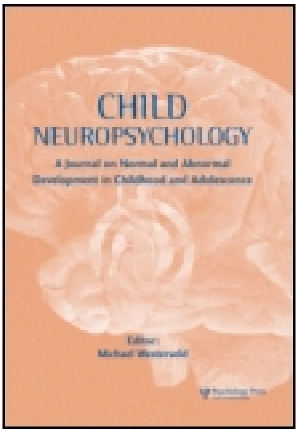

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Hyperactivity in boys with attention deficit/hyperactivity disorder (ADHD): The association between deficient behavioral inhibition, attentional processes, and objectively measured activity

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Contemporary models of ADHD hypothesize that hyperactivity reflects a byproduct of inhibition deficits. The current study investigated the relationship between children's motor activity and behavioral inhibition by experimentally manipulating demands placed on the limited-resource inhibition system. Twenty-two boys (ADHD = 11, TD = 11) between the ages of 8 and 12 years completed a conventional stop-signal task, two choice-task variants (no-tone, ignore-tone), and control tasks while their motor activity was measured objectively by actigraphs placed on their nondominant wrist and ankles. All children exhibited significantly higher activity rates under all three experimental tasks relative to control conditions, and children with ADHD moved significantly more than typically developing children across conditions. No differences in activity level were observed between the inhibition and noninhibition experimental tasks for either group, indicating that activity level was primarily associated with basic attentional rather than behavioral inhibition processes.

Keywords: ADHD; Behavioral inhibition; Stop-signal; Hyperactivity; Attention.

Contemporary models of attention deficit/hyperactivity disorder (ADHD) emphasize the presence of associated executive function (e.g., working memory and behavioral inhibition) impairments but vary considerably in their hypotheses concerning the processes by which executive functions are related functionally to specific cognitive and behavioral domains that reflect the ADHD phenotype (Barkley, 1997; Rapport, Kofler, Alderson, & Raiker, 2008; Sergeant, 2005; Sonuga-Barke, 2003). This is particularly evident for the core symptom of hyperactivity — motor activity that is developmentally inappropriate and excessive relative to same-aged peers (Rapport et al., 2008, 2009). The functional working memory model of ADHD, for example, hypothesizes that working memory deficits are a core component or endophenotype of the disorder that results from a complex interaction of environmental factors, genetic polymorphisms, and consequent neural abnormalities (Rapport, Chung, Shore, & Isaacs, 2001; Rapport et al., 2008), and that children with ADHD exhibit increased motor activity relative to typically developing (TD) peers in an

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attempt to increase cortical arousal needed for task demands related to central executive functioning (Rapport et al., 2009). In contrast, prevailing inhibition models of ADHD hypothesize that children's excessive gross motor activity is associated with deficient interference control — that is, the inability to exclude nonessential information from gaining access to working memory — which in turn results in nongoal-directed motor movement (Barkley, 1997). Other models that include behavioral inhibition as a core or complementary construct hypothesize that excessive activity is a byproduct of a child's attempt to minimize the aversive nature of waiting for delayed reinforcement by seeking alternate sources of stimulation or represents difficulty withholding or discontinuing a response in the presence of prepotent stimuli (Sonuga-Barke, Bitsakou, & Thompson, 2010). Hyperactivity has also been hypothesized to represent a manifestation of subcortical impairment that remains relatively static throughout life and is unrelated to executive functions such as working memory and behavioral inhibition (Halperin, Trampush, Miller, Marks, & Newcorn, 2008).

Inhibition models of ADHD (Barkley, 1997; Sonuga-Barke, 2002) are derived predominantly from Logan and Cowan's (1984) race model, which hypothesizes that the probability of inhibiting a controlled response depends on the relative finishing times between two competing processes — go and stop — that operate independently of one another. A slow reaction time to a stop-stimulus (stop-signal reaction time; SSRT) decreases the probability that the stop-process will overtake the go-process and increases the probability of an undesired response. Anatomical structures such as the prefrontal and frontal cortices are hypothesized correlates of behavioral inhibition (Aman, Roberts, & Pennington, 1998; Crosbie, Pérusse, Barr, & Schachar, 2008), such that motor responses initiated in response to prepotent stimuli are overridden or terminated following commands from these areas. Additionally, the basal ganglia may act as a moderator to ensure proper execution of desired motor responses (Crosbie et al., 2008), and the dopaminergic and noradrenergic systems are probable candidates involved in behavioral inhibition at the neurotransmitter level (Rieger, Gauggel, & Burmeister, 2003).

Extant evidence for an association between inhibitory deficits and hyperactivity is derived primarily from studies comparing ADHD subtypes on inhibition tasks, or correlating parent/teacher ratings of hyperactivity with inhibitory control measures (e.g., stop-signal reaction time). Children with the combined (ADHD-C) and predominantly hyperactive/impulsive subtypes (ADHD-H/I) are conventionally expected to exhibit greater inhibition deficits relative to typically developing children and children with the predominantly inattentive subtype (ADHD-I). In a similar vein, negative associations between parent/teacher hyperactivity ratings and behavioral inhibition indices are expected to the extent that deficient inhibitory processes underlie the excessive activity observed in children with ADHD.

