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ADHD and hyperactivity: The influence of cognitive processing demands on gross motor activity level in children

Tycho J. Dekkers[a,b,c,d], Mark D. Rapport[a], Catrina A. Calub[a], Samuel J. Eckrich[a] and Carolina Irurita[a]

[a]Department of Psychology, University of Central Florida, Orlando, FL, USA; [b]Department of Psychology, University of Amsterdam, Amsterdam, The Netherlands; [c]Academic Center for Child and Adolescent Psychiatry, de Bascule, Amsterdam, The Netherlands; [d]Department of Child and Adolescent Psychiatry, Free University Medical Center, Amsterdam UMC, Amsterdam, The Netherlands

ABSTRACT

Excessive gross motor activity is a prominent feature of children with ADHD, and accruing evidence indicates that their gross motor activity is significantly higher in situations associated with high relative to low working memory processing demands. It remains unknown, however, whether children's gross motor activity rises to an absolute level or accelerates incrementally as a function of increasingly more difficult cognitive processing demands imposed on the limited capacity working memory (WM) system – a question of both theoretical and applied significance. The present investigation examined the activity level of 8- to 12-year-old children with ADHD (n = 36) and Typically Developing (TD) children (n = 24) during multiple experimental conditions: a control condition with no storage and negligible WM processing demands; a short-term memory (STM) storage condition; and a sequence of WM conditions that required both STM and incrementally more difficult higher-order cognitive processing. Relative to the control condition, all children, regardless of diagnostic status, exhibited higher levels of gross motor activity while engaged in WM tasks that required STM alone and STM combined with upper level cognitive processing demands, and children with ADHD were motorically more active under all WM conditions relative to TD children. The increase in activity as a consequence of cognitive demand was similar for all experimental conditions. Findings suggest that upregulation of physical movement rises and remains relatively stable to promote arousal related mechanisms when engaged in cognitive activities involving WM for all children, and to a greater extent for children with ADHD.

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Attention-Deficit/Hyperactivity Disorder (ADHD) is a neurodevelopmental disorder characterized by clinically impairing levels of inattention, hyperactivity and impulsivity that adversely affect behavioral and cognitive functioning across multiple settings (American Psychiatric Association, 2013). Approximately 5–7% of children meet diagnostic criteria for the disorder (Thomas et al., 2015; Willcutt, 2012).

CONTACT Mark D. Rapport mdrapport@gmail.com Department of Psychology, University of Central Florida, Orlando, FL 32816, USA

The excessive gross motor activity associated with ADHD has been considered a hallmark of the disorder since its initial description by the German psychiatrist Heinrich Hoffman (Hoffmann, 1844), and immortalized as a central feature following the introduction of *Hyperkinetic Reaction of Childhood* to the Diagnostic and Statistical Manual of Mental Disorders in 1968 (American Psychiatric Association, 1968). Despite changes in the moniker over the past 50 years, gross motor activity remains a central feature of ADHD. Ironically, higher levels of gross motor activity are associated with desirable attributes such as positive social interactions, mental and motor maturity, and inquisitiveness in very young children (cf. Rapport et al., 2006, for a review). The persistence of high gross motor activity beyond age four, however, significantly increases the risk for ADHD by age 9 (Campbell & Ewing, 1990), portends multiple negative outcomes throughout childhood (DeAlwis et al., 2014; Hinshaw, 2002; Keown & Woodward, 2006), and is predictive of significant impairment in adulthood (Barkley et al., 2006; Erskine et al., 2016).

Earlier theoretical accounts considered hyperactivity a ubiquitous phenotypic trait unaffected by contextual factors (e.g. Porrino et al., 1983; Teicher et al., 1996), and some contemporary models continue to view excessive gross motor activity as an omnipresent feature of ADHD (Barkley, 2015; Halperin et al., 2012). The use of actigraphs and other mechanical measures to objectively quantify the excessive gross motor activity exhibited by children with ADHD over the past two decades, however, has challenged this long-standing view and identified environmental (e.g. low vs high stimulation settings), methodological (rigor of diagnostic criteria employed), and demographic (e.g. research clinic vs school or home) factors that systematically influence the extent to which hyperactivity is exhibited (cf. M. J. Kofler et al., 2016, for a meta-analytic review).

