THE JOURNAL OF
CHILD PSYCHOLOGY AND PSYCHIATRY

Journal of Child Psychology and Psychiatry 51:3 (2010), pp 223–232 doi:10.1111/j.1469-7610.2009.02163.x

Deficits in interval timing measured by the dual-task paradigm among children and adolescents with attention-deficit/hyperactivity disorder

Shoou-Lian Hwang,[1,2] Susan Shur-Fen Gau,[3,4] Wen-Yau Hsu,[1,5] and Yu-Yu Wu[6]

[1]Department of Psychology, National Chengchi University, Taipei, Taiwan; [2]Department of Applied Psychology, Hsuan Chuang University, Hsinchu, Taiwan; [3]Department of Psychiatry, National Taiwan University Hospital, Taipei, Taiwan; [4]Department of Psychiatry, College of Medicine, National Taiwan University, Taipei, Taiwan; [5]Research Center for Mind, Brain and Learning, National Chengchi University, Taipei, Taiwan; [6]Department of Child & Adolescent Psychiatry, Chang Gung Memorial Hospital and Chang Gung University College of Medicine, Tao-Yuan, Taiwan

Background: The underlying mechanism of time perception deficit in long time intervals in attention-deficit/hyperactivity disorder (ADHD) is still unclear. This study used the time reproduction dual task to explore the role of the attentional resource in time perception deficits among children and adolescents with ADHD. **Methods:** Participants included 168 children and adolescents with DSM-IV ADHD and 90 control children and adolescents without ADHD, aged 10 to 17 years, in Taipei. The DSM-IV diagnoses of ADHD and other psychiatric comorbid conditions were made by clinical assessments and confirmed by the psychiatric interviews of both parents and participants using the Chinese Kiddie Epidemiologic version of the Schedule for Affective Disorders and Schizophrenia. The participants were also assessed by using the Wechsler Intelligence Scale for Children-3rd edition (WISC-III), and time reproduction tasks (the single task and the simple and difficult versions of the dual tasks) at 5-second, 12-second, and 17-second intervals. The linear mixed model was used for data analysis. **Results:** Children and adolescents with ADHD had less precise time reproduction than the controls in all three tasks except the 5-second interval of the single task. There were significant interactions between group and interval (12-second vs. 5-second, $p = .030$; 17-second vs. 5-second, $p < .001$), and between group and task (simple dual task vs. single task, $p = .016$; difficult dual task vs. single task, $p < .001$) after controlling for FSIQ, comorbidity, sex, age, use of methylphenidate, and the performance of the non-temporal tasks in dual tasks, if relevant. **Conclusions:** Significantly increased estimation errors in ADHD with increased task difficulties suggest that impaired timing processing in children and adolescents with ADHD during long time intervals may be accounted for by the limited attentional capacity rather than a primary problem in timing per se. This finding does not apply to rapid time intervals, in which cerebellar circuitry is important. **Keywords:** Attention-deficit/hyperactivity disorder, time reproduction, dual task, attentional resource.

In addition to the three core symptoms of attention-deficit/hyperactivity disorder (ADHD), numerous studies have demonstrated deficits in neuropsychological functions such as attention, executive functions, state regulation, and motivation in individuals with ADHD (Nigg, 2005; Seidman, 2006); among them, time perception has been relatively less studied (Nigg, 2005). Although timing functions are integrally related to executive functions (Barkley, 1997), we do not know whether time perception deficits in individuals with ADHD reflect a deficit secondary to the impaired executive function (Barkley, Koplowitz, Anderson, & McMurray, 1997; Kerns, McInerney, & Wilde, 2001) or other neuropsychological processes such as motivation (Sonuga-Barke, Saxton, & Hall, 1998) or motivation and attentional capacity (Sergeant, 2005).

Conflict of interest statement: No conflicts declared.

Current theory and empirical work on ADHD suggest a relationship between ADHD and deficits in temporal information processing in a range from milliseconds to seconds (Barkley, 1997; Toplak, Dockstader, & Tannock, 2006), as shown by the poor performance in a variety of time perception tasks in a prospective paradigm in ADHD (Barkley et al., 1997; Bauermeister et al., 2005; Kerns et al., 2001; McInerney & Kerns, 2003; Smith, Taylor, Rogers, Newman, & Rubia, 2002; Sonuga-Barke et al., 1998; Toplak & Tannock, 2005). Estimating time intervals in a range from seconds to minutes is an important adaptive skill for making predictions about one's environment (Meck, 2005), such as crossing streets (Zakay & Block, 1997), and making decisions (Wittmann & Paulus, 2008). Several studies consider that frontal-striatal circuits are involved in interval timing in this time range (Meck, 2005; Toplak et al., 2006). In contrast, cerebellar circuitry plays an important role in fine temporal

Published by Blackwell Publishing, 9600 Garsington Road, Oxford OX4 2DQ, UK and 350 Main Street, Malden, MA 02148, USA

information processing (e.g., discrimination on milliseconds) (Meck, 2005).

For individuals with ADHD, deficits in interval timing might underlie several problems, such as having difficulty waiting (Barkley, 1997), and delaying responses (Sonuga-Barke, Taylor, Sembi, & Smith, 1992). The consistent findings are that individuals with ADHD demonstrate deficits in interval timing by displaying more discrepant reproduction errors in time reproduction tasks (Barkley et al., 1997; Bauermeister et al., 2005; Kerns et al., 2001; McInerney & Kerns, 2003). Time reproduction has been recognized as a more suitable approach than time production and verbal estimation as a means to assess one's subjective time sense (Zakay, 1990). Current theoretical models of ADHD, however, provide different accounts of time perception deficits in interval timing (Toplak et al., 2006).

