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Joshua B. Ewen [a] [b] , Jeffrey S. Moher [c] , Balaji M. Lakshmanan [a] , Matthew Ryan [d] , Priya Xavier [d] , Nathan E. Crone [b] , Martha B. Denckla [d] [b] [e] [f] , Howard Egeth [c] & E. Mark Mahone [f] [g]

[a] Department of Neurology and Developmental Medicine, Kennedy Krieger Institute, Baltimore, Maryland, USA

[b] Department of Neurology, Johns Hopkins School of Medicine, Baltimore, Maryland, USA

[c] Department of Psychological and Brain Sciences, Johns Hopkins University, Baltimore, Maryland, USA

[d] Department of Developmental Cognitive Neurology, Kennedy Krieger Institute, Baltimore, Maryland, USA

[e] Department of Pediatrics, Johns Hopkins School of Medicine, Baltimore, Maryland, USA

[f] Department of Psychiatry and Behavioral Sciences, Johns Hopkins School of Medicine, Baltimore, Maryland, USA

[g] Department of Neuropsychology, Kennedy Krieger Institute, Baltimore, Maryland, USA
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Multiple Task Interference is Greater in Children With ADHD

Joshua B. Ewen

Department of Neurology and Developmental Medicine, Kennedy Krieger Institute, Baltimore, Maryland, and Department of Neurology, Johns Hopkins School of Medicine, Baltimore, Maryland

Jeffrey S. Moher

Department of Psychological and Brain Sciences, Johns Hopkins University, Baltimore, Maryland

Balaji M. Lakshmanan

Department of Neurology and Developmental Medicine, Kennedy Krieger Institute, Baltimore, Maryland

Matthew Ryan and Priya Xavier

Department of Developmental Cognitive Neurology, Kennedy Krieger Institute, Baltimore, Maryland

Nathan E. Crone

Department of Neurology, Johns Hopkins School of Medicine, Baltimore, Maryland

Martha B. Denckla

Department of Developmental Cognitive Neurology, Kennedy Krieger Institute, Baltimore, Maryland, Department of Neurology, Johns Hopkins School of Medicine, Baltimore, Maryland, Department of Pediatrics, Johns Hopkins School of Medicine, Baltimore, Maryland, and Department of Psychiatry and Behavioral Sciences, Johns Hopkins School of Medicine, Baltimore, Maryland

Howard Egeth

Department of Psychological and Brain Sciences, Johns Hopkins University, Baltimore, Maryland

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Correspondence should be addressed to Joshua B. Ewen, M.D., Kennedy Krieger Institute, 707 North Broadway, Baltimore, MD 21205. E-mail: ewen@kennedykrieger.org

E. Mark Mahone

Department of Psychiatry and Behavioral Sciences, Johns Hopkins School of Medicine, Baltimore, Maryland, and Department of Neuropsychology, Kennedy Krieger Institute, Baltimore, Maryland

There is considerable lay discussion that children with attention deficit hyperactivity disorder (ADHD) have increased difficulty with multitasking, but there are few experimental data. In the current study, we examine the simultaneous processing of two stimulus–response tasks using the Psychological Refractory Period (PRP) effect. We hypothesized that children with ADHD would show a greater PRP effect, suggesting a prolonged "bottleneck" in stimulus–response processing. A total of 19 school-aged children with ADHD showed a prolonged PRP effect compared with 25 control children, suggesting a higher cognitive cost in ADHD for multitasking.

The ubiquity of electronic entertainment and communication devices, along with a perceived cultural shift toward immediate and brief responses to inputs has spurred popular (Richtel, 2010) and scientific (Meyer & Kieras, 1997) interest in multi-tasking. In particular, the relationship between attention deficit hyperactivity disorder (ADHD) and multi-tasking has been a subject of interest for medical websites, which posit that individuals with ADHD are uniquely challenged when it comes to multi-tasking. Further, anecdotal information suggests that any potential difficulties with multi-tasking (e.g., Biggs, 1995) may place children with ADHD at an amplified disadvantage in classrooms, which are increasingly demanding multi-tasking (Hembrooke & Gay, 2003). Despite the scope of the possible issue of multi-tasking in ADHD, there are few data to substantiate these claims or to examine which neuropsychological characteristics of ADHD might lead to increased difficulty with multi-tasking.

The term "multi-tasking" includes a number of constructs. One set of abilities includes *strategic,* top-down control of the allocation of attention and task switching. In everyday behavior, people show a tendency to switch among multiple tasks in order to accomplish long-term goals (Gonzalez & Mark, 2004); however, there is a high initial cost to these switches, as task performance typically decreases immediately following the switch from one task to another (Garavan, 1998; Rogers & Monsell, 1995). Overcoming this cost in order to allocate limited attentional resources effectively toward task-relevant processes is a critical component for accomplishing both short and long-term behavioral goals.

This aspect of multi-tasking is related to *executive function*, a term used to refer to a set of cognitive functions such as inhibition, planning, and goal-directed behavior (Barkley, 1997). Deficient executive function has been well characterized in ADHD (Mahone & Slomine, 2007; O'Brien, Dowell, Mostofsky, Denckla, & Mahone, 2010). Strategic multi-tasking in ADHD has been examined directly in at least three studies (Chan et al., 2006; Clark, Prior, & Kinsella, 2000; Siklos & Kerns, 2004), in which children with ADHD performed below control peers. All three of these studies used a version of the Six Elements Test (Shallice, 1982), which requires children to plan and monitor their completion of several subtests. This task, however, does not capture another aspect of multi-tasking: the *simultaneous* processing of multiple cognitive inputs (i.e., literally doing two things at once).