A natural extension of this research evolved – explicating the relation between hyperactivity and children's cognitive functioning – based on a growing consensus that key executive functions such as working memory (WM) are deficient in a majority (89%) of children with ADHD (Kofler et al., 2018). Contemporary theoretical models of this phenomenon postulate that increased gross motor activity is exhibited unconsciously in an effort to activate brain-based arousal mechanisms that support the executive/supervisory attentional component of working memory, which is integral for a wide range of goal-directed cognitive activities (M. D. Rapport et al., 2018). For example, controlled experimental investigations using high-precision actigraphs (Alderson et al., 2012; Rapport et al., 2009; Hudec et al., 2015; Orban et al., 2018) and model-derived hypotheses uniformly report three central findings: (a) all children evince higher levels of gross motor activity when engaged in tasks that involve high relative to minimal cognitive demand (Hudec et al., 2015; Kofler et al., 2016); (b) children with ADHD exhibit substantially higher rates of gross motor activity relative to typically developing (TD) children under cognitively demanding conditions (Orban et al., 2018; Sarver et al., 2015); and (c) the activity level of children with ADHD and TD children remains relatively stable when completing WM tasks with unchanging processing demands but varying cognitive loads (e.g. number of stimuli to be processed).

Despite the valuable contribution of these investigations, an enigma remains whether children's gross motor activity increases and remains relatively stable when required to simply attend to and hold a limited amount of information (i.e. cognitive load) in short-term memory (STM), which could be described as an *all-or-nothing* explanation, or increases incrementally when upper level cognitive processing demands such as updating, re-ordering, or dual processing/manipulation are required to act on or transform stimuli held in STM in the service of problem solving[1] (i.e. *incremental threshold* explanation).

Only one study to date has experimentally manipulated cognitive processing demands while concomitantly measuring actigraph recorded gross motor activity in children with ADHD and TD children (Hudec et al., 2015). The authors replicated findings of previous investigations – children with ADHD evidenced disproportionately higher levels of movement relative to TD children under low and high cognitive task demand conditions – and extended those findings by demonstrating that both groups of children exhibited significantly higher levels of gross motor activity under high relative to low cognitive processing demand conditions. A subsequent meta-analytic review examined the extent to which differences in task-related processing demands affect movement based on 53 studies of mechanically measured gross motor activity in children with ADHD relative to TD children (Kofler et al., 2016). In contrast to the Hudec et al. (2015) study, low cognitive demand was operationalized as involving activities such as painting, free play and television watching. Overall, larger between-group effect sizes (ES) were reported for activities associated with high relative to low processing demands.

Collectively, the lone experimental investigation and recent meta-analytic review provide preliminary evidence that movement in all children may escalate as a function of increasing cognitive processing demands, and disproportionately so in children with ADHD. This evidence, however, must be viewed tentatively due to the potential contribution of uncontrolled variables in both studies. For example, Hudec et al. (2015) examined activity level differences while children completed two reaction time tasks and two n-back tasks (1-back, 2-back)[2]. The proposition that n-back tasks require higher cognitive processing demands relative to basic reaction time tasks is well documented, as is the notion that n-back tasks are more difficult than basic reaction time tasks. Increasing cognitive load within an n-back task, however, relies primarily on the identical upper level cognitive process (viz., memory updating), leaving open the question as to whether activity level differs with the imposition of different and/or multiple upper level processing demands (e.g. tasks that require dual processing or both updating and reordering). The meta-analysis by Kofler et al. (2016) was similarly disadvantaged due to the categorical approach used for assigning tasks – including tasks known to rely on WM or other types of executive functions (e.g. behavioral inhibition) into a single category – and potentially obfuscates the extent to which specific upper level cognitive processes influence children's gross motor activity.

Finally, neither the Hudec et al. (2015) study nor the Kofler et al. (2016) meta-analysis controlled for preexisting between-group differences in children's WM capacity. Consequently, it is not possible to discern the extent to which changes in activity level under the different processing demand conditions occur as a function of the imposed cognitive processing demands or because the number of stimuli (cognitive load) used in particular tasks exceed the WM capacity of some (particularly ADHD) children.

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[1] STM and upper level cognitive processing both involve *effortful attention* – a term used to denote an individual's voluntary/purposeful control over thoughts and emotions.

[2] An n-back task requires participants to identify an identical stimulus that preceded the current stimulus by "n" presentations (e.g. a, d, x, z, x represents a 2-back with x as the designated target).