Studies examining behavioral inhibition performance among children with ADHD-Combined subtype, ADHD-Inattentive subtype, and typically developing children have resulted in equivocal findings to date. For example, Nigg, Blaskey, Huang-Pollock, and Rappley (2002) reported that children with ADHD-C exhibited significantly slower reaction times to a stop-signal relative to children with ADHD-I and typically developing children, whereas Scheres, Oosterlaan, and Sergeant (2001) failed to find significant stop-signal reaction time differences among children with ADHD-C, ADHD-I, ADHD-H/I, and typically developing children.

Past investigations examining the relationship between ADHD symptoms (inattention, hyperactivity/impulsivity) and inhibitory processes have also produced mixed results. For example, Brocki, Tillman, and Bohlin (2010) reported a modest association ($r = .30$) between parent/teacher activity ratings and children's performance on a commonly used inhibition task (i.e., the Go/No-Go task) but did not include clinically diagnosed children with ADHD. In contrast, other studies have reported nonsignificant relationships between behavioral inhibition indices and parent and teacher ratings of hyperactivity (Kuntsi, Oosterlaan, & Stevenson, 2001; Nigg, 1999) or classroom observations of gross motor movement (Solanto et al., 2001).

The discrepancy between studies reporting significant and nonsignificant relationships between behavioral inhibition and hyperactivity in children with ADHD may reflect subtle differences among the studies, including sample demographics, diagnostic procedures, and methodological confounds. This latter variable is a promising candidate for explaining between-study differences. Specifically, the ratings used by Kuntsi et al. (2001) and Solanto et al. (2001) reflect adult retrospective perceptions of children's activity level throughout the day across multiple settings for the preceding week and month, respectively, in contrast to the brief time (typically 15 to 30 min.) required to complete the behavioral inhibition tasks in both studies. Controlling for setting and time parameter effects, however, does not remedy the modest agreement ($r = .32$ to $.58$) conventionally found between subjective (e.g., rating-scale scores) and objective (actigraphs) measures of children's activity (Rapport, Kofler, & Himmerich, 2006). This discrepancy is potentially problematic given (a) the ability of actigraphs but not hyperactivity ratings to differentiate hyperactive from impulsive subtypes of ADHD (Marks, Himelstein, Newcorn, & Halperin, 1999) and (b) the improved predictive validity of actigraphs for differentiating groups of ADHD children from both typically developing and other clinical groups relative to hyperactivity ratings (Halperin, Matier, Bedi, Sharma, & Newcorn, 1992).

To date, only one study has examined the relationship between inhibition and actigraph-measured activity level and found that both hypoactive and hyperactive traumatic brain injured patients (TBI) showed evidence of deficient behavioral inhibition (i.e., slower SSRTs) relative to unaffected children (Konrad, Gauggel, Manz, & Schöll, 2000). These findings suggest that inhibitory deficits may lack specificity with respect to their relationship with activity level.

The present study is the first to manipulate behavioral inhibition experimentally and observe its effect on the objectively measured activity level of children with ADHD and typically developing children. This was accomplished by administering the stop-signal task and two additional tasks that are identical to the stop-signal with the exception of the demands they place on behavioral inhibition. The stop-signal task is frequently used in clinic- and laboratory-based research to investigate behavioral inhibition in children with ADHD due to its ability to capture theoretically important go- and stop-processes described by the race model of inhibition (Alderson, Rapport, & Kofler, 2007; Logan & Cowan, 1984). The stop-signal task is particularly well suited for the current study, because its go component (choice reaction time task) may be measured separately from the stop task as a measure of control, to determine the relative contribution of inhibition and attention on activity changes.

Previous studies have demonstrated that performance on a choice reaction-time task relies on controlled attentional processes associated with the central executive component of working memory (Chen & Cowan, 2009; Schmiedek, Oberauer, Wilhelm, Süβ, & Wittmann, 2007). Consequently, children with ADHD and typically developing children were both expected to exhibit increased motor activity while performing the choice reaction-time tasks relative to control conditions, as predicted by the working memory model of ADHD (Rapport et al., 2001, 2008) and recent findings demonstrating a significant relationship between working memory mediated attentional processes — particularly the central executive — and activity level (Rapport et al., 2009). We also predicted that children's motor activity would be significantly higher during the stop-signal task relative to control conditions and two choice reaction-time tasks. In addition, we predicted that the activity level of children with ADHD would increase disproportionately relative to typically developing children during the stop-signal task. These predictions were based on Logan and Cowan's (1984) theoretical model and more recent research of self-control and inhibition (Muraven & Baumeister, 2000; Muraven et al., 2006), which postulates that inhibition is a limited resource that will be depleted when competing demands exceed behavioral inhibition resources, and prevailing views of underlying behavioral inhibition deficits in ADHD (Barkley, 1997; Sonuga-Barke, 2003). Thus, children with ADHD were expected to have fewer available inhibitory resources to control tertiary motor behavior (e.g., limb movements, restlessness while seated), particularly when these resources were diminished by imposed stop-signal task demands.