One widely cited model proposed by Barkley (1997) has argued that impaired behavioral inhibition affects working memory, which consequently affects interval timing (Barkley, 1997; McInerney & Kerns, 2003). This model has been supported by several studies (Bauermeister et al., 2005; Kerns et al., 2001; McInerney & Kerns, 2003; Mullins, Bellgrove, Gill, & Robertson, 2005). For example, time reproduction performance has been reported to be associated with nonverbal working memory by the Simon Task (Bauermeister et al., 2005); attention by the Continuous Performance Test (Kerns et al., 2001; Mullins et al., 2005); interference controls by the Stroop Color and Word test (Bauermeister et al., 2005). However, Kerns et al. (2001) did not find any association between a Stroop interference task or a visual spatial working memory task and a reproduction task. These executive tasks may reflect a wide variety of processes (Sergeant, Geurts, & Oosterlaan, 2002), and may tap into different modalities (verbal or visual-spatial) and mechanisms (maintenance or manipulation) (Kerns et al., 2001). However, the above-mentioned studies have been limited by a lack of discriminative ability to identify specific executive functioning processes involving estimation of interval timing.

Sonuga-Barke et al. (1998) used the delay aversion model to explain the greater magnitude of time underestimation in ADHD in the un-signaled condition than in the signaled condition (Sonuga-Barke, 2005), and suggested that a delay aversion may contribute more to time reproduction deficits in ADHD than response disinhibition. Smith et al. (2002) reported that children with ADHD significantly underestimated time by prematurely responding in a 12-second rather than a 5-second time reproduction task, suggesting that children with ADHD are more sensitive to the length of time intervals.

However, there are still some inadequate explanations in Barkley's model (1997) and the delay aversion model (Sonuga-Barke et al., 1998). First, it is difficult to identify which specific executive function influences temporal information processing (Kerns et al., 2001; McInerney & Kerns, 2003; Mullins et al., 2005). Moreover, some studies have demonstrated that although children with ADHD perform better on time reproduction tasks in a reward situation than in a non-reward situation, they still perform worse than children without ADHD (McInerney & Kerns, 2003; Van Meel, Oosterlaan, Heslenfeld, and Sergeant, 2005).

With the evidence of attentional resource involvement in interval timing (Barrouillet, Bernardin, Portrat, Vergauwe, & Camos, 2007; Hemmes, Brown, & Kladopoulos, 2004), the current study aimed to test the theoretical model of the influence of the attentional resource in interval timing (Brown, 1997; Brown, 2006; Fuggetta, 2006; Karatekin, 2004). The cognitive-energetic model (Sergeant, Geurts, Huijbregts, Scheres, & Oosterlaan, 2003; Sergeant, Oosterlaan, & Meere, 1999; Sergeant, 2005), one of influential theoretical models of ADHD, suggests that temporal processing should also consider resources allocation as related to the energetic pools, like the effort pool affected by cognitive load or task demanding. This study used the dual-task paradigm with both simple and difficult versions to elucidate the association between attentional resources and time reproduction in children and adolescents with ADHD.

Attentional resources are at all times divided among all tasks, including time perception tasks (Hicks, Miller, & Kinsbourne, 1976; Zakay, 1989). The estimated duration is a direct function of the amount of attention allocated to the passage of time (Hicks et al., 1976). When subjects perform a temporal and a non-temporal task simultaneously, the processing of these different kinds of information may compete for the limited pool of attentional resources. The attentional-gate resource models (Zakay & Block, 1997) predicts that the more the attentional resources are allocated to the non-temporal task, the fewer the resources are available for temporal processing, and the shorter and more variable are the durations that are estimated (Brown, 1997). These predictions have been validated in many studies using a dual-task paradigm in subjects with attention or memory deficits, like those involved in the aging process (Baudouin, Vanneste, Pouthas, & Isingrini, 2006; Pouthas & Perbal, 2004), Parkinson's disease (Perbal et al., 2005) and traumatic brain injury (Pouthas & Perbal, 2004), rather than ADHD.

Some studies have shown that children with ADHD performed poorly in the dual-task paradigm (Fuggetta, 2006; Karatekin, 2004). Moreover, the increasing proportionally interfering effect in the dual task is supposed to be associated with ADHD (Fuggetta, 2006). These studies lend evidence supporting the decreased capacity of children with ADHD to divide their attention in dual tasks. If children with ADHD had the same problems with limited attentional resources, they would show similar patterns in the time perception dual-task paradigm. Therefore, we can directly manipulate attentional resources by using different levels of demand on attention in non-temporal tasks (McClain, 1983) to explore the role of attentional resources in interval timing in ADHD.

To the best of our knowledge, the present study is the first to investigate attentional resources in time perception performance in ADHD by using time reproduction dual tasks. If time perception deficits in ADHD are related to limited attentional resources, the estimation errors would disproportionately increase in dual tasks. On the other hand, if attentional resources are not related to time perception deficits in ADHD, our analysis would reveal the effects from the group (ADHD vs. controls) and time intervals rather than tasks with different difficulties or interactions between group and tasks. The present study aimed to answer the following research questions: (1) whether children and adolescents with ADHD would be less precise in time reproduction than those without ADHD; and (2) whether the group difference increased with increased time intervals, complexity of tasks (single and dual tasks), and difficulties of dual tasks (simple and difficult).

Methods

Study participants

The clinical sample consisted of 168 patients (male, 86.9%), aged 10–17, who were clinically diagnosed with DSM-IV ADHD at the mean age of 10.0 (SD = 2.7). ADHD and other psychiatric disorders were confirmed by psychiatric interviews using the Chinese version of the Kiddie epidemiologic version of the Schedule for Affective Disorders and Schizophrenia (K-SADS-E) (Gau, Chong, Chen, & Cheng, 2005), at the mean age of 12.8 (SD = 1.5). The patients were recruited consecutively from National Taiwan University Hospital. Those patients with psychosis, autism spectrum disorders, a learning disability, or a Full-Scale IQ (FSIQ) score less than 80 were excluded.

The school comparison participants (school controls), who were assessed to have no lifetime DSM-IV ADHD using the Chinese K-SADS-E, were recruited from the same school district as the patients with ADHD: 90 school controls (male, 81.1%), with a mean age of 13.2 (SD = 1.8). The distribution of current ADHD subtypes were 123 (73.2%) for combined types, 41 (24.4%) for inattentive types, and 4 (2.4%) hyperactive-impulsive types.

