*Perceptual and Motor Skills*, 2005, 100, 659-675. 

# TAPPING AND ANTICIPATION PERFORMANCE IN ATTENTION DEFICIT HYPERACTIVITY DISORDER[1,2]

M. E. TOPLAK

*Psychology Department*
*York University*

R. TANNOCK

*Brain and Behaviour Research Programme*
*Research Institute of The Hospital for Sick Children, Toronto*

*Summary.*—The objective of this study was to examine the precise timing of a motor response in a sample of adolescents with ADHD and comparison participants. 46 participants with ADHD (*M* age = 15.6, *SD* = 1.4; 40 boys) and 44 control participants (*M* age = 15.3, *SD* = 1.4; 40 boys) were recruited through a metropolitan hospital. Participants were administered a tapping task and an anticipation task. Adolescents with ADHD displayed significantly more intra-individual variability on the visual 1000-msec. frequency interval of the tapping task and displayed lower accuracy on the cued and uncued trials of the anticipation task than comparison participants. Intra-individual variability on the tapping task was correlated with intra-individual variability on the anticipation task within both the ADHD and control groups. These findings suggest that adolescents with ADHD have impairments in both the cognitive representation and motor production of the precise timing of a motor response.

Attention Deficit Hyperactivity Disorder is a neurodevelopmental disorder that is typically first diagnosed in childhood, but symptoms continue to persist into adolescence and adulthood (DSM-IV–TR, American Psychiatric Association, 2000). A fairly substantive number of cognitive studies in individuals with ADHD have implicated time perception and time estimation as potentially important cognitive deficits in ADHD, including performance on tasks like duration discrimination, duration reproduction, anticipation or motor timing, and tapping (Barkley, 1997a, 1998; Barkley, Koplowitz, Anderson, & McMurray, 1997; Sonuga-Barke, Saxton, & Hall, 1998; Rubia, Overmeyer, Taylor, Brammar, Williams, Simmons, & Bullmore, 1999; Rubia, Taylor, Taylor, & Sergeant, 1999; West, Douglas, Houghton, Lawrence, Whiting, & Glasgow, 2000; Barkley, Edwards, Laneri, Fletcher, & Metevia, 2001; Barkley, Murphy, & Bush, 2001; Kerns, McInerney, & Wilde, 2001; Rubia, Taylor, Smith, Oksannen, Overmeyer, & Newman, 2001; Smith, Taylor, Warner Rogers, Newman, & Rubia, 2002; Ben-Pazi, Gross-Tsur, Berg-

[1]This research was supported in part by research grants from the National Institute of Mental Health (Grant R21-MH066393), HSC Psychiatry Endowment Fund, and a Canadian Institutes of Health Research (CIHR) Fellowship granted to M. Toplak. We thank Rebecca Stewart for assistance with data collection and scoring, and Bilal Ahmed for programming the computer tasks. We also thank Dr. Umesh Jain and Ruth Barton at the Centre for Addiction and Mental Health (CAMH) for clinical support, and Karen Ghelani for assistance with interviewing.
[2]Address correspondence to Dr. Rosemary Tannock, Senior Scientist, Brain & Behaviour Research Program, The Hospital for Sick Children, 555 University Avenue, Toronto, Ontario, Canada M5G 1X8 or e-mail (Rosemary.Tannock@sickkids.ca).

man, & Shalev, 2003; Rubia, Noorloos, Smith, Gunning, & Sergeant, 2003; Toplak, Rucklidge, Hetherington, John, & Tannock, 2003). However, results of these studies have been mixed, with some reporting significant impairment in ADHD samples on these tasks and some not. This inconsistency of findings has also been evident in performance on tapping and anticipation tasks, so the purpose of this study was to reconcile some of these inconsistencies.

Tapping is a simple motor task that typically involves participants tapping during a synchronization phase followed by a free tapping phase. In the synchronization phase, participants are asked to tap along at the same pace with an auditory or visual stimulus. After a period the stimulus disappears, and participants are asked to continue tapping at the same pace. The target dependent measure that signals timing ability is the within-participant variability or standard deviation of the intertap intervals for a given individual (Ivry, 1997). Modality and frequency have been examined as important variables in the literature. Performance on visual and auditory tapping tasks have been examined, and it has been reported that performance tends to be more variable in the visual than in auditory modalities (Jäncke, Loose, Lutz, Specht, & Shah, 2000; Chen, Repp, & Patel, 2002). Frequencies, or intertap intervals, have also been examined, ranging from 400 msec. to 2200 msec.; there is reportedly more drift or variability at the longer than at the shorter intertap intervals (Madison, 2001).

There has been a recent surge of interest in tapping performance in the ADHD literature (Rubia, Overmeyer, Taylor, Brammar, Williams, Simmons, & Bullmore, 1999; Rubia, Taylor, Taylor, & Sergeant, 1999; Rubia, *et al.*, 2001; Pitcher, Piek, & Barratt, 2002; Ben-Pazi, *et al.*, 2003). These studies have used a range of tasks with different stimulus presentations, synchronization schedules, and frequency rates. The stimulus presentations have included visual, auditory, or both visual and auditory modalities. An alternative method has been a self-paced, free tapping task, in which participants are asked to tap at a consistent, self-chosen pace. Some of these studies have examined synchronized tapping, others have examined tapping after a synchronization phase, or also self-paced, free tapping. The frequencies have ranged from 300 msec. to 5000 msec.

Two of the studies that have examined synchronized visual tapping reported significantly more intra-individual variability in the ADHD than control groups for frequencies between 500 msec. and 1800 msec. (Rubia, Taylor, Taylor, & Sergeant, 1999; Rubia, *et al.*, 2003), but two other studies of visual tapping tasks reported no significant group differences in intra-individual variability for frequencies ranging from 600 msec. to 5000 msec. (Rubia, Overmeyer, Taylor, Brammar, Williams, Simmons, & Bullmore, 1999; Rubia, *et al.*, 2001). Participants were asked to tap for at least 40 taps on each of these tasks. Ben-Pazi, *et al.* (2003) used a synchronized tapping task that altered the frequency of the stimulus during the task, and they reported that children with ADHD had difficulty adapting their tapping rate to the different frequencies. Using a self-paced, free tapping task, Rubia, Taylor, Taylor, and Sergeant (1999) reported that children with ADHD displayed significantly more intra-individual variability than control participants even at a self-chosen pace. In another study, Pitcher, *et al.* (2002) presented boys with and without ADHD a tapping task using auditory stimuli at the rate of 300 msec. The practice trials were synchronized, followed by 25 uncued taps. Pitcher, *et al.* (2002) reported that the boys with ADHD as a group displayed significantly more variability than boys in the control group.