METHOD

Participants

The sample included 22[1] boys aged 8 to 12 years ($M = 9.05$, $SD = 1.40$), recruited by or referred to a university-based child assessment clinic through community resources (e.g., pediatricians, community mental health clinics, school system personnel, self-referral). Typically developing children (those without a suspected psychological disorder) were actively recruited through contact with neighborhood and community schools, family friends of referred children, and other community resources, and consisted primarily of self-referred families who were interested in learning more about their children's cognitive and academic strengths and weaknesses. A psychoeducational report was provided to the parents of all participants.

Two groups of children participated in the study: children with ADHD and typically developing children without a psychological disorder. All parents and children gave their informed consent/assent to participate in the study, and the university's Institutional Review Board approved the study prior to the onset of data collection.

Group Assignment

All children and their parents participated in a detailed, semi-structured clinical interview using the Kiddie-Schedule for Affective Disorders and Schizophrenia for School-Aged Children (K-SADS; Kaufman et al., 1997). Additionally, all K-SADS interviews were supplemented with parent and teacher ratings scales, including the Child Behavior Checklist (CBCL; Achenbach & Rescorla, 2001), Teacher Report Form (TRF; Achenbach & Rescorla, 2001), and Child Symptom Inventory – Parent & Teacher (CSI; Gadow, Sprafkin, & Salisbury, 2004).

Eleven children met the following criteria and were included in the ADHD-Combined Type group: (a) An independent diagnosis by the Children's Learning Clinic's

[1]The original sample included 23 children; however, one child was excluded from analyses due to actigraph failure during data collection.

(CLC) directing clinical psychologist using *Diagnostic and Statistical Manual of Mental Disorders*, fourth edition (*DSM-IV*) (American Psychiatric Association, 2000) criteria for ADHD-Combined Type based on K-SADS semi-structured interview with parent and child; (b) parent ratings of at least two standard deviations above the mean on the Attention Problems clinical syndrome scale of the CBCL, or exceeding the criterion score for the parent version of the ADHD-Combined subtype subscale of the CSI; and (c) teacher ratings of at least two standard deviations above the mean on the Attention Problems clinical syndrome scale of the TRF, or exceeding the criterion score for the teacher version of the ADHD-Combined subtype subscale of the CSI. Employing the either/or rating-scale criteria was adopted to improve diagnostic sensitivity and to provide additional screening for the possible presence of comorbid clinical disorders in children. All children in the ADHD group met criteria for ADHD-Combined Type, and six were comorbid for Oppositional Defiant Disorder (ODD).

Eleven children met the following criteria and were included in the TD group: (a) no evidence of any clinical disorder based on parent and child K-SADS interview; (b) normal developmental history by maternal report; (c) ratings below 1.5 standard deviations on all clinical syndrome scales of the CBCL and TRF; and (d) parent and teacher ratings within the nonclinical range on all CSI subscales.

All children were administered either the Wechsler Intelligence Scale for Children (WISC), third or fourth edition (Wechsler, 1991, 2003) to obtain an overall estimate of intellectual functioning and to exclude children with a full-scale IQ (FSIQ) below 85. The changeover to the fourth edition was due to its release during the conduct of the study and to provide parents with the most up-to-date intellectual evaluation possible. Children that presented with (a) gross neurological, sensory, or motor impairment, (b) history of a seizure disorder, or (c) psychosis were also excluded from the study. None of the children were receiving medication during the study; seven of the children with ADHD had previously received trials of psychostimulant medication.

Measures

Stop-Signal Task. The stop-signal task and administration instructions are identical to those described by Schachar, Mota, Logan, Tannock, and Klim (2000). Go stimuli are displayed for 1000 ms as uppercase letters X and O positioned in the center of a computer screen. Xs and Os appear with equal frequency throughout the experimental blocks. Each go stimulus is preceded by a dot (i.e., fixation point) displayed in the center of the screen for 500 ms. The fixation point serves as an indicator that a go stimulus is about to appear. A 1000 Hz auditory tone (i.e., stop stimulus) delivered through sound-deadening headphones is generated by the computer and presented randomly on 25% of the experimental trials. Stop-signal delays (SSD) — the latency between presentation of go and stop stimuli — are initially set at 250 ms but dynamically adjusted $\pm$ 50 ms contingent on a participant's performance on the previous trial. Successfully inhibited stop trials are followed by a 50 ms increase in SSD, and unsuccessfully inhibited stop trials are followed by a 50 ms decrease in SSD. The algorithm is designed to approximate successful inhibition on 50% of the stop-trials. A two-button response box is used wherein the left button is used to respond to the letter X, and the right button is used to respond to the letter O. All participants completed two practice blocks and five consecutive experimental blocks of 32 trials (24 go-trials, 8 stop-trials). The experimental blocks required four minutes to complete.

Choice Tasks. Two additional choice-task conditions were presented to control for changes in activity from control conditions (see below) that were due to basic attentional processes associated with the choice reaction-time task (i.e., choosing X and O) and not behavioral inhibition. All task parameters were identical to the previously described stop-signal condition with the following exceptions. A no-tone condition was administered without the presentation of an auditory tone. This condition was included to provide a pure measure of the relationship between children's activity and cognitive demands associated with a choice reaction-time task. An ignore-tone condition was administered also to determine whether the intermittent presentation of a neutral (nonmeaningful) auditory tone exerts an effect on children's activity and controls for activity changes that may result from increased processing demands (i.e., hearing a tone) that are independent of inhibition. This condition always preceded the stop-signal condition but was counterbalanced with the no-tone condition. The no-tone and ignore-tone conditions each required four minutes to complete.