There are a limited number of published investigations directly examining the effects of simultaneous multi-tasking in ADHD. A recent study by Tucha et al. (2010) found that gum chewing decreased vigilance among individuals with ADHD, although the authors also reported that gum chewing also impaired performance in healthy controls. As such, this study was not directly informative about the unique effects of multi-tasking among children with ADHD, other than to suggest that multi-tasking impedes performance just as it does in those without ADHD. Furthermore, it could be argued that gum chewing does not have adequate ecological validity in replicating the types of multiple cognitive demands that are found, for example, in classroom multi-tasking. Linterman and Weyandt (2001) hypothesized that college students with ADHD would have *better* performance in a simultaneous multi-tasking scenario than control subjects because in their model, ADHD is viewed as having the positive characteristic of augmented monitoring of the environment (cf. Hartmann, 1993). They investigated this hypothesis in college students with ADHD using the Colorado Neuropsychological Repeat Test (CNRT). In the CNRT, participants perform a visual search task while simultaneously monitoring for low-pitched tones. At the end of a block, they are required to report the number of low-pitched tones they heard. Contrary to hypotheses, the authors found no significant differences in performance on this task between ADHD and control groups.

The null findings in the Linterman and Weyandt (2001) study provide evidence not only against their hypothesis of augmented multi-tasking in ADHD but also serves as negative initial evidence against our hypothesis that individuals with ADHD have impairments (and therefore *worse* performance) in simultaneous multi-tasking. Further investigation is therefore prudent. First, given the protracted developmental trajectory of cognitive control skills (Diamond, 2000) and associated patterns of growth and pruning of the cerebral cortex in those with and without ADHD (Lenroot et al., 2007; Shaw et al., 2007), it may be that college students have "outgrown" the cognitive deficits that are dependent on processing speed. Furthermore, it cannot be ruled out that these results were affected by either a floor or ceiling effect and were therefore not sensitive to group differences in the young adult age range. The current study addresses these issues by testing school age children in whom multi-tasking differences may be more demonstrable, using a different task, for which there may be a different psychometric floor and ceiling.

Other types of experimental approaches that examine the effects of the "central bottleneck" have been published, and have the potential not only to show group differences, but also to explore the cognitive processes underlying these differences. One such approach relates to the division of stimulus–response processing into discrete stages. There is an extensive basic science literature relating to human capacity with regard to the processing of multiple stimuli (Pashler, 1994). A commonly used model breaks the processing of stimuli-responses into stages (Figure 1). These stages include perception (basic visual registration plus stimulus evaluation), response selection, and response execution. Some of these stages can be performed in a parallel fashion (i.e., there is limited interference if multiple streams are being processed simultaneously), while others are performed in a serial fashion (i.e., capacity limitations allow for only one stream to be processed at a time).

Response selection specifically has been demonstrated to act in a serial fashion when multiple stimuli are being processed at once (Pashler & Johston, 1989). The Psychological Refractory Period (PRP) is a well characterized experimental reaction-time effect that is a consequence of simultaneous processing of two stimulus–response streams. A typical paradigm that elicits the

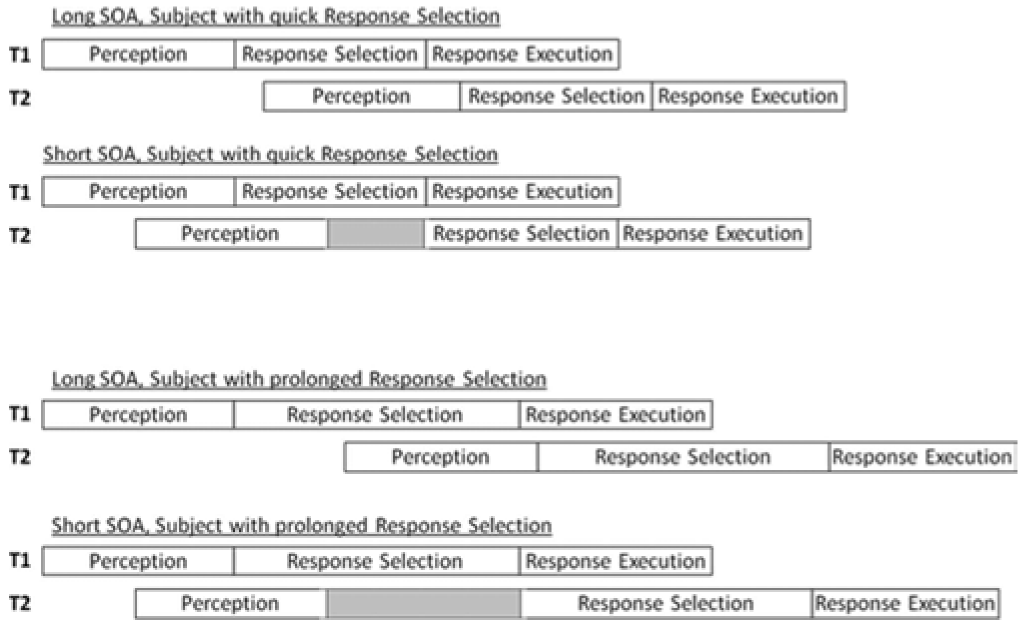

FIGURE 1 Schematic representation of the Psychological Refractory Period (PRP). At short stimulus-onset asynchrony (SOA), response selection for task 2 (T2) cannot begin until response selection for task 1 (T1) has been completed. This results in the slack period, which is represented by the grey area.

PRP effect consists of two independent stimulus–response tasks in which the stimulus for task 2 (T2) is presented following a variable stimulus-onset asynchrony (SOA) from the stimulus for task 1 (T1) (Figure 1). Stages including perception and response execution occur in a parallel fashion; that is, those stages do not suffer from interference caused by simultaneous processing of two stimulus–response streams. Response selection, however, is subject to severe capacity limitations such that response selection for T2 cannot begin until response selection for T1 has finished; thus response selection represents a "central bottleneck" in cognitive processing because it is a limiting factor when observers attempt to perform simultaneous cognitive tasks. When the SOA is sufficiently long, the response selection stages for the two tasks will not overlap because the response selection stage for T2 will not have started until response selection for T1 is already complete. When the SOA is short, however, response selection for T2 is "put on hold" while response selection for T1 finishes. This results in a "slack period" in the processing of T2, which consequently results in a prolongation of RT2 at short SOAs. The PRP effect creates a typical RT-*vs.*-SOA curve (see solid curves in Figure 2). Response selection is a central, amodal stage of processing, and the PRP effect has been demonstrated not only within several different input and output modalities but also when stimulus 1 is presented in a different modality than stimulus 2 (Pashler et al., 1989).