Measures

Chinese version of the Kiddie epidemiologic version of the Schedule for Affective Disorders and Schizophrenia (K-SADS-E). The K-SADS-E is a semi-structured interview scale for the systematic assessment of both past and current episodes of mental disorders in children and adolescents. Development of the Chinese K-SADS-E was completed by the Child Psychiatry Research Group in Taiwan (Gau & Soong, 1999). This included a two-stage translation and modification of several items with psycholinguistic equivalents relevant to the Taiwanese culture and further modification to meet the DSM-IV diagnostic criteria (Gau et al., 2005). The Chinese K-SADS-E has been widely used to assess DSM-IV psychiatric disorders in clinical (e.g., Gau & Soong, 1999) and epidemiological studies in Taiwan (e.g., Gau et al., 2005, 2007).

Time reproduction tasks. The time reproduction tasks were computerized and controlled by the Visual Basic 6.0 Software Package on an IBM laptop (ThinkPad R51). The joystick made for PS2 was used as the input instrument.

Time reproduction task – single version. We designed a computerized time reproduction paradigm based on Kerns et al.'s study (2001). After the participants heard a bee sound (1000 hz), lasting 100 milliseconds (ms), they were shown a green circle, with a diameter of 1.8 cm in the center of a blank screen, that remained visible for 5, 12 and 17 seconds, respectively. Immediately following this presentation the screen went blank and participants were instructed to 'press the joystick key and let the circle appear and last again, and raise the key when you think the same duration of time has elapsed.' Participants had several practice trials of the task to ensure they understood the instructions. Following the practice session, two trials, each with three intervals (5, 12, 17 seconds), were presented in a randomized order for a total of 6 trials.

Time reproduction task – dual tasks: simple and difficult versions. In the dual task, the temporal task was identical to the single version as described above. The concurrent non-temporal task was designed to ask participants to count the number of Arabic numerals 1 to 9, 1.5 cm in size, and 1.8 cm under the green circle, with each numeral lasting 200 ms. The inter-stimulus interval (ISI) of the Arabic numerals was randomly distributed, ranging from 1100 ms to 1800 ms in each trial. That is, the number of appearances of digits in each trial might not be the same, even at the same time intervals. The circle and the numeral stimuli on the screen appeared and disappeared simultaneously. The participants were asked to count all the numerals shown on the screen in the non-temporal task of the simple version, and to count only the odd numerals in the difficult version.

For the temporal tasks, the participants were asked 'Please do your best to do the two tasks simultaneously.' Immediately following this presentation, the screen went blank, and the participants were asked 'Please input the numbers of the target digit and press the key on the joystick continuously (this shows the green circle) until you think it lasts for the same time interval, then, raise the key.' The time intervals were 5, 12, and 17 seconds for each of the two trials. The circles were presented in a randomized order for a total of 6 trials. Each participant was given a full explanation of the task procedures and an opportunity to practice performing these tasks in a standardized way. The longer the time interval, the more digits the subjects needed to count in the non-temporal task.

Scoring. The raw scores of the temporal tasks were converted into the *absolute discrepancy score*, which was defined as the absolute value of the magnitude of the discrepancy between the participant's time reproduction and the actual time interval presented to the participants. This provided a measure of the magnitude of the errors (inaccuracy in time reproduction) made by the participants, regardless of the direction of the error (Barkley et al., 1997). The mean absolute discrepancy score of two trials was taken for the performance in each time reproduction interval. The accuracy of the non-temporal task was defined as the ratio of the number of the conditions in which the subjects had a perfect answer for the digits shown on the screen to the total number of the conditions.

Interviewer training. Three well-trained interviewers (H.Y. Luo, W.L. Tseng, and C.M. Lee), who majored in psychiatric nursing and psychology, had undergone one year of full-time intensive clinical and research training in child and adolescent psychiatry before receiving the Chinese K-SADS-E interview training. They reached over 90% agreement on all mental disorders assessed by the K-SADS-E against the rating of each item in the K-SADS-E by S.S. Gau for 30 clinical subjects before implementation of this study. The details of the interview training and best estimate of psychiatric diagnosis have been described elsewhere (Gau & Chiang, in 2009).

Best estimate of diagnosis. The best estimate of each diagnostic category was made by S.S. Gau, who was blind to the diagnostic status and name of the participant, and who was not involved in direct K-SADS-E interviews of any of the participants or their parents at follow-up. The diagnosis was made based on the K-SADS-E interviews of the participants and their mothers, medical records, and teachers' reports. The diagnostic coding was categorized into definite (reaching full DSM-IV diagnostic criteria), probable (either not reaching full, but more than half of the DSM-IV symptoms criteria, or no functional impairment), possible (some symptoms but no impairment), and no diagnosis.

Procedures

The Research Ethics Committee of National Taiwan University Hospital approved this study prior to its implementation. Written informed consent was obtained from both the participants and their parents. All the participants were administered the full assessment of the Wechsler Intelligence Scale for Children – 3rd edition (WISC-III) to exclude those whose FSIQ was lower than 80. All the adolescent participants and their mothers were interviewed independently by individual well-trained interviewers who made the child's DSM-IV psychiatric diagnoses at baseline and currently (past 6 months) using the Chinese K-SADS-E (Gau et al., 2007). Information regarding medication history was obtained by interviewing the participants and their parents, and was confirmed by medical records of prescription. In order to minimize the influence of methylphenidate and other medications, children with ADHD were asked to halt medications for at least 24 hours before the tests.

Each participant received the same sequence of time reproduction tasks in the same laboratory by the same assessor (S.L. Hwang), in a fixed time schedule. The participants performed the time reproduction single version first, followed by the simple version and the difficult version of dual tasks. We employed a counterbalance design, in which if the last digit of the participant's ID was an odd number, he/she received the simple version of the dual task as the second task followed by the difficult version of the dual task; if an even number, he/she performed the dual tasks in a reverse sequence.