Control (C) Conditions. Children's activity level was assessed while they used the Microsoft® Paint program for five consecutive minutes both prior to (C1) and after (C2) completing the no-tone, ignore-tone and stop-signal tasks during three consecutive Saturday assessment sessions. The paint program served as pre- and postconditions on all three testing days to assess and control for potential within-day fluctuations in activity level (e.g., fatigue effects). Children sat in the same chair and interacted with the same computer used for the choice tasks and stop-signal condition while interacting with a program that placed relatively minimal demands on inhibition and controlled-focused attention (i.e., the paint program allows children to draw/paint anything they like on the monitor using a variety of interactive tools). The three preactivity- and three postactivity-level control conditions were averaged separately to create pre- and postcomposite scores secondary to preliminary analyses that found no differences in children's pre- or postcondition activity level across days (all p values $> .10$).

Actigraph. An actigraph is an acceleration-sensitive device that measures motor activity. The estimated reliability for actigraphs placed at the same site on the same person ranges from .90 to .99 (Tryon, 1985). Actigraphs are correlated moderately with parent and teacher ratings of activity level ($r = .32$ to .58) and have superior predictive validity relative to parent and teacher ratings of hyperactivity for differentiating among children with ADHD, typically developing children, and children with other psychopathological disorders (Halperin et al., 1992; Rapport et al., 2006). MicroMini Motionlogger® actigraphs were used to measure children's activity level (Ambulatory Monitoring, 2004). The actigraphs resemble wristwatches and were set to Proportional Integrating Measure (low-PIM) mode, which measures the intensity of movement (i.e., quantifies gross activity level). Movement was sampled 16 times per second (16 Hz) and collapsed into 1-minute epochs. Data were downloaded via a hardware interface and analyzed using the Action-W2 software program (Ambulatory Monitoring, 2004) to calculate mean activity rates for each child during the control and experimental tasks described above.

Children were told that the actigraphs were "special watches" that let them play the computer learning games. The Observer (Noldus Information Technology, 2003) live observation software was used to code start and stop times for each task, which were matched to the time stamps from the actigraphs. Actigraphs were placed immediately above children's left and right ankles and nondominant hand using Velcro watch bands.

Nondominant hand and ankle placement was used in lieu of trunk placement due to the improved sensitivity of the former for detecting movement (Eaton, McKeen, & Saudino, 1996).

Total extremity scores (TES) served as the primary dependent variable and were calculated by summing activity level across the three actigraph sites (two ankle, one nondominant hand) to compute an estimate of overall movement for each of the five conditions (C1, no-tone, ignore-tone, stop-signal, and C2). An aggregate measure of activity level was employed in lieu of reporting separate extremity activity rates or using data-reduction techniques, such as averaging due to expected interindividual differences in movement across children's extremities while completing cognitive tasks (Eaton et al., 1996). This approach has the additional advantage of conserving power while providing the broader sampling of children's activity level needed to test hypotheses regarding the relationship between overall activity level and behavioral inhibition.

Procedure

The experimental tasks were administered as part of a larger battery of laboratory-based tests that required the child's presence for approximately 2.5 hours per session across three consecutive Saturday sessions. Each experimental condition (no-tone, ignore-tone, and stop-signal task) was administered on a separate day. Breaks were scheduled between tasks to minimize fatigue. Each child was administered a total of three experimental conditions: no-tone, ignore-tone, stop-signal, across the three testing sessions (one task per session, one week apart). The no-tone and ignore-tone conditions were counterbalanced so that each was administered before the other with equal frequency. The no-tone and ignore-tone conditions always preceded the Stop-Signal condition to allow for the measurement of reaction time in the absence of experience with a meaningful auditory tone.

Children were seated approximately 0.66 meters from the computer monitor. Prior to the administration of each experimental condition, they were required to complete two practice blocks, each consisting of 32 trials. Prior to administration of each experimental phase, children were told that they were going to begin the test portion of the session and that it would be longer in duration relative to the practice session. Instructions for the no-tone and ignore-tone conditions were identical to those of the stop-signal condition except for the explanation of the stop-signal tone. Specifically, the tone was not mentioned in the no-tone condition, and prior to the ignore-tone condition, children were administered the following additional instructions: "Sometimes you will hear a beep. When you hear the beep I want you to ignore it." The total time to complete the three experimental conditions and two control conditions was 22 minutes.