In general, it has been reported that participants with ADHD have shown more difficulty synchronizing their motor response with a stimulus, reproducing a previously presented frequency, and generating a consistent self-paced frequency. In making sense of these findings, an important discriminating feature is whether the dependent measure captures the participant's ability to synchronize their taps with a presented stimulus, or whether the participant must maintain a frequency based on an internal representation of a previously presented pace or generate a consistent, internally generated pace. Significant differences seem to appear consistently in the two studies of group differences on the tapping tasks that rely on maintenance or generation of an internally generated representation (Rubia, Taylor, Taylor, & Sergeant, 1999; Pitcher, *et al.*, 2002). Therefore, in the present study, we developed a tapping task in which the participant tapped during a synchronization phase but then continued to tap at the same pace. Our purpose was to examine whether individuals with ADHD have more difficulty with maintaining an internally represented frequency following a synchronization phase across visual and auditory modalities and two different frequencies compared to control participants. The dependent measure captured the intra-individual variability of tapping rate after the synchronization phase.

In addition, we were also interested in performance on anticipation tasks, as these tasks are also characterized by the precise timing of a motor response. Anticipatory responding has been described as the ability to adjust motor responses to coincide precisely with the onset of a stimulus (Smith, *et al.*, 2002). Similar to uncued tapping tasks, anticipatory responding requires maintenance of an internal representation of the critical durations to anticipate the impending stimulus and to execute a response precisely at the point of its occurrence. One aspect that differentiates tapping from anticipation tasks is that tapping tasks involve continuous rhythmic reproduction, while anticipation tasks are less continuous and less rhythmic. However, given the overlap in the cognitive demands of both tapping and anticipation tasks, one might expect the performance on these two tasks to be significantly correlated.

Thus far, three studies have provided estimations of onset of a stimulus in ADHD samples (Sonuga-Barke, *et al.*, 1998; Rubia, Taylor, Taylor, & Sergeant, 1999; Rubia, *et al.*, 2003), which is a component of anticipation. These authors examined accuracy of motor response in the estimation of stimulus onset using intervals between 5 and 15 sec. Notably, all three studies used realistic stimuli and a game-like format involving landing airplanes (Rubia, Taylor, Taylor, & Sergeant, 1999; Rubia, *et al.*, 2003) or turning frowning faces into happy ones (Sonuga-Barke, *et al.*, 1998). Sonuga-Barke, *et al.* (1998) demonstrated that boys with ADHD tended to make more underestimations (or impulsive errors) in uncued or nonsignalled trials than control participants. For the cued or signaled conditions, Sonuga-Barke, *et al.* (1998) reported that the boys with ADHD tended to make more overestimations or responded too late. Rubia, Taylor, Taylor, & Sergeant (1999) reported that children with ADHD tended to make more impulsive errors on the cued or signaled trials. These results, therefore, suggest that children with ADHD display difficulty coordinating their response in cued and uncued conditions. Similar to studies of tapping, impairment on the uncued trials suggests impairment in the internal representation of the planned motor response. Our goal was to examine anticipatory responding using shorter and longer duration intervals (to make it analogous to the tapping task), and to examine associations between performance on the anticipation and tapping tasks.

There is a fairly substantive literature which suggests that individuals with ADHD have general motor deficits (Stevens, Stover, & Backus, 1970; Denckla & Rudel, 1978; van der Meere, Vreeling, & Sergeant, 1992; Carte, Nigg, & Hinshaw, 1996; Piek, Pitcher, & Hay, 1999; Steger, Imhof, Coutts, Gundelfinger, Steinhausen, & Brandeis, 2001); therefore, we chose to focus on uncued or nonsignalled trials to examine more systematically the internal representation of tapping rhythm and anticipatory responding. There were four versions of the tapping task, using visual and auditory modalities, and 400-msec. and 1000-msec. intertap intervals or frequencies. The anticipation task was a visual task with cued and uncued components, and with intervals of 400 msec., 1000 msec., and 2000 msec. A range of durations were selected in the anticipation task to represent shorter durations (400 msec.) and longer durations (1000 msec., and 2000 msec.), as this range was thought to capture different cognitive mechanisms, with the shorter duration capturing processes purported to be related to an internal timing mechanism and the longer duration capturing processes related to working memory (Ivry, 1997). Anticipation may occur at even short intervals as it has been reported that the cerebellum can anticipate a predicted stimulus within 120–440 msec. after presentation (Tesche & Karhu, 2000).

We expected that participants with ADHD would have more difficulty with these tasks than control participants. Given that the frequencies or durations were matched in these two tasks, we expected that performance on the tapping and anticipation tasks would be associated within the ADHD and control samples, which would suggest that these tasks are measuring a similar underlying timing-related process (Ivry, & Keele, 1989; Ivry & Hazeltine, 1995). A substantial proportion of individuals with ADHD present with additional comorbid disorders, and in particular, the presence of reading disorders presents a potential confound in this work. To date, there is an extensive literature on timing deficits in reading disorders (Nicolson, Fawcett, & Dean, 1995, 2001; Wolf, 1999, 2001). Therefore, we included some measures of reading ability to examine the effect of a comorbid reading disorder.