The present investigation is the first to examine whether activity level changes in children with ADHD and TD children occur as a function of differences in cognitive processing demands while controlling for preexisting differences in their WM capacity (i.e. scope and control of attention). Increased understanding of this phenomenon is expected to have both theoretical and applied significance by helping to explicate the mechanisms and processes by which activity level and complex cognition interact, and by informing the design of behavior management accommodations for classroom settings.

The primary hypothesis of the current study involved the juxtaposition of the two most likely outcomes to occur in children's gross motor activity associated with increasing cognitive processing demands. An immediate increase from the baseline/control condition and incremental changes in gross motor activity corresponding to increases in cognitive processing demands are predicted by the *incremental threshold* explanation and would be characterized by a significant linear trend, whereas an immediate increase from baseline/control conditions and stabilization in gross motor activity across the increasingly difficult cognitive processing demand conditions are predicted by the *all-or-nothing* explanation and would be characterized by a quadratic trend (i.e. a single, significant change in slope and intercept). Finally, children's performance on the tasks (i.e. task accuracy) served to provide evidence concerning the internal validity of the experimental manipulation of cognitive processing demands, and was expected to worsen as a function of imposing increasingly more difficult processing demands across experimental conditions (Rapport et al., 2008, 2009; Dovis et al., 2013), and correlate weakly or non-significantly with activity level.[3]

Methods[4]

Participants

The sample consisted of 60 children (8–12 years, 92% boys) recruited by or referred to a university-based child study clinic through community resources. The ethnicity of the sample was representative of the surrounding metropolitan community and included 45 Caucasian non-Hispanic (75.0%), 9 Hispanic English speaking (15.0%), 4 bi- or multiracial (6.7%) and 2 African American (3.3%) children. Parents and children provided written consent/assent, respectively, and university Institutional Review Board approval was obtained prior to the study's onset.

Two groups participated in the study, children with ADHD (combined presentation) and typically developing (TD) children without ADHD. Children with a history of (a) gross neurological, sensory, or motor impairment, (b) parent-reported seizure disorder, (c) psychosis, or (d) Full Scale IQ score below 85 or above 120 were excluded.

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[3] Increased movement was not expected to correlate positively with task performance in children with ADHD as reported in past studies – the imposition of increasingly more difficult task processing demands was expected to diminish all children's performance.

[4] Several participants in the current study participated in two conceptually unrelated studies that examined the relative contribution of WM CE abilities to (a) general intellectual functioning (Calub et al., 2019), and (b) written expression deficits (Eckrich et al., 2019) in children with ADHD as part of a planned series of on-going investigations that are deemed completed when the n surpasses an *a priori* power analysis threshold.

Group assignment

All children and their parents participated in a semi-structured clinical interview using all modules of the Kiddie Schedule for Affective Disorders and Schizophrenia for School-Aged Children (K-SADS; Kaufman et al., 2016), which assesses onset, course, duration, severity, and impairment of current and past episodes of psychopathology based on DSM-5 criteria. Its psychometric properties are well established (Kaufman et al., 2016).

Thirty-six children meeting the following criteria were included in the ADHD group: (1) an independent diagnosis by the directing clinical psychologist using DSM-5 criteria for ADHD-combined presentation based on K-SADS interview with parent and child; (2) parent ratings of at least 2 standard deviations above the mean on the Attention-Deficit /Hyperactivity Problems DSM-Oriented scale of the Child Behavior Checklist (CBCL; Achenbach & Rescorla, 2001), or exceeding the criterion score for the parent version of the ADHD-combined presentation subscale of the Child Symptom Inventory (CSI-P; Gadow et al., 2004); and (3) teacher ratings of at least 2 standard deviations above the mean on the Attention-Deficit/Hyperactivity Problems DSM-Oriented scale of the Teacher Report Form (TRF; Achenbach & Rescorla, 2001), or exceeding the criterion score for the teacher version of the ADHD-combined subtype subscale of the Child Symptom Inventory (CSI-T; Gadow et al., 2004). The psychometric properties of the CBCL, TRF and CSI are well established (Achenbach & Rescorla, 2001; Gadow et al., 2004).

Twenty-four children met the following criteria and were included in the TD control group: (1) no evidence of any clinical disorder based on parent and child K-SADS interview; (2) normal developmental history by parental report; (3) ratings within 1.5 standard deviations of the mean on all CBCL and TRF scales; and (4) parent and teacher ratings within the nonclinical range on the CSI ADHD-combined subscale.