We checked the raw data immediately after the tasks were completed by each participant to ensure that they followed the rules correctly and used the joystick appropriately, to decide whether they needed to repeat the task within one week. We asked two participants with ADHD who counted the odd numbers rather than the whole numbers in the simple dual-task version, and 10 participants who did not use the joystick appropriately, to repeat the tasks within one week and then deleted their original data. We also deleted two observations that were numerically distant from the rest of the data (deviating from the mean by more than 3 standard deviations) before conducting data analysis.

Data analyses

The statistical analysis was conducted by using SAS 9.1 (SAS Institute Inc., Cary, NC). The pre-selected alpha value was $p < .05$. Major comparisons were made between (1) participants with ADHD and school controls, (2) different versions of tasks, and (3) different time intervals. The descriptive results of comparing demographics between the two groups were demonstrated in frequency, percentage, and chi-square statistics for categorical variables; and mean, SD, and one-way analyses of variance for continuous variables.

The raw scores of time reproduction in the single and two dual tasks were converted to absolute discrepancy scores as the dependent variables (Barkley et al., 1997). Cohen's d was used to compute the effect size (standardized difference between the two means) for the two group comparisons (Cohen, 1988).

A linear mixed model with fixed and random effects was used to address the repeated measures for the same subjects. The comparison group (ADHD vs. school controls) was treated as a fixed factor, and 3 time interval lengths and 3 different tasks, accuracy of non-temporal tasks as repeated measures, and participants' gender, age, FSIQ, use of methylphenidate, parental educational levels, and presence of psychiatric comorbidity were treated as covariates. The 3-way and 2-way interaction terms were included in the final model selection.

Results

Sample description

There were no significant group differences in age, sex and parental employment status except that there were higher parental educational levels and lower IQ scores for children and adolescents with ADHD (Table 1). One hundred and forty seven (87.5%) children and adolescents with ADHD had been treated, and 76 (45.2%) were still being treated, with methylphenidate (the only medication available for treating ADHD in Taiwan during the study period), with a mean treatment duration of 19.1 months (SD = 18.1).

One hundred and eighteen (71.1%) children and adolescents with ADHD and 23 (25.6%) school controls had at least one DSM-IV psychiatric disorder. Children and adolescents with ADHD were more likely to have oppositional defiant disorder, conduct disorder, and depressive disorder than the school controls (Table 2).

Time reproduction single tasks

Children and adolescents with ADHD had significantly higher absolute discrepancy scores than the controls at the 12- and 17-second intervals, with a small effect size, but there was no difference at the 5-second interval (Table 3). Multiple regression analyses revealed a significant main effect for group (ADHD vs. controls, $F_{1,462} = 4.48$, $p = .034$) and time interval length ($F_{2,462} = 57.69$, $p < .001$), showing decreased precision with increased interval length (Figure 1). Moreover, there was a significant group × interval interaction ($F_{2,462} = 3.56$, $p = .029$), suggesting a greater difference between the children and adolescents with ADHD and controls with increased interval length (Figure 1a).

Time reproduction dual tasks

The accuracy rates in the non-temporal tasks were included as covariates in the statistical models comparing the absolute discrepancy scores of the dual tasks between the children and adolescents with ADHD and controls (Table 3, Figure 1b, c). Participants with ADHD had less precision in the simple and difficult versions of time reproduction dual tasks than the controls for all three time intervals, with small to medium effect sizes (Table 3). Multiple regression analyses of the simple version showed a significant main effect for the interval length ($F_{2,408} = 206.38$, $p < .001$) and a significant group × interval interaction ($F_{2,408} = 4.69$, $p = .009$), suggesting that the magnitude of the poorer performance in the ADHD group significantly increased with the interval length (Figure 1b).

Multiple regression analyses of the difficult version showed a significant main effect for interval length ($F_{2,408} = 234.52$, $p < .001$), and a significant group × interval interaction ($F_{2,408} = 5.68$, $p = .003$), suggesting that less precise time reproduction in children and adolescents with ADHD was more obvious as the interval length increased (Figure 1c).

Performance on the non-temporal tasks

There was no significant difference in the accuracy of the non-temporal tasks between children and adolescents with ADHD and the controls across different tasks with three time intervals (Table 4). Further analysis using a linear mixed model to address the repeated measures within the same subjects revealed that there were significant effects from three time intervals ($F_{2,1022} = 120.65$, $p < .001$) and different tasks ($F_{1,1022} = 122.66$, $p < .001$), but there were no significant effects from group ($F_{1,1022} = 1.07$, $p = .300$), the interaction between group and task difficulties ($F_{1,1022} = 1.26$, $p = .262$), or the interactions effect between group and time intervals ($F_{2,1022} = 0.47$, $p = .626$). The accuracy in non-temporal tasks was not correlated with the absolute discrepancy score under each same condition (Pearson's correlations = .06–.07). Our results did not show a trade-off effect from non-temporal tasks.

Table 1 Sample characteristics

	ADHD (N = 168) Mean (SD) or %	Control (N = 90) Mean (SD) or %	F-value or χ^2
Age	12.8 (1.5)	13.2 (1.8)	3.13
Gender, male	86.9%	81.1%	1.53
Intelligence Quotient			
Full IQ	102.7 (11.3)	112.3 (8.4)	49.3**
Verbal IQ	101.8 (11.1)	112.1 (8.4)	58.1**
Performance IQ	104.0 (13.7)	111.1 (11.4)	17.25**
Father's educational level			
College and above	60.8%	88.6%	16.57**
Senior high school	30.0%	9.8%	
Junior high school and below	9.2%	1.6%	
Mother's education level			
College and above	51.8%	79.7%	15.42**
Senior high school	39.0%	16.4%	
Junior high school and below	9.2%	3.9%	

Note: SD = standard deviation. * $p < .05$. ** $p < .01$.