## Method

### *Participants*

Two groups of adolescents participated: 46 adolescents (87% boys) with a confirmed clinical diagnosis of ADHD based on DSM-IV criteria and 44 comparison adolescents (45.5% boys). Of our ADHD sample, 46% ($n$ = 21) met criteria for ADHD–Predominantly Inattentive subtype, and 54% ($n$ = 25) met criteria for ADHD–Predominantly Combined subtype. All adolescents were between the ages of 13 and 18 years ($M$ = 15.5, $SD$ = 1.4). Nineteen (39.6%) of the adolescents with ADHD were recruited from patients who were previously assessed in childhood with a confirmed diagnosis of ADHD. The remaining clinical participants were recruited through advertisements at pediatric offices as well as from new referrals to the Hospital for Sick Children. Adolescents in the control comparison group were recruited through hospital staff and community resources. All adolescents participating in the study were native English speakers. Adolescents were excluded if they had evidence of psychosis, pervasive developmental disorder, a serious medical condition, or an estimated IQ below 80.

*ADHD sample.*— All adolescents had a DSM-IV diagnosis of ADHD confirmed by a systematic and comprehensive clinical diagnostic assessment. The assessment comprised a semistructured clinical diagnostic interview (Schedule for Affective Disorders and Schizophrenia for School-age Children–Present and Lifetime Versions) conducted separately with parents and adolescents by a Ph.D. level clinical psychologist (MT) or a supervised Ph.D. candidate in clinical psychology. Note that the information from the adolescent Schedule for Affective Disorders and Schizophrenia for School-age Children (PL versions) administered did not supersede parental report for the presence or absence of externalizing symptoms. The Schedule for Affective Disorders and Schizophrenia for School-age Children (PL versions) has been used extensively to make diagnostic decisions based on DSM criteria and has been validated with children ages 6 to 17 (Kaufman, Birmaher, Brent, Rao, & Ryan, 1997). Also, parents, teachers, and adolescents completed the Conners Rating Scales–Revised (Conners, 1997) to obtain standardized ratings of behaviour. Diagnosis of ADHD in adolescents was based on the following algorithm: (1) the participants met DSM-IV criteria for ADHD according to the clinician summary based on using the Schedule for Affective Disorders and Schizophrenia for School-age Children (PL versions) in parent and adolescent interviews; (2) they met the clinical cut-offs for inattentive or hyperactive and impulsive symptoms of ADHD on Conners' Rating Scales to ensure pervasiveness of symptoms across settings; (3) evidence of ADHD symptoms prior to the age of seven was established either through a past diagnosis of ADHD or in new cases, according to parental report and school report cards; and (4) symptoms of ADHD were accompanied by evidence of impairment. In addition, all adolescents were asked to stop taking any psychoactive medication 24 hours prior to the assessment and were therefore medication free during testing.

*Comparison sample.*—Parents and adolescents confirmed on the Conners questionnaire that the adolescent did not have any Axis I diagnosis or any history or current complaints of problems in attention, behavior, mood disturbances, or learning. If any concerns were raised on the Conners questionnaires, a complete interview was done to rule out any of these difficulties. A total of four such interviews were conducted to follow up issues raised on the Conners questionnaires in the comparison control group.

*Standardized measures.*—Additional components of the adolescent assessment included measures of intellectual ability and accuracy and efficiency of single-word reading and reading-related skills. The Wechsler Abbreviated Scale of Intelligence (Wechsler, 1999), which comprised four subtests (Vocabulary, Block Design, Similarities, and Matrices), was used to provide an estimate for intellectual ability. The reading measures included the Reading subtest from the Wide Range Achievement Test-3 (Wilkinson, 1993) and the Test of Word Reading Efficiency (Wagner, Torgesen, & Rashotte, 1999).

*Group differences on standardized measures.*—Table 1 displays the diagnostic characteristics of the ADHD and comparison control groups of adolescents. Overall, as might be expected, the individuals with ADHD differed from normal control participants on virtually all of the standardized measures, including intellectual ability, reading, and the behavioral symptoms of ADHD.

### *Experimental Tasks*

*Tapping task.*— The tapping task was developed using Superlab software. Presentation and data collection were done using a Pentium PC computer. A 6-button box from Cedrus (producers of Superlab) was used

TABLE 1
DIAGNOSTIC CHARACTERISTICS OF THE ADHD AND COMPARISON CONTROL GROUPS

| Measure | ADHD Group | | | Control Group | | | $t$ |
|---|---|---|---|---|---|---|---|
| | $M$ | $SD$ | $n$ | $M$ | $SD$ | $n$ | |
| Age | 15.6 | 1.4 | 46 | 15.3 | 1.4 | 44 | – 0.77 |
| Estimated Full-Scale IQ | 104.1 | 9.9 | 46 | 110.7 | 9.9 | 44 | 3.14† |
| Reading Measures (Standard Scores) | | | | | | | |
| WRAT–3 Reading | 103.7 | 9.9 | 46 | 108.1 | 8.8 | 44 | 2.19* |
| Reading Efficiency (TOWRE) | 96.6 | 13.5 | 46 | 106.8 | 9.9 | 44 | 4.06‡ |
| Diagnostic Characteristics ($T$ Scores) | | | | | | | |
| Parent | | | | | | | |
| Conners Inattention | 72.2 | 11.0 | 45 | 49.3 | 8.0 | 42 | –11.04‡ |
| Conners Hyperactivity and Impulsivity | 71.4 | 13.3 | 45 | 51.0 | 9.1 | 42 | – 8.29‡ |
| Teacher | | | | | | | |
| Conners Inattention | 71.1 | 14.6 | 38 | 49.3 | 9.0 | 38 | – 7.81‡ |
| Conners Hyperactivity and Impulsivity | 65.9 | 16.6 | 38 | 50.2 | 9.0 | 38 | – 5.13‡ |
| Other Comorbid Disorders (% of Sample) | | | | | | | |
| Reading Disability | 24 | | 11 | | | | |
| Oppositional Defiant Disorder | 26 | | 12 | | | | |
| Conduct Disorder | 4 | | 2 | | | | |
| Substance Abuse | 2 | | 1 | | | | |
| Depression | 6 | | 3 | | | | |
| Generalized Anxiety Disorder or Phobias | 9 | | 4 | | | | |
| Math Learning Disorders | 11 | | 5 | | | | |
| Language Impairment | 2 | | 1 | | | | |

*$p < .05$. †$p < .01$. ‡$p < .001$.

for responding. There were a total of four tapping tasks varying in modality and frequency or intertap interval: auditory 400 msec., auditory 1000 msec., visual 400 msec., and visual 1000 msec. Participants were presented tones in the auditory version and a sequence of dots in the visual version.