The present study examined whether school-age children with ADHD show differences in simultaneous multi-tasking (measured by the PRP effect), compared to typically developing

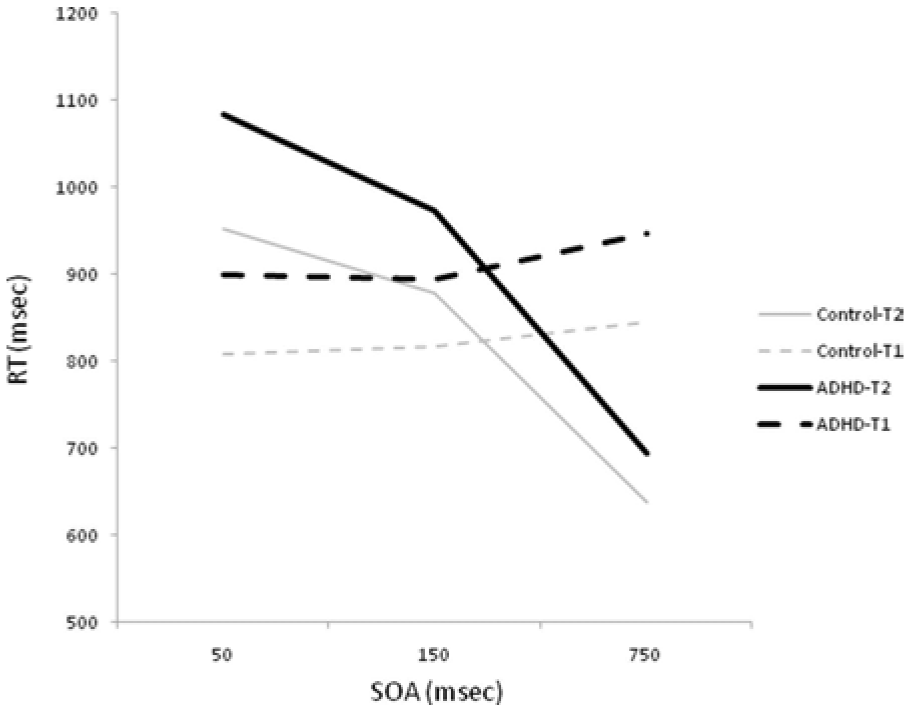

FIGURE 2 Both children with attention deficit hyperactivity disorder (ADHD) and controls demonstrate typical T2 reaction time curves consistent with the PRP effect: RT2 decreases as the stimulus onset asynchrony (SOA) increases. The gap between groups increases at short SOAs compared with long SOAs, suggesting an interaction effect ($p = .02$, $\eta_p{}^2 = 0.12$).

control children. We hypothesized that children with ADHD would demonstrate greater difficulty with simultaneous multi-tasking. This interference would manifest as a PRP effect of greater magnitude than controls, reflecting greater costs (performance decrements) associated with the performance of simultaneous cognitive tasks. This would suggest a prolonged central bottleneck associated with ADHD in children. This investigation represents a first step toward better understanding of how inefficient multi-tasking in ADHD is associated with later emerging academic difficulties.

METHOD

Participants and Screening Measures

Participants were recruited as part of a multi-aim, multi-hypothesis study of brain–behavior relationships in children with and without ADHD. The current study represents complete results from the initial investigation phase involving components of multi-tasking in children with ADHD. All participants were in grades 4 through 8. The populations were highly refined to exclude individuals with conditions that commonly co-occur with ADHD. Exclusion criteria for both ADHD and control groups included intellectual disability, pervasive developmental disorder, any psychiatric disorder treated with medications (other than ADHD), known neurological disorder, significant visual impairment, single word reading deficits (as assessed by prior school evaluation or performance below the 25th percentile on Woodcock-Johnson–III [WJ–III] Basic Reading Index) (Woodcock, McGrew, & Mather, 2001), and performance below –1.5 *SD* on either Receptive Language Index or Expressive Language Index of the Clinical Evaluation of Language Fundamentals–4 (CELF–4) (Semel, Wing, & Secord, 2004), or –1 *SD* on both indices of the CELF–4. Individuals with Full Scale IQ (FSIQ) greater than 130 on the Wechsler Intelligence Scale for Children, Fourth Edition (WISC–IV) (Wechesler, 2003) were also excluded. This decision was based on research that suggests that clinical behavioral measures of executive function are less sensitive among children in clinical groups who have superior IQ (Mahone et al., 2002). Children whose performance on the PRP task was below chance (i.e., $<$ 25% trials with both responses correct) were excluded.

Children in the ADHD group were required to have T-scores $\geq$ 65 on either Scale L (*Diagnostic and Statistical Manual of Mental Disorders*–IV [DSM–IV] Inattentive) or Scale M (DSM–IV Hyperactive/Impulsive) of the Conners' Parent Rating Scale-Revised or the Conners' Teacher Rating Scale–Revised (Conners, 1997). The participants with ADHD also needed to have clinically significant scores on the Home or School versions of the ADHD Rating Scale–IV (DuPaul, Power, Anastopoulis, & Reid, 1998); the threshold consisted of responses of 2 or higher for 6 out of 9 items on the Inattentive scale or 6 out of 9 items on the Hyperactive/Impulsive scale. Subjects with ADHD also had to meet DSM–IV (American Psychiatric Association, 1994) criteria for ADHD as measured in the Diagnostic Interview for Children and Adults, Fourth Edition (DICA–IV) (Reich, Welner, & Herjanic, 1997). Children with ADHD taking stimulant medications were included; however, those taking psychotropic medications other than stimulants were excluded.