Table 2 Psychiatric disorders of children and adolescents with ADHD and unaffected controls

	ADHD (N = 168)		Control (N = 90)				
Psychiatric disorders	N	(%)	N	(%)	Odds Ratio	(95% C.I.)	p-value
Oppositional defiant disorder	86	(52.1)	4	(4.4)	23.41	(8.21–66.75)	<.001
Conduct disorder	30	(18.2)	0	(0)			<.001*
Tic disorder	12	(7.2)	1	(1.1)	6.93	(.89–54.21)	.065
Mood disorders	16	(12.9)	2	(2.2)	6.32	(.80–49.73)	.080
Depressive disorder	15	(10.0)	1	(1.1)	8.84	(1.15–68.07)	.036
Bipolar disorder	1	(.6)	1	(1.1)	0.54	(.03–8.73)	.664
Anxiety disorders	41	(24.7)	18	(20.0)	1.31	(.70–2.45)	.395
Any comorbid psychiatric disorder	118	(71.1)	23	(25.6)	7.16	(4.01–12.80)	<.001

Note: * Fisher's exact p-value.

Table 3 Comparisons of the absolute discrepancy scores in different time reproduction tasks between children and adolescents with ADHD and the controls

	ADHD (n = 168) Mean (SD)	Control (n = 90) Mean (SD)	Statistic	
			F-value	Cohen's d
Single task				
5 sec	.78 (.73)	.73 (.40)	.47	.08
12 sec	2.10 (1.82)	1.58 (1.46)	5.28*	.31
17 sec	2.77 (2.94)	1.94 (2.00)	5.30*	.33
Dual task (simple)¶				
5 sec	1.20 (.81)	.97 (.59)	4.34*	.32
12 sec	2.98 (2.09)	2.47 (1.46)	3.15*	.28
17 sec	4.89 (3.23)	3.73 (2.34)	7.74**	.41
Dual task (difficult) ¶				
5 sec	1.49 (.91)	1.15 (.68)	8.57**	.42
12 sec	3.73 (2.39)	2.86 (1.79)	7.78**	.41
17 sec	6.03 (3.67)	4.43 (2.99)	11.01**	.47

Note: Absolute discrepancy score in seconds; SD = standard deviation; * p < .05. ** p < .01. ¶The accuracy of the non-temporal tasks as covariates in the analysis of absolute discrepancy scores between the two groups.

A model with three task designs

In order to explore the interactions among the group, interval lengths, and task designs on the effect of accuracy of time reproduction, we included the three main effects and their 2-way and 3-way interaction terms in the model controlling for FSIQ, sex, age, comorbidity, use of methylphenidate, and parental educational levels. We found significant main effects for group ($F_{1,1680}$ = 5.67, p = .017), 3 time intervals ($F_{2,1680}$ = 422.36, p < .001) and the tasks ($F_{2,1680}$ = 143.25, p < .001). Moreover, there were significant interactions from group × interval ($F_{2,1680}$ = 12.01, p < .001), group × task ($F_{2,1680}$ = 3.96, p = .019), and interval × task ($F_{4,1680}$ = 28.82, p < .001). There was a significant effect from FSIQ (p < .001). The 3-way interaction was not significant (p = .830).

Table 5 summarizes the parameter estimates of regression coefficients and t statistics in the final fitted model using the backward elimination procedure in the model selection, including the 3-way interactions and the 2-way interactions. We found that there were significant interactions between group and interval lengths (12-second vs. 5-second, p = .030; 17-second vs. 5-second, p < .001), and between group and task (dual task with simple version vs. single task, p = .016; dual task with difficult version vs. single task, p < .001, Table 5) controlling for all confounding variables.

Discussion

The current study is the first to investigate the cognitive process (attentional resource) for time reproduction deficits in children and adolescents with ADHD using the dual-task design, including temporal and non-temporal tasks, in a large youth sample in Taiwan. Several important findings in this study contribute to our knowledge of the cognitive mechanism of time reproduction deficits in ADHD. The results of difference in performance on time reproduction tasks were consistent with previous studies with similar interval lengths and methodology (Barkley, Edwards, Laneri, Fletcher, & Metevia, 2001; Barkley et al., 1997; Bauermeister et al., 2005; Kerns et al., 2001). Our findings lend evidence to support the greater number of discrepancy errors and less precise time reproduction in children and adolescents with ADHD than school controls (Barkley et al., 2001; Rommelse,

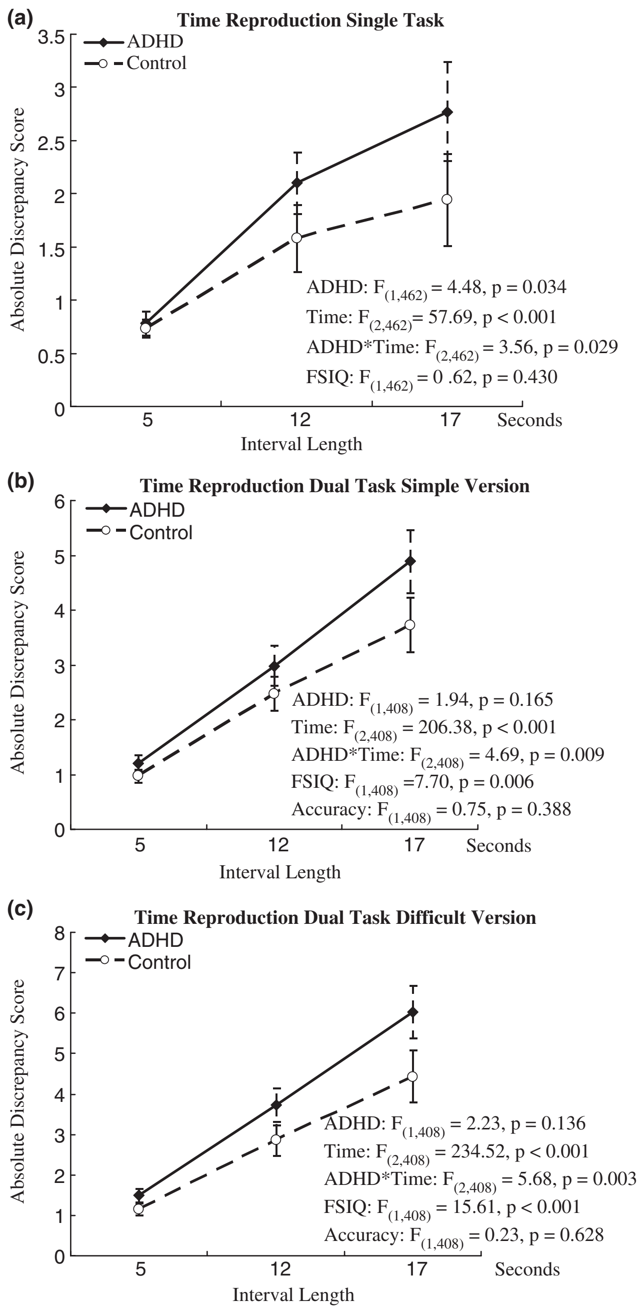

Figure 1 a) Absolute discrepancy score on the time reproduction single task by 3 time interval lengths for the ADHD and control groups. b) Absolute discrepancy score of the simple version of the time reproduction dual task by 3 time interval lengths for the ADHD and control groups. c) Absolute discrepancy score of the difficult version of the time reproduction dual task by 3 time interval lengths for the ADHD and control groups