RESULTS

Data Screening

Power Analysis. GPower software version 3.0.5 (Faul, Erdfelder, Lang, & Buchner, 2007) was used a priori to determine the needed sample size for omnibus tests as recommended by Cohen (1992). An average effect size (ES) of 1.04 was calculated from three studies providing actigraph means and standard deviations for children with ADHD and typically developing (TD) children during laboratory tasks (Dane, Schachar, & Tannock, 2000; Halperin et al., 1992; Rapport et al., 2008). GPower software version

3.0.5 (Faul et al., 2007) was used to determine the needed sample size using this ES, with power set to .80 as recommended by Cohen (1992). For an ES of 1.04, $\alpha = .05$, power $(1 - \beta) = .80$, two groups, and five conditions (C1, no-tone, ignore-tone, stop-signal, C2 as described below), 20 total subjects are needed for a mixed-model analysis of variance (ANOVA) to reliably detect between-group and within-group effects and reliably reject H_0. The power analysis was completed a second time with an effect size of .69 that was calculated from a previous study's interaction effect of group (ADHD, TD) by condition (control, experimental conditions) on activity (Rapport et al., 2008). With power set to .80 as recommended by Cohen (1992), $\alpha = .05$, power $(1 - \beta) = .80$, two groups, and five conditions, 22 total participants are needed for a mixed-model ANOVA to detect an interaction effect and reliably reject H_0. A less conservative estimate that assumes at least moderate correlations between the conditions suggests 12 total participants are needed to reliably reject H_0. Twenty-two children participated in the current study.

Outliers. The dependent variable for each task was screened for univariate outliers, defined as scores of greater than three standard deviations above or below the group mean. This procedure resulted in no outliers.

Preliminary Analyses. Demographic data are shown in Table 1. Sample race consisted of 20 Caucasians (90.9%) and 2 African Americans (9.1%). All parent and teacher behavior ratings scale scores were significantly higher for the ADHD group relative to the TD group (see Table 1). Children with ADHD and typically developing children did not differ on age, $F(1, 20) = 1.98$, $p = .18$, or measured intelligence based on WISC-III or WISC-IV Full Scale Scores (Wechsler, 1991, 2003), $F(1, 20) = 2.09$, $p = .16$. A univariate ANOVA revealed that families of children with ADHD had lower average Hollingshead (1975) socioeconomic status (SES) scores than TD children, $F(1, 20) = 7.49$, $p = .01$, so all analyses below were run with and without SES as a covariate. Inclusion of SES as a covariate, however, did not change the results. We, therefore, report simple model results with no covariates. Means, standard deviations, and between-group contrasts are presented in Table 2.

Behavioral Inhibitory Performance

Averaged across children, the mean probability of successful inhibition was 45% (ADHD 41%, TD 50%), which indicates the tracking algorithm successfully resulted in inhibition on approximately half of the stop trials (Bedard, Ickowicz, Logan, Hogg-Johnson, Schachar, & Tannock, 2003; Ridderinkhof, Band, & Logan, 1999). In addition, children with ADHD exhibited slower stop-signal reaction times during the standard stop-signal condition, suggesting a significant inhibition deficit relative to children in the typically developing group, $t(20) = -3.747$, $p < .001$.[2]

[2]Consistent with findings from previous meta-analytic reviews (Alderson et al., 2007; Lijffijt, Kenemans, Verbaten, & van Engeland, 2005), children with ADHD were previously reported to exhibit significantly slower and more variable reaction times during go trials. In addition, children exhibited slower go-trial reaction times during the stop-signal task, relative to the no-tone and ignore-tone conditions (Alderson, Rapport, Sarver, & Kofler, 2008).

Table 1 Sample and Demographic Variables.

	ADHD		Typically Developing		
Variable	*M*	*SD*	*M*	*SD*	*F*
Age	8.64	1.29	9.45	1.44	1.98
FSIQ	101.98	15.93	110.18	13.11	2.09
SES	42.36	12.21	54.41	7.99	7.49*
CBCL					
Attention Problems	79.55	10.37	55.64	7.06	39.97***
TRF					
Attention Problems	65.91	8.96	53.90	5.88	12.89**
CSI-Parent					
ADHD-Combined	78.82	9.87	48.82	11.38	43.63***
CSI-Teacher					
ADHD-Combined	65.45	9.40	49.50	9.57	14.84***

Note. CBCL = Child Behavior Checklist; CSI = Child Symptom Inventory – symptom severity *T*-scores; FSIQ = Full Scale Intelligence; SES = Socioeconomic Status; TD = Typically Developing Children; TRF = Teacher Report Form.
* $p \leq .05$. ** $p \leq .01$. *** $p \leq .001$.

Effects of Inhibition Demands on Activity Level. A group (ADHD, TD) by condition (C1, no-tone, ignore-tone, stop-signal, C2) mixed-model ANOVA on activity level revealed significant main effects for condition, $F(4, 80) = 67.40$, $p < .001$, and group, $F(1, 20) = 9.34$, $p = .006$. The group-by-condition interaction was not significant, $F(1, 20) = 2.36$, $p = .06$. Least Significant Difference (LSD) post hoc analyses indicated that children exhibited significantly more activity during the experimental conditions (no-tone, ignore-tone, and stop-signal) relative to both control conditions (all $p < .01$); however, activity level was not significantly different across experimental conditions (all $p > .139$). Activity during C2 was significantly greater than activity exhibited during C1 ($p < .01$). Computation of Hedges' *g* indicated that the average magnitude difference between children with ADHD and TD children was 1.08 standard deviation units (range: 0.81 to 1.35), while the average magnitude of activity differences between the control (C1 and C2) and experimental conditions (no-tone, ignore-tone, and stop-signal) revealed exceptionally large magnitude effect sizes that ranged between 2.60 and 3.69. Activity differences between the choice-reaction time and Stop-Signal condition revealed exceptionally small effect sizes (effect sizes = 0.11 to 0.27).