Participants in the control group were required to have T-scores of $\leq$ 60 on both scales of both Conners' Parent Rating Scale-Revised and Conners' Teacher Rating Scale–Revised as well as non-significant scores on both Home and School versions of the ADHD Rating Scale–IV. They had to be free of all psychiatric disorders, as determined by history and the DICA–IV. They also had to have performance at or above the 37th percentile on all three reading comprehension measures (described below).

Parents of participants were screened by telephone to obtain demographic information, school history, and developmental history. Parents of children with ADHD were asked not to administer stimulant medication on the day of and the day prior to testing. Participants provided written consent (caregivers) and assent (children) before beginning testing and received a copy of the consent form. Following initial telephone screening, participants were screened for psychiatric diagnoses using a structured parent interview. Additionally, socioeconomic information from the Hollingshead Index was collected (Hollingshead, 1975). This study was approved by the local institutional review board.

There were a total of 44 participants (19 with ADHD and 25 controls) (Table 1). Four additional subjects were excluded: two with ADHD and one control due to high error rates and one with ADHD because the subject had persistent problems recalling the correct button mapping

TABLE 1
Demographic Information

	Control (n = 25)		*ADHD (n = 19)*		
	Mean	*SD*	*Mean*	*SD*	*p*
Age (years)	11.5	1.8	11.5	1.5	0.91
SES	45.5	18.6	43.4	16.4	0.69
	#	%	#	%	
Sex					0.57
Boys	11	44	10	53	
Girls	14	56	9	47	
Ethnicity					0.25
Hispanic	0	0	1	5.3	
Non-Hispanic	25	100	18	94.7	
Race					0.83
Caucasian	18	72	13	69	
African American	4	16	3	16	
Asian	2	8	1	5	
Native American	0	0	1	5	
More than one race	1	4	1	5	
ADHD subtype					N/A
Inattentive	N/A	N/A	7	37	
Hyperactive/Impulsive	N/A	N/A	1	5	
Combined	N/A	N/A	11	58	
Stimulant usage	N/A	N/A	8	42	N/A

Note. "Stimulant Usage" refers to patients routinely on stimulants (although taken off on the day prior to and of testing). Significance testing for categorical variables was performed using the chi-squared test. ADHD = attention deficit hyperactivity disorder (ADHD); SES = socioeconomic status.

throughout the testing. There were no significant differences between groups in age (mean Control = 11.5 years; mean ADHD = 11.5; $p = .91$) and sex ratio (percent male Control = 44; ADHD = 47, $p = .57$). There were, however, significant group differences in FSIQ, such that the mean FSIQ of the control group was 117.3 and the mean FSIQ of the ADHD group was 98.9 ($p < .01$). Thirty-seven percent of children in the clinical group had inattentive-type ADHD, while 63% had either hyperactive/impulsive- or combined-type ADHD. Forty-two percent of children with ADHD were regularly taking stimulant medication. All ADHD medication was of the stimulant class, either methylphenidate or amphetamine salts. Because therapy with stimulant medication has been demonstrated to affect neuropsychological performance positively (Jepsen, Fagerlund, & Mortensen, 2008), we held the medication for the day of testing and for the preceding day. Testing was therefore conducted approximately 36–48 hours after the last stimulant dose.

Psychological Refractory Period Task

The dual task paradigm used was similar to the task used by Luck (1998; see also Pashler, 1994). This specific task is experimental in nature and does not have established psychometrics. Children were seated 3 feet away from a late-model LCD monitor and held a video-game-like controller. On each trial, two stimuli were presented, separated by a variable SOA. The first stimulus (T1) in each pair was a colored square (4.4° visual angle), which was either blue or yellow. The second stimulus (T2) was a white letter, either an X or an O (3.4° visual angle). Each stimulus was displayed for 100 msec, and the SOA consisted of 3 levels (50 msec, 150 msec, 750 msec, with probabilities of 0.25, 0.25 and 0.5, respectively). The stimulus presentation time is longer than that used by Luck in order to make the task easier for younger participants. The longest SOA condition was also longer that that used by Luck in order to attempt to reduce the likelihood of response grouping. "Response grouping" refers to a potential tendency by subjects to wait for both stimuli to be presented before executing both responses, thus artificially increasing the measured interference at longer SOAs. Increasing the length of the longest SOA encourages the subjects to respond to each task as it comes, thus avoiding response grouping. SOA levels were varied randomly within each block. Each square color was presented with a probability of 0.5; the X and O were presented with one of the stimuli having a frequency of 0.75 and the other of 0.25. This was done in order to elicit a P3 response during simultaneous electroencephalogram (EEG) recording for elucidation of processing speed of stimulus evaluation; these results speak to a different theoretical issue and will be presented elsewhere. There was no predictive relationship between the color of the square used for T1 and the identity of the letter used for T2.

A hand-held button pad was used to record responses. Children were instructed to respond to square color with the left hand. They pressed one button with the ring finger for a blue square and another button with the middle finger for a yellow square. They were further instructed to respond to letter identity with the right hand. They pressed one button with the ring finger for an O and another button with the middle finger for an X. Participants were told to emphasize accuracy, but also to respond as fast as possible. The participants were given three practice blocks of 8 trials apiece to ensure that they understood the instructions.

The stimuli were presented in five blocks of 112 trials (224 stimuli) each using Advanced Neuro Technology (ANT) eevoke software (Enschede, The Netherlands). Response times were recorded through an ANT asa-lab EEG amplifier. The use of X and O as frequent and infrequent T2 were counterbalanced within subjects, between blocks. Rest breaks were given at regular intervals, and the participants were monitored by a research assistant sitting in the room for signs of distraction. The stimuli and responses were monitored by a second research assistant. Children were redirected if they seemed to be off-task, and a break was given if they seemed to be fatigued. Reaction times (RT) were recorded as the time (in milliseconds) between the stimulus onset and onset of the corresponding response. Therefore, the RT for T1 was recorded as the time between the stimulus onset for T1 and the response onset for T1; the measurement of the RT for T2 was performed similarly. We examined reaction times only for trials where the responses for both T1 and T2 were correct. Participation took approximately 1 hour, including scheduled breaks.