Oosterlaan, Buitelaar, Faraone, & Sergeant, 2007); and that decreased time reproduction accuracy is associated with increased interval lengths (Kerns et al., 2001; Rommelse et al., 2007) and increased task difficulties (Rommelse et al., 2007), from the single task to the simple version and subsequently to the difficult version of dual tasks. Hence, the findings lend evidence to support our hypothesis that time perception deficits in ADHD are related to a limited attentional resource.

Table 4 The accuracy rates of the non-temporal tasks of the time reproduction dual tasks

	ADHD (n = 168) Mean (SD)	Control (n = 90) Mean (SD)	Statistics	
			t-value	p-value
Dual task (simple)				
5 sec	.65 (.33)	.70 (.33)	1.23	.22
12 sec	.39 (.37)	.31 (.34)	1.51	.13
17 sec	.25 (.33)	.26 (.33)	.16	.87
Dual task (difficult)				
5 sec	.80 (.29)	.83 (.30)	.91	.36
12 sec	.56 (.36)	.64 (.35)	1.68	.09
17 sec	.50 (.39)	.53 (.32)	.5	.62

Although the behavioral disinhibition model (Barkley et al., 1997) and the delay aversion model (Sonuga-Barke et al., 1998) provide different accounts of time perception deficits in ADHD, the present study provides sufficient data to support the notion that the attentional resource, which is related to the cognitive-energetic model, is crucially involved in time perception deficits in ADHD (Sergeant, 2005). Our findings clearly demonstrated that children and adolescents with ADHD performed as well as those without ADHD at the 5-second interval condition in the single task, but performed obviously worse on more demanding conditions at 12-seconds and 17-seconds in simple and difficult dual tasks. This figure corresponds to the attentional resource hypothesis because the ADHD patients' deficits in subjective timing (time reproduction task) are noted especially in longer intervals and difficult dual tasks due to there being less of the attentional resource for the temporal task. The current results also offer suitable empirical data to support the cognitive-energetic model (Sergeant et al., 2003, 1999) in interval timing. Children and adolescents with ADHD might have impairments in the energetic pools leading to their having difficulty regulating the resource to meet the task demands.

In summary, children and adolescents with ADHD may have an intact timing ability within the short duration while performing time reproduction on single tasks because the attentional load is low, but they may have a poor timing ability when the attentional load is high. However, this conclusion cannot be applied to fine temporal information processing (e.g., discrimination in milliseconds), which is related to another timing system, like the cerebellum (Meck, 2005).

Methodological consideration

Several methodological limitations need to be taken into consideration when interpreting our findings. First, the generalization of our findings may be questionable, because of the clinic-based sample with ADHD. Second, despite the lack of a group difference in age distribution, the wide age range

Table 5 The final model integrating the effects of group, time interval, and task versions controlling for confounding variables

Variable	β (95% CI)	*t*-value	*p*-value
Time reproduction			
ADHD (vs. Control)	–.36 (–.85, .13)	–1.44	.151
12 sec (vs. 5 sec)	.76 (.39, 1.13)	3.98	<.001
17 sec (vs. 5 sec)	.92 (.55, 1.29)	4.74	<.001
ADHD*12 sec	.44 (.05, .83)	2.18	.030
ADHD*17sec	.99 (.60, 1.38)	4.93	<.001
ADHD*Dual task Simple (vs. Single task)	.40 (.07, .73)	2.42	.016
ADHD*Dual task Difficult (vs. Single task)	.73 (.40, 1.06)	4.39	<.001
12 sec * Dual task Simple (vs. Single task)	.70 (.31, 1.09)	3.56	<.001
17sec * Dual task Difficult (vs. Single task)	2.61 (2.22, 3.00)	13.31	<.001
12 sec * Dual task Difficult (vs. Single task)	1.12 (.73, 1.51)	5.73	<.001
17 sec * Dual task Simple (vs. Single task)	1.91 (1.52, 2.30)	9.73	<.001
FSIQ	–.03 (–.05, –.01)	–3.62	<.001

Note: β = regression coefficient estimate; other covariates including sex, age, comorbidity, use of methylphenidate, and maternal and paternal educational levels.

(10–17 years old) in the sample suggests the need of future studies to examine the developmental trajectory of time reproduction deficits in ADHD by using a longitudinally prospective study design. Third, we did not assess the performance of the non-temporal tasks alone, so we were not able to assess bidirectional interference (Brown, 2006). Hence, this study cannot provide data on whether the non-temporal task interferes with the temporal tasks. Future studies using an experimental design with both temporal and non-temporal tasks, separately and concurrently, are warranted. Fourth, the use of only two trials per condition constitutes another limitation of this study because it impedes further calculation of the index of coefficient of variation, which represents the variation in timing performance. Observing the difference in timing performance variability between the participants with ADHD and those without ADHD by increasing the trial numbers per condition in future studies would be worthwhile. Fifth, higher accuracy in the non-temporal tasks for the difficult version than for the simple version seems to contradict the rationale of the attention resource of manipulation. However, based on the concept of level of process (Craik & Lockhart, 1972; McClain, 1983), the demanding condition would depend on the level of information process. The non-temporal task of the simple version belongs to the graphemic encoding task (McClain, 1983), the difficult version belongs to the semantic encoding task (McClain, 1983). The latter would interfere with the temporal task more than the former, according to the concept of the level of process (McClain, 1983). Hence, it would be reasonable to determine task difficulties based on the theoretical inference rather than the accuracy of the concurrent tasks. Sixth, by not using executive function tasks as the non-temporal tasks, we were unable to make any inference regarding the roles of specific executive functions in interval timing. This will be our next step. Lastly, the present study is limited by its lack of ability to rule out the motivation effect simply because we did not manipulate the rewarding issue, but exploring the motivation issue by manipulating the motivational energetic pool proposed by the cognitive-energetic model (Sergeant, 2005) would be worthwhile.