The omnibus mixed-model ANOVA was repeated with only the three experimental conditions (no-tone, ignore-tone, stop-signal) to determine if the trending interaction ($p = .06$) reflected activity changes due to inhibition demands. There was a significant main effect for group, $F(1, 20) = 7.61$, $p = .012$. The main effects for condition, $F(1, 20) = 0.94$, $p = .40$, and for the group-by-condition interaction, however, were not significant, $F(1, 20) = 0.30$, $p = .74$.

Finally, two planned comparison repeated-measures ANOVAs were conducted to further examine the effect of condition on each group independently. The pattern of results was consistent with the overall mixed-model ANOVA and the lack of a significant group-by-condition interaction. Both groups evidenced a stable pattern of activity level during the experimental conditions (no-tone, ignore-tone, and stop-signal; all $p > .05$) that

Table 2 Control, Choice-Reaction Tasks, and Inhibition Conditions Activity-Level Analyses.

	Condition								
	C1	NT	IT	SS	C2				
	M (*SD*)	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)	*F*	*p*	Partial Eta-Squared	Condition Contrasts
ADHD	4751.72 (2579.96)	34056.18 (14446.40)	29808.42 (13370.59)	32024.67 (12927.66)	5962.97 (2917.42)	35.37	<.001	.780	C1 < C2 < NT = IT = SS
TD	1753.95 (818.45)	21984.52 (8502.02)	20500.94 (7140.33)	19645.31 (8982.33)	2798.28 (1253.94)	33.89	<.001	.772	C1 < C2 < NT = IT = SS
Mixed-Model ANOVA with Control and Experimental Conditions									
Between-Group						9.34	.006	.318	
Within-Group						67.40	<.001	.771	C1 < C2 < NT = IT = SS
Interaction						2.36	.061	.105	
Mixed-Model ANOVA with Only Experimental Conditions									
Between-Group						7.61	.012	.276	
Within-Group						0.94	.40	.045	NT = IT = SS
Interaction						0.30	.74	.015	

Note. Actigraph Proportional Integrating Measure (PIM) values can range from 0 (no movement) to 65,535; C1=control condition (pre); C2=control condition (post); NT=no tone; IT=ignore tone; SS=stop signal; ADHD=attention deficit/hyperactivity disorder; TD=typically developing children.

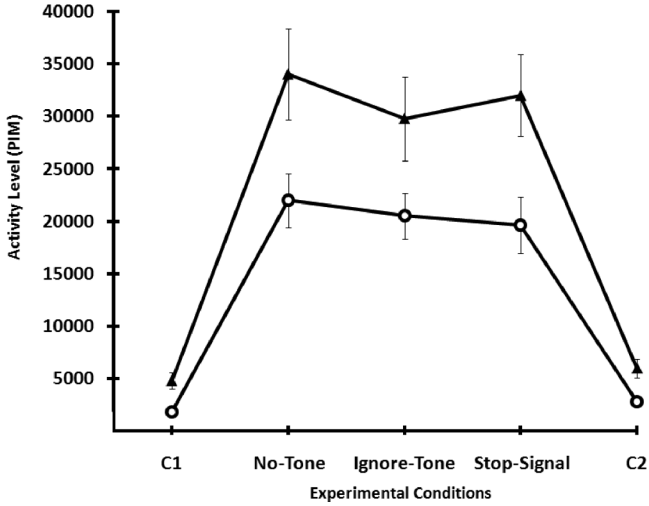

Figure 1 Total extremity activity level (summed across right foot, left foot, and nondominant hand) expressed in Proportional Integrated Measure (PIM) units for children with ADHD (triangles) and typically developing children (circles) under control (C1, C2) and experimental (no-tone, ignore-tone, stop-signal) conditions. Vertical bars represent standard error.

was significantly greater relative to both control conditions (C1, C2; all $p < .01$). Results are depicted in Table 2 and Figure 1.

Activity Level During the Control Conditions. Latent variable analyses were used to assess the extent to which observed group differences in activity level during the two control conditions (C1, C2) represent ADHD-related activity that occurs independent of task demands (Halperin et al., 2008; Porrino et al., 1983), or the influence of attentional demands associated with the paint program (Rapport et al., 2009). Residual scores were computed for both control tasks by regressing the no-tone condition onto C1 ($R^2 = .31$) and C2 (R^2=.32) activity level to remove variance associated with basic attentional processes associated with choice-reaction time tasks. A 2 (group) by 2 (condition: C1, C2) mixed-model ANOVA was significant for condition ($p < .001$) but nonsignificant for the main effect of group or the group-by-condition interaction (all $p > .05$). These findings indicate that children with ADHD were not hyperactive relative to typically developing children during the control conditions after accounting for attentional processes associated with the choice-reaction time task.