Participants were told that they would hear some tones (or see dots in the visual version) appearing at a consistent pace. They were told that the task was to tap along at the same pace with the tones (or dots), and that they should join in as soon as they could. They were also told that at some point the tones (or dots) would disappear, but that they needed to continue tapping at the same pace until they were told to stop. Participants' tapping rate was recorded for 11 taps after the cues disappeared, and the intertap interval for the last ten taps was scored. The coefficient of variation, an index of intra-individual variability, was calculated for each participant as the $SD$ of tapping rate/mean tapping rate $\times$ 100 and served as the dependent measure. The coefficient of variation is one of multiple methods to examine intra-individual variability (Slifkin & Newell, 1998). The faster frequency was presented before the slower frequency, modality was counterbalanced, and the two auditory and visual task versions were always presented together.

Participants used the index finger of the dominant hand for responding. One participant in the ADHD group had missing data on all of the tapping tasks, and another had missing data on two versions of the tapping task. Two participants in the control group had missing data on all of the tapping tasks. These missing data were due to technical problems with the computer.

*Anticipation task.*—This task was programmed in Superlab on a Pentium PC computer so stimulus presentation and data collection were done by the computer. The same 6-button box used for the tapping task was used for responding in this task. Participants were asked to use the index finger of the dominant hand for responding. There was no auditory analog for this task.

Based on the method described by Rubia, Taylor, Taylor, and Sergeant (1999), participants were told to pretend that they were explorers flying in space in a blue spaceship. A brief narrative was created to indicate that outer space was filled with many enemies who wanted to destroy their ship. They were told that their task was to fire at the enemies before the enemy fired at them. They were told to fire at the enemy ship as soon as they saw the ship, and it was emphasized that the shot had to be precisely timed because the enemy ship always appeared at the same time. Further, they were told that, if they fired too early, the missile would destroy their own ship, and if they fired too late, the enemy ship would destroy their ship. They were also told that approximately halfway through the task the enemies would become crafty and would be able to make their ship turn invisible (uncued trial). They were told that it was very important for them to predict when the enemy ship would appear, even when the enemy ship was invisible (uncued trial).

There were three consecutive parts to this task, varying in the interval of time that the enemy ship appeared, including: 400 msec., 1000 msec., and 2000 msec. Participants had 10 practice trials in which the enemy ship was cued, followed by 11 uncued trials. The number of shots fired too early and overall accuracy were scored for the last 10 uncued trials; the first of the uncued trials was not scored, as participants were given one trial to adapt to the uncued trials. Participants had a 750-msec. window of time to respond correctly. Participants were given feedback for their performance on each trial, indicating whether they fired too early, on time, or too late. Mean number of responses that were "too early," and accuracy were the dependent measures for each of the three intervals. There were very few "too late" responses, so they are not reported. Note only a subset of participants had responses which had missing data on this task due to technical problems with the computer.

*Statistical Methods and Group Differences on Standardized Measures*

*Outliers.*—Some individuals displayed extreme performance on individual tasks but were within a normal range on others. Each deviant score (>3 *SD* from the group mean) was changed to equal the next highest score in the distribution, plus one unit. There were one to two extreme outliers on the tapping task measures; however, these outliers occurred in both the ADHD and control groups and were not consistently by the same participant. Even after accommodating for outliers, scatterplots continued to display a positive skew, particularly in the ADHD group on the coefficient of variation measure in the tapping task. We also used a square root transformation (Tabachnick & Fidell, 2001) to minimize the skew; however, when the transformed data were analyzed, the results were identical. Therefore, we opted to report the original untransformed data for simplicity of interpretation.

*Reading disorder.*—Adolescents with comorbid reading disorder exhibited significantly lower performance on the reading measures than adolescents with only ADHD, but no group differences were observed on the tapping and anticipation tasks.

*Sex.*—As the sex ratios in the ADHD and control groups were unequal, we conducted *t* tests on all of the standardized and experimental measures separately in the control and ADHD groups to assess whether the adolescent boys and girls differed in any important ways from each other. No significant differences emerged within either group, suggesting that it was not necessary to control statistically for effects of sex.

## Results

*Group Differences on Tapping and Anticipation Tasks*

*Tapping task: coefficient of variation.*—A 2 (group: ADHD, control participants) × 2 (modality: visual, auditory) × 2 (frequency: 400 msec., 1000 msec.) multivariate analysis of variance was conducted, with group as a between-subjects factor and modality and frequency as within-subject factors. These analyses were performed for the coefficients of variability of the intertap interval. The data reported here are for the final ten uncued trials, which followed the synchronized practice trials. Means and standard deviations for this task are presented in Table 2. There were no significant effects of frequency ($F_{1,85} = 2.78$, ns) or modality ($F_{1,85} = 0.39$, ns). There was a group effect which fell just short of significance ($F_{1,85} = 8.40$, $p = .07$). There was a significant interaction for frequency by modality by group ($F_{1,85} = 5.38$, $p = .02$). Using *post hoc* analyses (Bonferroni correction), this interaction indicated that participants with ADHD displayed significantly more variability on the 1000-msec. frequency in the visual modality than comparison control participants ($p = .007$).