Clinical implications

An increased magnitude of time reproduction deficits with increased interval lengths in the dual tasks implies that children and adolescents with ADHD may encounter difficulties in estimating time duration due to the increased attentional load, subsequently leading to disorganization and poor time management. Thus, it can be expected that organization is aided by reducing attention load to leave enough space to trace the timing message and monitor the ADHD patients' pace of work in a structured environment (Solanto, Marks, Mitchell, Wasserstein, & Kofman, 2008). Moreover, the limited attentional resource in ADHD implies that the ADHD patients should focus on and execute one task at a time before moving to the next, that a suitable time schedule is imperative for them to get sufficient rest to regain the attentional resource for the next task, and that extra assistance and educational intervention are needed when they are assigned to finish complex tasks within a limited time.

Acknowledgement

This work was supported by grants from the National Science Council, Taiwan (NSC96-2628-B-002-069-MY3) and the National Health Research Institute, Taiwan (NHRI-EX94-9407PC; NHRI-EX95-9407PC; NHRI-EX96-9407PC; NHRI-EX97-9407PC). *Trial Registration:* clinicaltrials.gov Identifier: NCT00 491647.

Correspondence to

Susan Shur-Fen Gau, Department of Psychiatry, National Taiwan University Hospital, No. 7, Chung-Shan South Road, Taipei, 10002, Taiwan; Tel: +886-2-23123456 ext.66802; Fax: +886-2-23812408; Email: gaushufe@ntu.edu.tw

Key points

- ADHD is related to time perception deficits in long time intervals. However, different theoretic models cannot provide compatible explanations for underlying mechanisms for such relationship; and no study has investigated attentional resources in time perception performance in ADHD by using time reproduction dual tasks.
- The findings suggest that impaired timing processing in ADHD during long time intervals may be explained by the limited attentional capacity rather than a primary problem in timing per se.
- The findings imply that organization can be aided by reducing attention load by a suitable time schedule, and by focusing on and executing one task at a time before moving to the next in children and adolescents with ADHD.

References

Barkley, R.A. (1997). Behavioral inhibition, sustained attention, and executive functions: Constructing a unifying theory of ADHD. *Psychological Bulletin*, *121*, 65–94.

Barkley, R.A., Edwards, G., Laneri, M., Fletcher, K., & Metevia, L. (2001). Executive functioning, temporal discounting, and sense of time in adolescents with attention deficit hyperactivity disorder (ADHD) and oppositional defiant disorder (ODD). *Journal of Abnormal Child Psychology*, *29*, 541–556.

Barkley, R.A., Koplowitz, S., Anderson, T., & McMurray, M.B. (1997). Sense of time in children with ADHD: Effects of duration, distraction, and stimulant medication. *Journal of the International Neuropsychological Society*, *3*, 359–369.

Barrouillet, P., Bernardin, S., Portrat, S., Vergauwe, E., & Camos, V. (2007). Time and cognitive load in working memory. *Journal of Experimental Psychology: Human Learning and Memory*, *33*, 570–585.

Baudouin, A., Vanneste, S., Pouthas, V., & Isingrini, M. (2006). Age-related changes in duration reproduction: Involvement of working memory processes. *Brain and Cognition*, *62*, 17–23.

Bauermeister, J.J., Barkley, R.A., Martinez, J.V., Cumba, E., Ramirez, R.R., Reina, G., Matos, M., & Salas, C.C. (2005). Time estimation and performance on reproduction tasks in subtypes of children with attention deficit hyperactivity disorder. *Journal of Clinical Child and Adolescent Psychology*, *34*, 151–162.

Brown, S.W. (1997). Attentional resources in timing: Interference effects in concurrent temporal and nontemporal working memory tasks. *Perception and Psychophysics*, *59*, 1118–1140.

Brown, S.W. (2006). Timing and executive function: Bidirectional interference between concurrent temporal production and randomization tasks. *Memory and Cognition*, *34*, 1464–1471.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd edn). Hillsdale, NJ: Lawrence Erlbaum Associates.

Craik, F.I.M., & Lockhart, R.C. (1972). Levels of processing: A framework for memory research. *Journal of Verbal Learning and Verbal Behavior*, *11*, 671–674.

Fuggetta, G.P. (2006). Impairment of executive functions in boys with attention deficit/hyperactivity disorder. *Child Neuropsychology*, *12*, 1–21.

Gau, S.F., & Soong, W.T. (1999). Psychiatric comorbidity of adolescents with sleep terrors or sleepwalking: A case–control study. *Australian and New Zealand Journal of Psychiatry*, *33*, 734–739.

Gau, S.S., & Chiang, H.L. (2009). Sleep problems and disorders among adolescents with persistent and subthreshold attention-deficit/hyperactivity disorders. *Sleep*, *32*, 671–679.

Gau, S.S., Chong, M.Y., Chen, T.H., & Cheng, A.T. (2005). A 3-year panel study of mental disorders among adolescents in Taiwan. *American Journal of Psychiatry*, *162*, 1344–1350.

Gau, S.S., Chong, M.Y., Yang, P., Yen, C.F., Liang, K.Y., & Cheng, A.T. (2007). Psychiatric and psychosocial predictors of substance use disorders among adolescents: Longitudinal study. *British Journal of Psychiatry*, *190*, 42–48.

Hemmes, N.S., Brown, B.L., & Kladopoulos, C.N. (2004). Time perception with and without a concurrent nontemporal task. *Perception and Psychophysics*, *66*, 328–341.