DISCUSSION

Inhibition models of ADHD hypothesize that excessive motor activity occurs when children are unable to delay gratification or to withhold a response in the presence of a prepotent stimulus (Barkley, 1997; Sonuga-Barke, 2003). These models imply that hyperactivity in children with ADHD occurs independent of changing environmental or cognitive demands (Porrino et al., 1983), given the low threshold by which stimuli become prepotent (i.e., any stimulus that has previously elicited a response that was followed by reinforcement; Morein-Zamir, Hommersen, Johnston, & Kingstone, 2008) and the consequent high prevalence of prepotent stimuli that pervade daily life. To date, only a few studies have attempted to quantify the relationship between inhibitory processes and children's activity, primarily by examining the degree to which activity scores based on retrospective observations correlate with behavioral inhibition measures (Kuntsi et al., 2001; Nigg, 1999; Solanto et al., 2001). In contrast, the current study was the first to experimentally manipulate demands placed on the limited-resource inhibition system to determine whether motor activity is functionally related to deficient inhibition. Children with ADHD and typically developing children were expected to exhibit increased activity during the stop-signal task relative to control and choice-reaction time conditions due to fewer available inhibitory resources concurrently allocated to complete the stop-signal task (Boehler, Tsotsos, Schoenfeld, Heinze, & Hopf, 2009; Logan & Cowan, 1984).

Collectively, both groups of children (ADHD, TD) exhibited significantly more activity during experimental conditions (no-tone, ignore-tone, and stop-signal) relative to control conditions (paint program), and activity level remained stable across experimental conditions. In addition, children with ADHD were more active than typically developing children across all experimental conditions. The increase in activity from the control (paint program) to the choice-reaction time conditions (no-tone and ignore-tone) for all children may reflect increased demands placed on controlled attentional processes associated with the central executive component of working memory (Chen & Cowan, 2009; Schmiedek et al., 2007). This interpretation is consistent with recent evidence that the central executive may fully account for increased motor activity in children with ADHD (Rapport et al., 2009). The significant between-group effects are also consistent with Rapport and colleagues' (2008) working memory model of ADHD and suggest that the relatively minimal central executive demands associated with monitoring stimuli and making a two-choice response (Chen & Cowan, 2009) appear sufficient to produce large-magnitude between-group differences in children's activity level. These interpretations are tentative, however, and suggest the need for further investigation, particularly since the current study did not directly examine working memory.

Although activity during the inhibition condition (stop-signal) was significantly greater relative to both control conditions, it was not significantly different from activity observed during the no-tone and ignore-tone conditions. This finding was consistent across groups: Increasing inhibitory demands did not produce higher rates of motor activity and did not differentially affect children with ADHD relative to typically developing children. At least two explanations may account for this finding. First, the stop-signal paradigm may place insufficient demands on the inhibition system to elicit a significant increase in activity above and beyond attentional demands alone, whereas other measures of inhibition may have resulted in a stronger effect. The stop-signal task, however, is one of the most widely used laboratory measures of behavioral inhibition (Lijffijt, Kenemans, Verbaten, & Engeland, 2005), and studies of the stop-signal task reliably report between-group effect sizes that are as large as or larger than those obtained from other inhibition and executive function tasks (Willcutt, Doyle, Nigg, Faraone, & Pennington, 2005). An alternate explanation is that the large magnitude between-group (ADHD, TD) performance differences observed in previous studies of the stop-signal task do not reflect behavioral inhibition differences, and that the increased motor activity observed in the current study is due primarily to increased demands placed on attentional processes associated with choice-reaction time tasks. This explanation is supported by previous meta-analytic (Alderson et al., 2007; Lijffijt et al., 2005) and experimental (Alderson et al., 2008) studies, which concluded that ADHD-related impairments on the stop-signal task's primary dependent variable (stop-signal reaction time) are predominantly due to basic cognitive processing impairments rather than behavioral inhibition deficits. In addition, a more recent study found that performance on the stop-signal task was fully mediated by central executive processes (Alderson, Rapport, Hudec, Sarver, & Kofler, 2010), and previous studies have demonstrated a significant relationship between memory span and inhibitory processes, such as susceptibility to interference (Kane & Engle, 2000) and prepotent inhibition (Friedman & Miyake, 2004). Collectively, current and past findings raise questions about the role of behavioral inhibition in producing ADHD behavioral symptoms and appear to be converging around the conclusion that inhibitory processes may be intact in children with ADHD.

Although the current findings appear at odds with previous correlational studies that find a significant association between parent/teacher ratings of activity and performance on inhibition tasks (Kuntsi et al., 2001; Nigg, 1999; Solanto et al., 2001), consideration of theoretically discreet cognitive processes needed to initiate and withhold/stop a behavior may provide clarity. An isolated comparison of motor activity during the current study's stop-signal and control conditions — a methodological approach analogous to that used in previous studies (e.g., Nigg et al., 2002) — would have inaccurately suggested that inhibition demands are associated with significant increases in activity level. Interpretation of the current findings, however, diverge from previous studies due to the inclusion of no-tone and ignore-tone conditions that allowed for comparison of variability associated with go (choice reaction-time task) processes independently from the stop-signal task. In addition, previous studies relied primarily on retrospective parent/teacher ratings of hyperactivity (rather than actigraphs) and thus compared behavioral inhibition performance and subjective ADHD symptoms over nonoverlapping time periods (Kuntsi et al., 2001; Nigg, 1999; Solanto et al., 2001). These correlational studies can conclude only that children who perform worse on behavioral inhibition tasks also tend to have more ADHD symptoms but cannot inform the directionality of this relationship or rule out third-variable explanations such as those found by Alderson and colleagues (2010).