TABLE 2
COEFFICIENTS OF VARIATION ON TAPPING TASK FOR ADOLESCENTS WITH ADHD AND COMPARISON CONTROL PARTICIPANTS

| Condition | ADHD Group | | | Control Group | | |
|---|---|---|---|---|---|---|
| | *M* | *SD* | *n* | *M* | *SD* | *n* |
| 400 msec. | | | | | | |
| Auditory | 10.8 | 12.1 | 44 | 6.8 | 4.4 | 42 |
| Visual | 8.3 | 9.0 | 44 | 7.1 | 5.2 | 42 |
| 1000 msec. | | | | | | |
| Auditory | 6.0 | 6.4 | 44 | 7.9 | 8.8 | 42 |
| Visual | 8.8 | 8.5 | 44 | 5.4 | 2.4 | 42 |

*Anticipation task.*—We performed a 2 (group: ADHD, control participants) × 3 (frequency: 400 msec., 1000 msec., 2000 msec.) × 2 (cuing: cued, uncued) multivariate analysis of variance with group as a between-subjects factor and duration and cuing as within-subjects factors. This was done separately for the mean number of "too early" responses and mean accuracy. Notably, not all participants had too early responses (between 34 and 44 in the ADHD group and between 22 and 38 participants in the control group). These data are presented in Table 3. As can be seen in this table, a higher proportion of participants with ADHD tended to respond "too early" as compared to the control participants.

TABLE 3
MEAN PERFORMANCE (NUMBER OF "TOO EARLY" RESPONSES AND ACCURACY) ON ANTICIPATION TASK ADOLESCENTS WITH ADHD AND COMPARISON CONTROL PARTICIPANTS

| Measure | | ADHD Group | | | Control Group | | |
|---|---|---|---|---|---|---|---|
| | | *M* | *SD* | *n* | *No* | *SD* | *n* |
| "Too Early" Responses | | | | | | | |
| 400 msec.: *M* No. | Cued | 0.17 | 0.00 | 34 | 0.15 | 0.00 | 22 |
| | Uncued | 0.20 | 0.10 | 34 | 0.16 | 0.00 | 22 |
| 1000 msec.: *M* No. | Cued | 0.30 | 0.18 | 44 | 0.26 | 0.15 | 38 |
| | Uncued | 0.31 | 0.16 | 44 | 0.29 | 0.14 | 38 |
| 2000 msec.: *M* No. | Cued | 0.30 | 0.18 | 41 | 0.23 | 0.14 | 38 |
| | Uncued | 0.40 | 0.20 | 41 | 0.27 | 0.16 | 38 |
| Accuracy | | | | | | | |
| 400 msec. | Cued | 0.80 | 0.14 | 46 | 0.84 | 0.11 | 42 |
| | Uncued | 0.74 | 0.20 | 46 | 0.80 | 0.17 | 42 |
| 1000 msec. | Cued | 0.71 | 0.18 | 46 | 0.75 | 0.16 | 42 |
| | Uncued | 0.64 | 0.24 | 46 | 0.72 | 0.16 | 42 |
| 2000 msec. | Cued | 0.73 | 0.20 | 46 | 0.78 | 0.15 | 42 |
| | Uncued | 0.54 | 0.27 | 46 | 0.69 | 0.20 | 42 |

For too early responses there was a significant effect of duration ($R_{2,24}$ = 22.12, $p$ = .0001), indicating that there were more "too early" responses at the longer duration intervals of 1000 msec. and 2000 msec. than at the shorter, 400-msec. duration. There was nonsignificant effect of group, but there was a significant interaction for duration by group ($F_{2,24} = 5.54$, $p = .01$). Using *post hoc* analyses (Bonferroni correction), this interaction indicated that participants with ADHD made more "too early" responses at the 2000-msec. interval than participants in the control group ($p < .02$).

With respect to accuracy there was a significant effect of cuing ($F_{1,86} = 28.08$, $p = .0001$), indicating less overall accuracy on uncued than cued trials. There was a significant effect of duration ($F_{2,85} = 19.45$, $p = .0001$), indicating less accurate performance at the longer intervals of 1000 msec. and 2000 msec. There was also an interaction for cuing by duration ($F_{2,85} = 3.26$, $p = .04$). This interaction indicated that accuracy was lowest in the uncued condition of the 2000-msec. interval ($p < .02$). There was also a significant group effect, indicating that participants with ADHD displayed lower overall accuracy than participants in the control group across all three durations and across both cued and uncued conditions ($F_{1,86} = 10.07$, $p = .002$).

*Correlational Analyses*

We performed correlational analyses between the tapping and anticipation tasks separately in the ADHD and control samples. Specifically, we correlated the coefficients of variation on the tapping tasks with "too early" and accuracy means on the anticipation task. This resulted in a total of 24 correlations. None of these correlations reached significance.

It was apparent that correlating the coefficient of variation in the tapping task and accuracy of performance on the anticipation task was an inadequate way to examine performance on these tasks. Instead, it seemed more reasonable to examine associations between intra-individual variability on these two tasks. For the anticipation task, we had available intra-participant variability or the *SD* of "too early" and accuracy responses for each participant. We therefore correlated the coefficient of variation on the tapping task with intra-individual variability on the anticipation task separately in the ADHD and control samples, resulting in another 24 correlations.

In this analysis, there were a few correlations, in particular, between the coefficients of variation and the variability of performance on the anticipation task. Specifically in the control sample, the variability of "too early" responses at the 1000-msec. frequency in the uncued condition of the anticipation task was significantly correlated with the visual 400-msec. coefficient of variation on the tapping task ($r = -.45$, $p = .007$). Also in the control sample, the variability of accuracy at the 1000-msec. frequency in the uncued condition of the anticipation task was significantly correlated with the visual 1000-msec. coefficient of variation on the tapping task ($r = -.36$, $p = .02$). In the ADHD sample, the variability of "too early" responses at the 400-msec. frequency in the cued condition of the anticipation task was significantly correlated with the visual 400-msec. coefficient of variation on the tapping task ($r = .35$, $p = .05$). Also in the ADHD sample, the variability of accuracy at the 1000-msec. frequency in the cued condition of the anticipation task was significantly correlated with the visual 400-msec. coefficient of variation on the tapping task ($r = .33$, $p = .03$). Although only four of the 24 correlations were significant, raising the possibility that these associations are spurious, this particular pattern of correlations suggests that intra-individual variability on the tapping task is associated with intra-individual variability on the anticipation task.