Data Analysis

Group was the independent variable. Group comparisons of demographic and clinical neuropsychological variables used in characterizing the cohorts were analyzed using analyses of variance (ANOVAs) (Table 1). Group differences for categorical demographic information were analyzed using Pearson's chi-square test.

The slack period (i.e., PRP effect) was the sole dependent variable and was quantified by subtracting the mean T2 reaction time at an SOA of 750 msec from the mean T2 reaction time at an SOA of 50 msec; this is mathematically equivalent to the group × SOA interaction effect for the two conditions. (RT2 for the 750 msec SOA condition is expected to be shorter, as there is less dual-task interference.) Because RT results may be skewed, we examined the normality of the RT distributions for T2 at SOAs of 50 and 750 msec, as well as the normality of the calculated PRP effect measurement using the Shapiro-Wilk test for skewness (W). The mean slack period for each group was then compared using a one-way ANOVA. We also performed a Mann-Whitney U test on the RT2 values as well as the PRP, as this approach does not rely on the assumption of normality. The intermediate SOA (150 msec) was included in the paradigm to demonstrate the expected curve of the PRP effect in both populations but was not included in the analysis of the slack period duration, as it does not contribute information beyond the reaction times to the other two SOA conditions.

In order to assess the effects of single-word reading and IQ on group differences in the PRP, we performed two Analyses of Covariance (ANCOVAs) with PRP effect as the dependent variable, group as the independent variable and WJ–III Letter-Word Identification and WISC–IV Perceptual Reasoning Index (PRI) as covariates in separate ANCOVAs. We used the PRI rather than Full Scale IQ (FSIQ), as the FSIQ includes items dependent on speed. We subsequently examined correlations between WISC–IV PRI and PRP effect in each group separately, using Pearson correlations. Finally, we examined differences in the magnitude of the PRP between ADHD subtypes.

RESULTS

Forced Choice Reaction Time Task Results

T1 mean RTs did not differ significantly by group at any of the three SOAs (Table 2). While the distribution for T2 at SOA 50 msec ($W = 0.987$, $p = .89$) was normally distributed, the distribution for T2 at SOA 750 msec ($W = 0.948$, $p = .05$) was mildly skewed. T2 mean RT at an SOA of 750 msec was not significantly different (ANOVA $p = .48$; Mann-Whitney U $p = .59$), while there was a trend towards a shorter T2 mean RT in the control group compared with the ADHD group at an SOA of 50 msec (1065 msec vs. 952 msec; ANOVA $p = .07$; Mann-Whitney U $p = .126$). There were no group differences in error rates for either T1 or T2 responses.

PRP Effect

Both groups showed a RT curve that is typical for tasks that elicit the PRP (Figure 2). There was a significant group difference in the PRP effect, which is equivalent to the duration of the response selection slack period (Figure 1). The PRP effect was normally distributed ($W = 0.983$, $p = .75$). Among controls, the mean difference between RT2 at 50 msec SOA versus 750 msec SOA was 313 ± 93 msec; for the ADHD group, the mean difference was 384 ± 109 msec [$F(1,43) = 5.57$, $p = .02$; $\eta_p^2 = 0.12$; Mann-Whitney U $p = .009$], suggesting that the ADHD group had a longer slack period, and thus, greater multi-task interference, compared to the control group.

TABLE 2
Choice Reaction Time Task Results (msec)

	Control $n = 25$	*ADHD* $n = 19$	p	η_p^2
RT2 at 750 msec SOA	639 ± 180	680 ± 198	0.48	0.01
RT2 at 50 msec SOA	952 ± 181	1065 ± 224	0.07	0.08
T2 percent correct	59 ± 32	53 ± 28	0.55	0.09
PRP effect	313 ± 93	384 ± 109	0.02	0.12
RT1 at 750 msec SOA	846 ± 301	932 ± 318	0.36	0.02
RT1 at 50 msec SOA	809 ± 174	885 ± 212	0.20	0.04
T1 percent correct	58 ± 32	52 ± 28	0.53	0.01

Note. ADHD = attention deficit hyperactivity disorder (ADHD); SOA = stimulus onset asynchrony; RT2 = reaction time for task 2 (T2); RT1 = reaction time for task 1 (T1). Values expressed as mean ± *SD*.

When Letter-Word Identification was used as a covariate, the mean PRP effect still showed significant group differences [$F(1,43) = 4.79$, $p = .034$, $\eta_p^2 = 0.11$]. When PRI was used as a covariate, the group effect on PRP was no longer significant [$F(1,42) = 0.711$, $p = .41$, $\eta_p^2 = 0.017$]. PRI data were missing for one subject. There were significant correlations between PRP effect and PRI when all subjects were examined ($r = –0.47$, $p = .02$). When the pattern of correlations was analyzed separately within groups, the relationship between PRP and PRI remained significant within the ADHD group ($r = –0.65$, $p = .03$), but not within the control group ($r = –0.054$, $p = .80$) (Figure 3). Finally, no significant differences in PRP effect were observed between the children with the Inattentive ADHD subtype and those with the Hyperactive/Impulsive or Combined subtype ($p = .86$).

DISCUSSION

The current data suggest an increased central bottleneck in children with ADHD during the simultaneous processing of two tasks. This group difference does not appear to be influenced by individual reading ability. This evidence suggests that simultaneous multi-tasking in daily tasks may indeed be more difficult for individuals with ADHD than for those without. However, the reason for this decreased central capacity is not clear. There are at least three possibilities. The first is that the central capacity is one dimension of executive function; many aspects of executive function are known to be impaired in individuals with ADHD.