Although not the focus of the current study, a few additional findings are worth noting. The ignore-tone condition was included to control for potential increases in activity that may result from additional processing demands associated with hearing the intermittent stop tone. Stimuli that momentarily capture the attention of a participant (i.e., singleton distracters) often exert increased demands on attentional processing and a slowing effect on reaction time (Dalton & Lavie, 2004), even when the distracter is minimally associated with the task or target stimulus (Mason, Humphreys, & Kent, 2004, 2005). The nonsignificant difference in activity level between the no-tone and ignore-tone conditions in the current study, however, is consistent with a previous study that found the reaction times of children with ADHD and typically developing children were unaffected by the introduction of a meaningless intermittent tone (Alderson et al., 2008).

Finally, our initial finding that children with ADHD were more active than typically developing children during the control conditions appears consistent with extant models that imply excessive motor activity in children with ADHD is not functionally related to changes in environmental, academic, or cognitive demands (Porrino et al., 1983). Previous studies using these tasks, however, revealed that these conditions required a modest level of attentional demands, and that activity level was no longer significantly different between the two groups after controlling for basic controlled attentional processes attributed to the central executive component of working memory (Rapport et al., 2009). This conclusion is consistent with previous studies indicating that hyperactivity reflects a secondary outcome of underlying cognitive deficits (Rapport et al., 2009) such as central executive-mediated attentional processes (Alderson et al., 2010).

The current study's unique contribution was the objective measurement of activity level while concurrently manipulating inhibitory demands. Several caveats merit consideration despite this methodological refinement. Several children with ADHD also met diagnostic criteria for ODD. The frequency of comorbidity in the current study, however, is similar to the rate reported commonly in recent epidemiological studies (i.e., 59 %; Wilens et al., 2002), and a recent meta-analytic review revealed that CD/ODD comorbidity did not significantly moderate ADHD children's performance on children's stop-signal task performance (Lijffijt et al., 2005). In addition, the current sample only included male children. Further research is needed to determine whether these findings generalize to females, particularly since females experience less severe executive function deficits relative to boys (Seidman et al., 1997) and are more likely to exhibit attention difficulties in the absence of hyperactivity-impulsivity symptoms (Abikoff et al., 2002; Biederman & Faraone, 2004; Graetz, Sawyer, & Baghurst, 2005). Although the no-tone and ignore-tone conditions were counterbalanced across the first two testing days, the stop-signal condition was always presented on the third day to assure that children were not exposed to meaningful stop-signals prior to administration of the no-tone and ignore-tone conditions. Consequently, the possibility of an order effect cannot be entirely eliminated but is unlikely given that the current findings differ from those expected if order effects are influencing the results (i.e., children are expected to exhibit increased restlessness and activity with each task in a series; Llorente, Sines, Rozelle, Turcich, & Casatta, 2000). In addition, we acknowledge that the current findings may not generalize to other measures of inhibition such as Continuous Performance Tasks (CPT), Go/No-Go tasks, or measures of cognitive inhibition (e.g., Stroop). Our expectation of divergent findings with other inhibition measures is relatively low, however, given the high similarity in task parameters/design (Nigg, 2001), robust correlation amongst inhibition measures (Epstein, Johnson, Varia, & Conners, 2001), emerging evidence that working memory deficits underlie ADHD-related hyperactivity (Rapport et al., 2009), and previous evidence that working memory fully mediates inhibition performance (Alderson et al., 2010).

Finally, generalization of findings from highly controlled laboratory-based experimental investigations to the larger population of children with ADHD is always limited to some extent, and studies with relatively small sample sizes are vulnerable to Type II errors. Our cell sizes were nevertheless sufficient based on the a priori power analysis. Further, examination of activity differences between the control conditions and experimental conditions (no-tone, ignore-tone and stop-signal) revealed exceptionally large magnitude effect sizes that ranged between 2.60 and 3.69, while activity differences between the choice-reaction time and stop-signal conditions revealed small, nonsignificant effect sizes (effect sizes = 0.11 to 0.27). That is, increased power with a larger sample may, at best, suggest that inhibitory processes only contribute to a small portion of between-group activity, relative to the contribution of basic attentional processes.

The current findings add to emerging evidence from meta-analytic (Alderson et al., 2007; Lijffijt et al., 2005), experimental (Alderson et al., 2008), and mediation (Alderson et al., 2010) studies that raise important questions about the central role of behavioral inhibition in extant models of ADHD (Barkley, 1997; Sonuga-Barke, 2003). Further, we believe that these findings are consistent with models proposing controlled-focused attention associated with the central executive, as a core feature of ADHD that is functionally related to the excessive motor activity characteristic of these children (Rapport et al., 2008). Additional research is needed, however, to explicate whether these findings are specific to the stop-signal task or to behavioral inhibition more generally. Finally, these findings have potentially important clinical implications, and may help explain the disparity between strong-immediate treatment effects and poor long-term outcomes when behavioral therapies target symptoms related to impulsivity/behavioral inhibition deficits (Rapport et al., 2001).

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