## Discussion

There are three notable findings in the present study. First, participants with ADHD displayed significantly more intra-individual variability on the visual tapping task at the 1000-msec. interval than control participants. Second, participants with ADHD displayed less accurate performance than control participants on the anticipation task. Finally, there was some evidence to suggest that intra-individual variability on the tapping and anticipation tasks were associated within the ADHD and control samples.

The tapping task used in the present investigation was not as rigorous experimentally as tasks that have been used in the cognitive timing literature. However, it is notable that we obtained an effect based on a set of ten uncued taps, indicating the robustness of these effects. There was a significantly interaction for frequency by modality by group, indicating that the adolescents with ADHD displayed significantly more intra-individual variability than members of the control group on the visual version of the 1000-msec. interval tapping task. This is consistent with those studies that report significant group differences in intra-individual variability in tapping performance on visual tasks (Rubia, Taylor, Taylor, & Sergeant, 1999; Rubia, *et al.*, 2003), but not with the evidence of group differences in variability on auditory tapping tasks (Pitcher, *et al.*, 2002). Although variability tends to increase in the visual modality (Jäncke, *et al.*, 2000; Chen, *et al.*, 2002) at longer intervals (Madison, 2001), it has been demonstrated that the effect for group observed in the visual modality is consistent with the growing literature that ADHD is characterized by visual-spatial memory deficits (Kempton, Vance, Maruff, Luk, Costin, & Pantelis, 1999; Barnett, Maruff, Vance, Luk, Costin, Wood, & Pentelis, 2001; Nigg, Blaskey, Huang-Pollock, & Rappley, 2002; Martinussen, Hayden, Hogg-Johnson, & Tannock, 2005). This work will require further replication. Importantly the critical variable of interest is the variability of the intertap intervals, such as the coefficient of variation, that must be examined as the dependent measure, as this variability is diagnostic of timing deficits in cerebellar patients (Ivry, 1997).

Anticipatory responding has also been of interest in the ADHD literature, likely because performance on this type of task is easily inferred to be associated with the impulsive tendencies of children and adolescents with ADHD. The results of the current study indicate that participants with ADHD made more "too early" responses only at the 2000-msec. duration but not at the shorter durations. These results are consistent with previous work, which has shown that individuals with ADHD make more underestimations or impulsive errors and increased variability at durations of at least five seconds on anticipation tasks (Sonuga-Barke, *et al.*, 1998; Rubia, Taylor, Taylor, & Sergeant, 1999; Rubia, *et al.*, 2003). Notably, all of these studies have used visual tasks, similar to the task employed in the current investigation. Interestingly, we obtained a significant group effect on overall accuracy across all three intervals and across both cued and uncued conditions, which is consistent with the findings from Sonuga-Barke, *et al.* (1998). The interpretation of the findings from Sonuga-Barke, *et al.* (1998) was that the visually unstructured conditions of the task increased impulsive responding, as apposed to considering the possibility that these differences may be attributable to abilities for duration estimation (Sonuga-Barke, *et al.*, 1998).

The fact that the findings from Sonuga-Barke, *et al.* (1998) and the current study obtained significant group differences on accuracy in both cued and uncued trials signals the importance of understanding the motor contribution versus the cognitive contribution to anticipation performance. This issue also pertains to the tapping task. Namely, Ivry (1997) argued that inflated variability observed on the tapping task can signal two possible problems in the system, either indicating that the internal timing system has been damaged or that the commands are being executed inconsistently because there are problems in the motor implementation system. Wing and Kristofferson (1973) developed a technique to partition the total variability attributable to the internal timing system and to the motor implementation system. We would expect that, based on the current study and from previous work, individuals with ADHD may have deficits in both of these domains. Specifically, there has been some evidence to suggest that individuals with ADHD are impaired in time perception (Smith, *et al.*, 2002; Rubia, *et al.*, 2003; Toplak, *et al.*, 2003), which is more purely a cognitive timing measure, and additionally there is a fairly substantive literature reporting general motor deficits associated with ADHD (Stevens, *et al.*, 1970; Denckla & Rudel, 1978; van der Meere, *et al.*, 1992; Carte, *et al.*, 1996; Piek, *et al.*, 1999; Steger, *et al.*, 2001). An empirical question is specification of the relative contributions of these two domains to the impairments observed in ADHD. This is an area for continued research.

The pattern of correlations in the present study indicated associations between the intra-individual variability of performance on each task in both the ADHD and control participants. While these correlations were modest, the fact that these associations were only obtained with the intra-individual variability of performance on the anticipation task suggests that this notion of intra-individual variability is not unique to tapping performance and that intra-individual variability may be related to similar cognitive mechanisms in these tasks. These associations suggest that other tasks, such as anticipation, may also be used to advance our understanding of intra-individual variability in ADHD.