Neuroimaging data are mixed in their support of the view that this central bottleneck represents a dimension of executive function that may be associated with frontal lobe function. Dux, Ivanoff, Asplund, and Marois (2006) had participants perform two cognitive tasks (T1 and T2) separated by a variable SOA in order to elicit a PRP effect. They predicted that brain regions related to a “central bottleneck” representing an amodal, capacity-limited processing stage (such as response selection) would show different patterns of activity in response to T2 depending on the SOA. Specifically, they predicted that these regions would show “serial queuing,” meaning that the onset of activity in response to T2 would be delayed at short SOAs because capacity-limited resources from those brain regions were still being devoted to completing T1. The presence of serial queuing was tested by correlating T1 response time with the time-course of

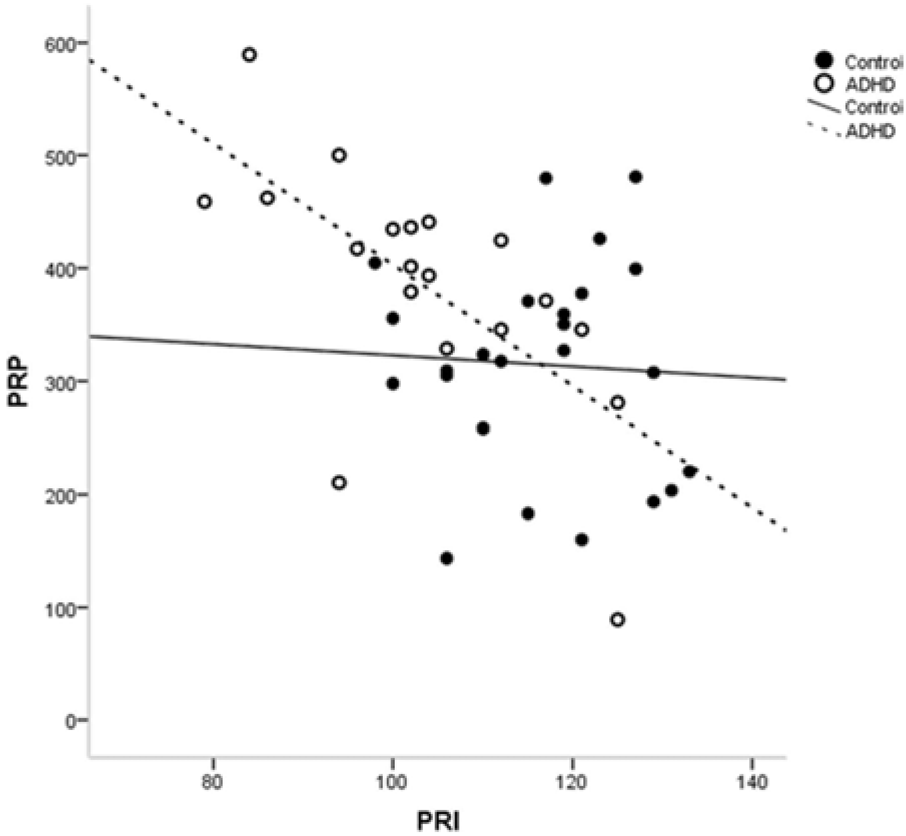

FIGURE 3 Significant association between Wechsler Intelligence Scale–Fourth Edition (WISC–IV) Perceptual Reasoning Index (PRI) and Psychological Refractory Period (PRP) effect in attention deficit hyperactivity disorder (ADHD) group ($\eta^2 = 0.42$), but not in controls ($\eta^2 = 0.003$).

activity following the presentation of T2 in various brain regions of interest; a significant correlation at the short but not the long SOA between these two measures would be indicative of a region associated with a central bottleneck. They found evidence for this serial queuing in the posterior lateral prefrontal regions (known to be associated with general executive functions (Macdonald, Cohen, Stenger, & Carter, 2000) and, to a lesser extent, in the supplementary and pre-supplementary motor areas. They concluded that these regions were part of the network representing a central bottleneck that limits dual-task processing (Dux et al., 2006). Similarly, Sigman and Dehaene also used functional magnetic resonance imaging (fMRI) to investigate the central bottleneck and found a bilateral parietal-frontal network involved (Sigman & Dehaene, 2008). Jiang, Saxe, and Kanwisher (2004) had previously used a non-time-resolved analysis of a similar paradigm under fMRI and found no such association. In summary, there are inconsistent data relating the PRP-elicited central bottleneck and brain regions previously associated with executive function.

A second possibility is that children with ADHD may exhibit greater dual-task interference because they are less able to perform basic tasks efficiently and therefore have to introduce top-down or effortful strategies to accomplish the same results. Some researchers refer to this type of basic efficiency as "automaticity." The data on automaticity in ADHD are somewhat limited; those that do exist demonstrate normal functioning during simple, automatic tasks while performance on effortful tasks is impaired (Borcherding et al., 1988). Nevertheless, this does not address the proposition that moderately difficult tasks (such as those found in the current paradigm) may be shunted from an automatic mode to a top-down, more effortful mode. In fact, such a redirection from automatic to effortful processing has been demonstrated in Parkinson's disease (Redgrave et al., 2010), a condition which, like ADHD, also involves the dopaminergic system and frontal-striatal pathology. A third possibility is that the central processing capacity limitation that is increased in ADHD is a unique faculty and reflects neither executive function nor automaticity. This explanation seems plausible, though careful examination of control and clinical populations to determine the associations and independence among the concepts of central processing bottlenecks, top-down executive function and automaticity will be critical for a full understanding of the psychology of multi-tasking.

