. Child Psychol. 33, 639–654.
Toplak, M.E., Rucklidge, J.J., Hetherington, R., John, S.C.F., Tannock, R., 2003. Time perception deficits in attention-deficit/hyperactivity disorder and comorbid reading difficulties in child and adolescent samples. J. Child Psychol. Psychiatry 44, 888–903.
Van Meel, C.S., Oosterlaan, J., Heslenfeld, D.J., Sergeant, J.A., 2005. Motivational effects on motor timing in attention-deficit/hyperactivity disorder. J. Am. Acad. Child Adolesc. Psych. 44, 451–460.
Vandierendonck, A., Kemps, E., Fastame, M.C., 2004. Working memory components of the Corsi blocks task. Br. J. Psychol. 95, 57–79.
Wang, X.D., Wang, X.L., Ma, H., 1999. Manual of Mental Health Rating Scales (Supplementary). Periodical publishing house of Chinese Mental Health, Beijing.
West, J., Douglas, G., Houghton, S., Lawrence, V., Whiting, K., Glasgow, K., 2000. Time perception in boys with attention/hyperactivity disorder according to time duration, distraction and mode of presentation. Child Neuropsychol. 6, 241–250.