While most research suggests that ADHD is a frontal lobe syndrome or a disorder of executive function (Pennington & Ozonoff, 1996; Barkley, 1997b; Sergeant, Geurts, & Oosterlaan, 2002), the current work on time perception extends this line of work. Barkley's neuropsychological model of ADHD (1998) was the first to include time perception as another cognitive impairment in ADHD, and this impairment was conceptualized as another aspect of the executive function deficits observed in ADHD (Barkley, 1997b). Some evidence suggests that tapping activates cerebellar regions in the brain (Rivkin, Vajapeyam, Hutton, Weiler, Hall, Wolraich, Yoo, Mulkern, Forbes, Wolff, & Waber, 2003; Rubia, *et al.*, 2003; Ullén, Forssberg, & Ehrsson, 2003), as well as the caudal supplementary motor area, the putamen of the basal ganglia, and the left ventrolateral thalamus (Rao, Harrington, Haaland, Bobholz, Cox, & Binder, 1997). Anticipation of somatosensory input has also been associated with cerebellar function (Tesche & Karhu, 2000) and may also activate working memory, prefrontal functions with longer durations (Rammsayer, 1999). Also, neuroimaging studies have reported that children and adolescents with ADHD have smaller cerebellar volumes than healthy control participants (Castellanos, Giedd, Berquin, Walter, Sharp, Tran, Vaituzis, Blumenthal, Nelson, Bastain, Zijdenbos, Evans, & Rapoport, 2001). If time perception is impaired in ADHD and time perception processes have been localized to cerebellar processes, then converging evidence from neuroimaging studies of ADHD are consistent with the idea of cerebellar deficits in ADHD. However, the neural interpretation of performance on these cognitive, timing-related tasks must be made cautiously. The recent research on the timing functions of the cerebellum (Ivry & Fiez, 2000) invite interpretations of performance on timing-related tasks as reflecting cerebellar processes; however, we have yet to confirm whether this is the case. Rubia, Overmeyer, Taylor, Brammar, Williams, Simmons, and Bullmore (1999) showed that adolescents with ADHD showed reduced right mesial frontal cortex activation compared with control participants during a tapping task (termed 'delay task') with alternating frequencies of 600 msec. and 5 sec., but this was not replicated by Rubia, *et al.* (2001). Indeed, frequency of the stimulus presentation will be an important variable, as faster frequencies may be more likely to engage other mechanisms, such as an internal timing mechanism that may be cerebellar, while slower frequencies may be more likely to tax working memory. It will be important to specify through further research whether time perception is another aspect of executive frontal function, cerebellar function, or both. In addition, given the heterogeneity of the presentation of ADHD and presence of comorbid disorders, such as reading disorders, it will be important to also take this into account in interpreting this work. The prevalence of comorbid reading disorders in the present study was comparable to typical clinical samples, but indeed the presence of comorbid disorders must be taken into account.

In conclusion, our results are consistent with previous work reporting deficits in tapping performance and anticipatory responding in ADHD. The interpretation of these findings, however, is critical. There is growing evidence in the ADHD literature that time-related processes are impaired, and further work must continue to disentangle whether such differences are attributable to executive function types of mechanisms, such as inhibition and sustained attention (Rubia, Taylor, Taylor, & Sergeant, 1999; Rubia, *et al.*, 2001), or whether indeed these differences signal impairment in other important domains in ADHD, such as cerebellar timing deficits (Toplak, *et al.*, 2003). This disentangling will have extremely important implications for the advancement of understanding cognitive processes in ADHD.

## REFERENCES


American Psychiatric Association. (2000) *Diagnostic and statistical manual of mental disorders (DSM-IV–TR).* (4th ed., Text Rev.) Washington, DC: American Psychiatric Association.

Barkley, R. A. (1997a) *ADHD and the nature of self-control.* New York: Guilford.

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

Barkley, R. A. (1998) *Attention-deficit hyperactivity disorder.* (2nd ed.) New York: Guilford.

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.

Barkley, R. A., Murphy, K. R., & Bush, T. (2001) Time perception and reproduction in young adults with attention deficit hyperactivity disorder. *Neuropsychology*, 15, 351-360.

Barnett, R., Maruff, P., Vance, A., Luk, E. S. L., Costin, J., Wood, C., & Pantelis, C. (2001) Abnormal executive function in attention deficit hyperactivity disorder: the effect of stimulant medication and age on spatial working memory. *Psychological Medicine*, 31, 1107-1115.

Ben-Pazi, H., Gross-Tsur, V., Bergman, H., & Shalev, R. S. (2003) Abnormal rhythmic motor response in children with attention-deficit-hyperactivity disorder. *Developmental Medicine and Child Neurology*, 45, 743-745.

Carte, E. T., Nigg, J. T., & Hinshaw, S. P. (1996) Neuropsychological functioning, motor speed, and language processing in boys with and without ADHD. *Journal of Abnormal Child Psychology*, 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., Bastain, T. M., Zijdenbos, A., Evans, A. C., & Rapoport, J. L. (2001) Quantitative brain magnetic resonance imaging in girls with attention-deficit/hyperactivity disorder. *Archives of General Psychiatry*, 58, 289-295.

Chen, Y., Repp, B. H., & Patel, A. D. (2002) Spectral decomposition of variability in synchronization and continuation tapping: comparisons between auditory and visual pacing and feedback conditions. *Human Movement Science*, 21, 515-532.

CONNERS, C. K. (1997) *Conners' Rating Scales–Revised: technical manual.* New York: Multi-Health Systems.

DENCKLA, M. B., & RUDEL, R. G. (1978) Anomalies in motor development in hyperactive boys. *Annals of Neurology*, 3, 231-233.

IVRY, R. B. (1997) Cerebellar timing systems. *International Review of Neurobiology*, 41, 555-573.

IVRY, R. B., & FIEZ, J. A. (2000) Cerebellar contributions to cognition and imagery. In M. S. Gazzaniga (Ed.), *The new cognitive neurosciences.* (2nd ed.) Cambridge, MA: MIT Press. Pp. 999-1017.

IVRY, R. B., & HAZELTINE, R. E. (1995) Perception and production of temporal intervals across a range of durations: evidence for a common timing mechanism. *Journal of Experimental Psychology: Human Perception and Performance*, 21, 3-18.

IVRY, R. B., & KEELE, S. W. (1989) Timing functions of the cerebellum. *Journal of Cognitive Neuroscience*, 1, 136-152.

JÄNCKE, L., LOOSE, R., LUTZ, K., SPECHT, K., & SHAH, N. J. (2000) Cortical activations during paced finger-tapping applying visual and auditory pacing stimuli. *Cognitive Brain Research*, 10, 51-66.

KAUFMAN, J., BIRMAHER, B., BRENT, D., RAO, U., & RYAN, N. (1997) Schedule for Affective Disorders and Schizophrenia for school-age children–Present and Lifetime Version (K-SADS–PL): Initial reliability and validity data. *Journal of the American Academy of Child and Adolescent Psychiatry*, 36, 980-988.

KEMPTON, S., VANCE, A., MARUFF, P., LUK, E., COSTIN, J., & PANTELIS, C. (1999) Executive function and attention deficit hyperactivity disorder: stimulant medication and better executive function performance in children. *Psychological Medicine*, 29, 527-538.

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.

MADISON, G. (2001) Variability in isochronous tapping: higher order dependencies as a function of intertap interval. *Journal of Experimental Psychology: Human Perception and Performance*, 27(2), 411-422.