Limitations of this study include a relatively small sample size. Nevertheless, despite the relatively small sample, these data demonstrate a significant association between diagnosis and central processing capacity with a robust effect size. Group differences account for 11% of the variance in the observed slack period durations. The preliminary examination in our sample yielded no significant differences between the subtypes, but future studies with larger sample sizes may allow for further investigation as to whether alterations of the PRP effect vary by ADHD subtype. Additionally, the highly refined nature of our clinical population both strengthens and weakens our conclusions. While our ADHD group is relatively homogeneous, an argument could be made that the broader ADHD population contains a number of common co-morbidities, and these results should also be demonstrated in a less refined ADHD group.

Group differences in IQ also present concerns to interpretation of these results and generally when dealing with pediatric clinical groups. This issue has been reviewed extensively by Dennis and colleagues (2009) and also discussed by Cornish, Wilding, and Hollis (2008). Although Dennis and Cornish reach different conclusions about whether covarying for IQ is appropriate in psychological studies of pediatric clinical groups, both groups raise similar issues. The most critical of these is that IQ does not represent an independent domain of "intelligence," but rather represents the intersection (and perhaps union) of many different cognitive abilities, potentially including the cognitive faculty being tested by the experimental paradigm. Covarying for IQ therefore increases the risk of a Type II error. An additional concern raised by both sets of authors is that close matching subjects by IQ can force one or both groups to be non-representative. Given that our sample is highly refined in terms of eliminating co-morbidities, it is our experience that it is difficult to achieve such a control group with a mean IQ around 100. Given these still controversial and unresolved issues with regard to covarying for IQ, we performed additional analyses to understand the effect of the group IQ difference on our data. Specifically, we wanted to address whether (and to what degree) the group differences in the PRP effect could be attributed to group differences in IQ. Examination of correlations between IQ (using PRI) and PRP effect showed a moderate correlation in the ADHD group but no correlation in the control group. We found these results reassuring, as they suggest the PRP effect measurements in the control group would not be significantly different even if the mean IQ of the control group were near 100. The presence of a correlation between IQ and other psychometric measurements in clinical groups but not in controls has been observed previously (Martin, Tigera, Denckla, & Mahone, 2010). Future research with larger samples may allow for further analyses that may resolve the relationship between IQ and the PRP effect more conclusively.

Finally, the effect of temporary withdrawal of stimulants in the relevant ADHD subjects is not fully understood. Stimulant medication has a brief activity with negligible blood levels reached after 24 hours even in long-acting formulations (Markowitz et al., 2003); however, it has not been definitively determined as to whether there is a lingering cognitive effect. A lingering positive effect would actually reduce power to show a difference and would therefore not invalidate our results. A lingering negative rebound effect could create a false positive result, although data suggest that the rebound effect would have peaked long before the testing was performed (Carlson & Kelly, 2003). Future studies could address this issue by either controlling for a history of medication usage or by using a longer wash-out period. A final gap in knowledge is the limited data on the typical developmental course of the central bottleneck, which may be worthy of examination in its own right.

Future research should examine the relationship of central processing limitations in ADHD to deficits in executive function and potential deficits in automaticity. In addition to behavioral investigations, neuroanatomic and neurophysiological investigations will be important to gaining a full understanding of the implications of this finding. Evidence from the PRP should also be correlated with real-world measures and progressively more complex and more ecologically valid measures. In conclusion, given ever increasing demands for multi-tasking in school and ever increasing availability of distractions, parents, teachers and affected individuals should be aware of the increased challenges presented by multi-tasking to children with ADHD, and consider accommodations that can potentially ease these demands.

REFERENCES

American Psychiatric Association. (1994). *Diagnostic and statistical manual of mental disorders: DSM-IV* (4th ed.). Washington, DC: American Psychiatric Association.

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

Biggs, S. H. (1995). Neuropsychological and psychoeducational testing in the evaluation of the ADD adult. In K. Nadeau (Ed.), *A comprehensive guide to attention deficit disorder in adults: Research, diagnosis, treatment* (pp. 109–134). New York, NY: Brunner/Mazel.

Borcherding, B., Thompson, K., Kruesi, M., Bartko, J., Rapoport, J. L., & Weingartner, H. (1988). Automatic and effortful processing in attention deficit/hyperactivity disorder. *Journal of Abnormal Child Psychology*, *16*, 333–345.

Carlson, G. A., & Kelly, K. L. (2003). Stimulant rebound: How common is it and what does it mean? *Journal of Child and Adolescent Psychopharmacology, 13,* 137–142.

Chan, R. C., Guo, M., Zou, X., Li, D., Hu, Z., & Yang, B. (2006). Multitasking performance of Chinese children with ADHD. *Journal of the International Neuropsychological Society*, *12*, 575–579.

Clark, C., Prior, M., & Kinsella, G. J. (2000). Do executive function deficits differentiate between adolescents with ADHD and oppositional defiant/conduct disorder? A neuropsychological study using the Six Elements Test and Hayling Sentence Completion Test. *Journal of Abnormal Child Psychology*, *28*, 403–414.

Conners, C. (1997). *Conners' rating scales–Revised*. Austin, TX: Pro-Ed.

Cornish, K. M., Wilding, J. M., & Hollis, C. (2008). Visual search performance in children rated as good or poor attenders: The differential impact of DAT1 genotype, IQ, and chronological age. *Neuropsychology*, *22*, 217–225.

Dennis, M., Francis, D. J., Cirino, P. T., Schachar, R., Barnes, M. A., & Fletcher, J. M. (2009). Why IQ is not a covariate in cognitive studies of neurodevelopmental disorders. *Journal of the International Neuropsychological Society*, *15*, 331–343.

Diamond, A. (2000). Close interrelation of motor development and cognitive development and of the cerebellum and prefrontal cortex. *Child Development*, *71*, 44–56.

DuPaul, G., Power, T., Anastopoulis, A., & Reid, R. (1998). *ADHD Rating Scale–IV*. New York, NY: Guilford Press.

Dux, P. E., Ivanoff, J., Asplund, C. L., & Marois, R. (2006). Isolation of a central bottleneck of information processing with time-resolved fMRI. *Neuron*, *52*, 1109–1120.