Hicks, R.E., Miller, G.W., & Kinsbourne, M. (1976). Prospective and retrospective judgments of time as a function of amount of information processed. *American Journal of Psychology*, *89*, 719–730.

Karatekin, C. (2004). A test of the integrity of the components of Baddeley's model of working memory in attention-deficit/hyperactivity disorder (ADHD). *Journal of Child Psychology and Psychiatry*, *45*, 912–926.

Kerns, K.A., McInerney, R.J., & Wilde, N.J. (2001). Time reproduction, working memory, and behavioral inhibition in children with ADHD. *Child Neuropsychology*, *7*, 21–31.

McClain, L. (1983). Interval estimation: Effect of processing demands on prospective and retrospective reports. *Perception and Psychophysics*, *34*, 185–189.

McInerney, R.J., & Kerns, K.A. (2003). Time reproduction in children with ADHD: Motivation matters. *Child Neuropsychology*, *9*, 91–108.

Meck, W.H. (2005). Neuropsychology of timing and time perception. *Brain and Cognition*, *58*, 1–8.

Mullins, C., Bellgrove, M.A., Gill, M., & Robertson, I.H. (2005). Variability in time reproduction: Difference in ADHD combined and inattentive subtypes. *Journal of the American Academy of Child and Adolescent Psychiatry*, *44*, 169–176.

Nigg, J.T. (2005). Neuropsychologic theory and findings in attention-deficit/hyperactivity disorder: The state of the field and salient challenges for the coming decade. *Biological Psychiatry*, *57*, 1424–1435.

Perbal, S., Deweer, B., Pillon, B., Vidailhet, M., Dubois, B., & Pouthas, V. (2005). Effects of internal clock and memory disorders on duration reproductions and duration productions in patients with Parkinson's disease. *Brain and Cognition*, *58*, 35–48.

Pouthas, V., & Perbal, S. (2004). Time perception depends on accurate clock mechanisms as well as unimpaired attention and memory processes. *Acta Neurobiologiae Experimentalis*, *64*, 367–385.

Rommelse, N.N., Oosterlaan, J., Buitelaar, J., Faraone, S.V., & Sergeant, J.A. (2007). Time reproduction in children with ADHD and their nonaffected siblings. *Journal of the American Academy of Child and Adolescent Psychiatry*, *46*, 582–590.

Seidman, L.J. (2006). Neuropsychological functioning in people with ADHD across the lifespan. *Clinical Psychology Review*, *26*, 466–485.

Sergeant, J.A. (2005). Modeling attention-deficit/hyperactivity disorder: A critical appraisal of the cognitive-energetic model. *Biological Psychiatry*, *57*, 1248–1255.

Sergeant, J. A., Geurts, H., Huijbregts, S., Scheres, A., & Oosterlaan, J. (2003). The top and the bottom of ADHD: A neuropsychological perspective. *Neuroscience and Biobehavioral Reviews*, *27*, 583–592.

Sergeant, J.A., Geurts, H., & Oosterlaan, J. (2002). How specific is a deficit of executive functioning for attention-deficit/hyperactivity disorder? *Behavioural Brain Research*, *130*, 3–28.

Sergeant, J. A., Oosterlaan, J., & Meere, v. d. J.J. (1999). Information processing and energetic factors in attention-deficit/hyperactivity disorder. In H.C. Quay, & A. Hogan (Eds.), *Handbook of disruptive behavior disorders* (pp. 75–104). New York: Plenum Press.

Smith, A., Taylor, E., Rogers, J.W., Newman, S., & Rubia, K. (2002). Evidence for a pure time perception deficit in children with ADHD. *Journal of Child Psychology and Psychiatry*, *43*, 529–542.

Solanto, M.V., Marks, D.J., Mitchell, K.J., Wasserstein, J., & Kofman, M.D. (2008). Development of a new psychosocial treatment for adult ADHD. *Journal of Attention Disorder*, *11*, 728–736.

Sonuga-Barke, E.J. (2005). Causal models of attention-deficit/hyperactivity disorder: From common simple deficits to multiple developmental pathways. *Biological Psychiatry*, *57*, 1231–1238.

Sonuga-Barke, E.J., Saxton, T., & Hall, M. (1998). The role of interval underestimation in hyperactive children's failure to suppress responses over time. *Behavioural Brain Research*, *94*, 45–50.

Sonuga-Barke, E.J., Taylor, E., Sembi, S., & Smith, J. (1992). Hyperactivity and delay aversion. I. The effect of delay on choice. *Journal of Child Psychology and Psychiatry*, *33*, 387–398.

Toplak, M.E., Dockstader, C., & Tannock, R. (2006). Temporal information processing in ADHD: Findings to date and new methods. *Journal of Neuroscience Methods*, *151*, 15–29.

Toplak, M.E., & Tannock, R. (2005). Time perception: Modality and duration effects in attention-deficit/hyperactivity disorder (ADHD). *Journal of Abnormal Child Psychology*, *33*, 639–654.

Van Meel, C.S., Oosterlaan, J., Heslenfeld, D.J., & Sergeant, J.A. (2005). Motivational effects on motor timing in attention-deficit/hyperactivity disorder. *Journal of the American Academy of Child and Adolescent Psychiatry*, *44*, 451–460.

Wittmann, M., & Paulus, M.P. (2008). Decision making, impulsivity and time perception. *Trends in Cognitive sciences*, *12*, 7–12.

Zakay, D. (1989). Subjective time and attentional resource allocation: An integrated model of time estimation. In I. Levin, & D. Zakay (Eds.), *Time and human cognition: A life span perspective* (pp. 365–397). Amsterdam: North-Holland.

Zakay, D. (1990). The evasive art of subjective time measurement: Some methodological dilemmas. In R.A. Block (Ed.), *Cognitive models of psychological time* (pp. 58–84). Hillsdale, NJ: Lawrence Erlbaum Associates.

Zakay, D., & Block, R.A. (1997). Temporal cognition. *Current Directions in Psychological Science*, *6*, 12–16.

Manuscript accepted 28 July 2009