MARTINUSSEN, R., HAYDEN, J., HOGG-JOHNSON, S., & TANNOCK, R. (2005) A meta-analysis of working memory impairments in children with Attention-Deficit Hyperactivity Disorder. *Journal of the American Academy of Child and Adolescent Psychiatry*, 44, 377-384.

NICOLSON, R. I., FAWCETT, A. J., & DEAN, P. (1995) Time estimation deficits in developmental dyslexia: evidence for cerebellar involvement. *Proceedings of the Royal Society*, 259, 43-47.

NICOLSON, R. I., FAWCETT, A. J., & DEAN, P. (2001) Developmental dyslexia: the cerebellar deficit hypothesis. *Trends in Neurosciences*, 24, 508-511.

NIGG, J. T., BLASKEY, L. G., HUANG-POLLOCK, C. L., & RAPPLEY, M. D. (2002) Neuropsychological executive functions and DSM-IV ADHD subtypes. *Journal of the American Academy of Child and Adolescent Psychiatry*, 41, 59-66.

PENNINGTON, B. F., & OZONOFF, S. (1996) Executive functions and developmental psychopathology. *Journal of Child Psychology and Psychiatry*, 37, 51-87.

PIEK, J. P., PITCHER, T. M., & HAY, D. A. (1999) Motor coordination and kinaesthesis in boys with attention deficit-hyperactivity disorder. *Developmental Medicine and Child Neurology*, 41, 159-165.

PITCHER, T. M., PIEK, J. P., & BARRATT, N. C. (2002) Timing and force control in boys with attention deficit hyperactivity disorder: subtype differences and the effect of comorbid developmental coordination disorder. *Human Movement Science*, 21, 919-945.

RAMMSAYER, T. H. (1999) Neuropharmacological evidence for different timing mechanisms in humans. *Quarterly Journal of Experimental Psychology: Comparative and Physiological Psychology*, 52B, 273-286.

RAO, S. M., HARRINGTON, D. L., HAALAND, K. Y., BOBHOLZ, J. A., COX, R. W., & BINDER, J. R. (1997) Distributed neural systems underlying the timing of movements. *The Journal of Neuroscience*, 17, 5528-5535.

RIVKIN, M. J., VAJAPEYAM, S., HUTTON, C., WEILER, M. L., HALL, E. K., WOLRAICH, D. A., YOO, S. S., MULKERN, R. V., FORBES, P. W., WOLFF, P. H., & WABER, D. P. (2003) A functional magnetic resonance imaging study of paced finger tapping in children. *Pediatric Neurology*, 28, 89-95.

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. *Journal of Abnormal Child Psychology*, 31, 301-313.

Rubia, K., Overmeyer, S., Taylor, E., Brammar, M., Williams, S. C. R., Simmons, A., & Bullmore, E. T. (1999) Hypofrontality in Attention Deficit Hyperactivity Disorder during higher-order motor control: a study with functional MRI. *American Journal of Psychiatry*, 156, 891-896.

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. *Perceptual and Motor Skills*, 89, 1237-1258.

Rubia, K., Taylor, E., Smith, A. B., Oksannen, H., Overmeyer, S., & Newman, S. (2001) Neuropsychological analyses of impulsiveness in childhood hyperactivity. *British Journal of Psychiatry*, 179, 138-143.

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.

Slifkin, A. B., & Newell, K. M. (1998) Is variability in human performance a reflection of system noise? *Current Directions in Psychological Science*, 7, 170-177.

Smith, A., Taylor, E., Warner Rogers, J., 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.

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. *Behavioural Brain Research*, 94, 45-50.

Steger, J., Imhof, K., Coutts, E., Gundelfinger, R., Steinhausen, H. C., & Brandeis, D. (2001) Attentional and neuromotor deficits in ADHD. *Developmental Medicine and Child Neurology*, 43, 172-179.

Stevens, D. A., Stover, C. E., & Backus, J. T. (1970) The hyperkinetic child: effect of incentives on the speed of rapid tapping. *Journal of Consulting and Clinical Psychology*, 34, 56-59.

Tabachnick, B. G., & Fidell, L. S. (2001) *Using multivariate statistics.* (4th ed.) Boston, MA: Allyn & Bacon.

Tesche, C. D., & Karhu, J. J. T. (2000) Anticipatory cerebellar responses during somatosensory omission in man. *Human Brain Mapping*, 9, 119-142.

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. *Journal of Child Psychology and Psychiatry*, 44, 888-903.

Ullén, F., Forssberg, H., & Ehrsson, H. (2003) Neural networks for the coordination of the hands in time. *Journal of Neurophysiology*, 89, 1126-1135.

van der Meere, J., Vreeling, H. J., & Sergeant, J. (1992) A motor presetting study in hyperactive, learning disabled and control children. *Journal of Child Psychology and Psychiatry*, 3, 1347-1354.

Wagner, R. K., Torgesen, J. K., & Rashotte, C. A. (1999) *Comprehensive Test of Phonological Processing (CTOPP).* Austin, TX: Pro-Ed.

Wechsler, D. (1999) *Wechsler Abbreviated Scale of Intelligence (WASI).* San Antonio, TX: Psychological Corp.

West, J., Douglas, G., Houghton, S., Lawrence, V., Whiting, K., & Glasgow, K. (2000) Time perception in boys with Attention-Deficit/Hyperactivity Disorder according to time duration, distraction and mode of presentation. *Child Neuropsychology*, 6, 241-250.

Wilkinson, G. S. (1993) *WRAT-3 administration manual.* Wilmington, DE: Wide Range.

Wing, A. M., & Kristofferson, A. B., (1973) Response delays and the timing of discrete motor responses. *Perception & Psychophysics*, 14, 5-12.

Wolf, M. (1999) What time may tell: towards a new conceptualization of developmental dyslexia. *Annals of Dyslexia*, 49, 3-28.

Wolf, M. (2001) *Dyslexia, fluency, and the brain.* (Ed. vol.) Timonium, MD: York Press.

*Accepted March 16, 2005*