Garavan, H. (1998). Serial attention within working memory. *Memory & Cognition*, *26*, 263–276.

Gonzalez, V. M., & Mark, G. (2004). "Constant, constant, multi-tasking craziness": Managing multiple working spheres. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (pp. 113–120).

Hartmann, T. (1993). *Attention deficit disorder: A different perception.* Grass Valley, CA: Underwood Miller.

Hembrooke, H., & Gay, G. (2003). The laptop and the lecture: Effects of multitasking in learning environments. *Journal of Computing in Higer Education*, *15*, 46–64.

Hollingshead, A. (1975). *Four factor index of social status*. New Haven, CT: Yale University, Department of Sociology.

Jepsen, J. R., Fagerlund, B., & Mortensen, E. L. (2008). Do attention deficits influence IQ assessment in children and adolescents with ADHD? *Journal of Attention Disorders, 12,* 551–562.

Jiang, Y., Saxe, R., & Kanwisher, N. (2004). Functional magnetic resonance imaging provides new constraints on theories of the psychological refractory period. *Psychological Science*, *15*, 390–396.

Lenroot, R. K., Gogtay, N., Greenstein, D. K., Wells, E. M., Wallace, G. L., Clasen, L. S., . . . Giedd, J. N. (2007). Sexual dimorphism of brain developmental trajectories during childhood and adolescence. *Neuroimage, 36*(4), 1065–1073.

Linterman, I., & Weyandt, L. (2001). Divided attention skills in college students with ADHD: Is it advantageous to have ADHD? *The ADHD Report, 9*, 1–10.

Luck, S. (1998). Sources of dual-task interference: Evidence from human electrophysiology. *Psychological Science*, *9*, 223–227.

Macdonald, A. W., Cohen, J. D., Stenger, V. A., & Carter, C. S. (2000). Dissociating the role of dorsolateral prefrontal and anterior cingulate cortex in cognitive control. *Science, 288,* 1835–1838.

Mahone, E. M., Hagelthorn, K. M., Cutting, L. E., Schuerholz, L. J., Pelletier, S. F., Rawlins, C., . . . Denckla, M. B. (2002). Effects of IQ on executive function measures in children with ADHD. *Child Neuropsychology*, *8*, 52–65.

Mahone, E. M., & Slomine, B. (2007). Managing dysexecutive disorders. In S. Hunter & J. Donders (Eds.), *Pediatric neuropsychological intervention* (pp. 287–313). Cambridge, UK: Cambridge University Press.

Martin, R., Tigera, C., Denckla, M. B., & Mahone, E. M. (2010). Factor structure of paediatric timed motor examination and its relationship with IQ. *Developmental Medicine and Child Neurology*, *52*, e188–194.

Meyer, D. E., & Kieras, D. E. (1997). A computational theory of executive cognitive processes and multiple-task performance: Part 1. Basic mechanisms. *Psychological Review*, *104*, 3–65.

O'Brien, J. W., Dowell, L. R., Mostofsky, S. H., Denckla, M. B., & Mahone, E. M. (2010). Neuropsychological profile of executive function in girls with attention-deficit/hyperactivity disorder. *Archives of Clinical Neuropsychology*, *25*, 656–670.

Pashler, H. (1994). Dual-task interference in simple tasks: Data and theory. *Psychological Bulletin*, *116*, 220–244.

Pashler, H., & Johston, J. (1989). Chronometric evidence for central postponement in temporally overlapping tasks. *Quarterly Journal of Experimental Psychology*, *41A*, 19–45.

Redgrave, P., Rodriguez, M., Smith, Y., Rodriguez-Oroz, M. C., Lehericy, S., Bergman, H., . . . Obeso, J. A. (2010). Goal-directed and habitual control in the basal ganglia: Implications for Parkinson's disease. *Nature Reviews Neuroscience*, *11*, 760–772.

Reich, W., Welner, Z., & Herjanic, B. (1997). *The diagnostic interview for children and adolescents–IV*. North Tonawanda: Multi-Health Systems.

Richtel, M. (2010, August 16). Outdoors and out of reach, studying the brain. *The New York Times*, p. A1.

Rogers, R. D., & Monsell, S. (1995). Costs of a predictable switch between simple cognitive tasks. *Journal of Experimental Psychology: General, 124,* 207–231.

Semel, E., Wing, E., & Secord, W. (2004). *Clinical evaluation of language fundamentals*—Fourth. San Antonio, TX: The Psychological Corporation.

Shallice, T. (1982). Specific impairments of planning. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *298*, 199–209.

Shaw, P., Eckstrand, K., Sharp, W., Blumenthal, J., Lerch, J. P., Greenstein, D., . . . Rapoport, J. L. (2007). Attention-deficit/hyperactivity disorder is characterized by a delay in cortical maturation. *Proceedings of the National Academy of Sciences of the USA, 104*(49), 19649–19654. doi:10.1073/pnas.0707741104

Sigman, M., & Dehaene, S. (2008). Brain mechanisms of serial and parallel processing during dual-task performance. *Journal of Neuroscience*, *28*, 7585–7598.

Siklos, S., & Kerns, K. A. (2004). Assessing multitasking in children with ADHD using a modified Six Elements Test. *Archives of Clinical Neuropsychology*, *19*, 347–361.

Tucha, L., Simpson, W., Evans, L., Birrel, L., Sontag, T. A., Lange, K. W., & Tucha, O. (2010). Detrimental effects of gum chewing on vigilance in children with attention deficit hyperactivity disorder. *Appetite, 55*, 679–684.

Wechesler, D. (2003). *Wechsler intelligence scale for children*, *fourth edition*. San Antonio, TX: The Psychological Corporation.

Woodcock, R., McGrew, K., & Mather, N. (2001). *Woodcock-Johnson psychoeducational battery–Third edition*. Chicago, IL: Riverside Publishing.