Measures

Intelligence and socioeconomic status

Children were administered the full WISC-IV or WISC-V to obtain an overall estimate of intellectual functioning based on each child's estimated Full-Scale IQ (FSIQ; Wechsler, 2003, 2014). The changeover to the fifth edition was due to its release during the course of the study and to provide parents with an up-to-date intellectual evaluation. The Hollingshead Four Factor Index of Social Status (Hollingshead, 1975) was used to estimate socioeconomic status (SES) based on parental education, occupation, age, and marital status, and its psychometric properties compare favorably to more recent measures of SES (Cirino et al., 2002).

Gross motor activity (actigraph)

MicroMini Motionlogger® (Ambulatory Monitoring, 2004) actigraphs were used to measure children's activity level. The acceleration-sensitive device resembles a plastic wristwatch and was set to Proportional Integrating Measure mode, which measures the intensity of movement (i.e. quantifies gross activity level). Movement was sampled 16 times per second (16 Hz) and collapsed (average count per minute) into 1-minute epochs, which in turn, was averaged across the total minutes for each task. Data were analyzed using the Action-W2 software program (Ambulatory Monitoring, 2004) to calculate mean activity rates for each child. Children were told that the actigraphs were "special watches" that let them play the learning games. The Observer (Noldus Information Technology, 2011) 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 using velcro attachment bands. Ankle placement was used *in lieu* of trunk placement due to the improved sensitivity of the former for detecting movement (Eaton et al., 1996). A third actigraph was placed on children's non-dominant wrist, because the tasks required movement using the dominant hand. The sum of the three actigraphs (i.e. TES: total extremity score) was used to measure gross motor activity and served as a primary dependent variable.

Operation span task (OST)

The OST is a complex span task used conventionally in cognitive science to estimate WM capacity in children (Shipstead et al., 2015). Complex span tasks rely on two interrelated and complementary mechanisms – the maintenance capacity of focused attention and the ability to select and stabilize relevant information in focal attention for further processing – referred to as the scope and control of attention, respectively (Cowan et al., 2006; Redick et al., 2012; Shipstead et al., 2015). The common feature of complex span tasks involves holding a given number of stimuli in short-term memory (words, numbers, dots) while performing an unrelated cognitive task that interferes with the maintenance of these stimuli. Complex span tasks are assumed to put a heavy burden on domain-general controlled processing (Engle, 2002; Engle & Kane, 2004; Redick et al., 2012) The present version was based on the *Ospan* task developed by Turner and Engle (1989). Each trial of the OST required children to (a) read aloud a simple math problem (e.g. '4 + 2 = 5′) centered on a computer monitor; (b) press a "Y" or "N" key to indicate whether the math statement is correct; and (c) read aloud an easily recognized word that appeared in the center of the monitor. Four trials containing a fixed number of math problem-word presentations (set sizes 3, 4, or 5) separated by a 1-s interval were presented for each of the set size conditions following the procedures detailed below. Children were instructed to recall each of the words that followed the math statements in the order they occurred at the conclusion of each of the four trials.

OST trials were presented initially using a four-item set of math problem-word presentations based on the mean expected WM capacity of typically developing children between 8 and 12 years of age (Cowan, 2010; Wechsler, 2014). If a child answered fewer than two of the four sets correctly (<50% trials correct), a three-math problem/word presentation set size was administered (i.e. a lower set size was administered). Conversely, if a child correctly recalled four of the four problem sets correctly (100% trials correct), an OST consisting of 5 math problem/word presentations was administered (i.e. a higher set size was administered).[5] Finally, children answered three orally presented simple math problems using digits not included in any of the OST trials (e.g. 'how much is 10 plus 10′, without regard for accuracy) between each of the four trials

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[5] Note: all children were able to achieve 50% or more on the set size 3 OST; no child correctly recalled 100% of the words in the 5 math problem/word list trial which rendered the creation of a 6 word list trial unnecessary.

within a given set size condition as well as between different set size conditions to decrease the likelihood of digit related proactive interference.[6]

The WM capacity of each child was established based on cognitive literature and defined as the highest number of stimuli (words) that could be recalled correctly on at least 50% of the trials at a given set size (Conway et al., 2005).

Experimental tasks

The short-term memory task and working memory tasks (see Figure 1) in the present study are similar to the Digit Span Forward and Letter-Number Sequencing subtests on the WISC-V, and assess the short-term memory (STM) phonological maintenance component alone and in conjunction with upper level cognitive processes (e.g. serial reordering, manipulation, updating) respectively. In each task, children listen to a computer-generated series of numbers and a letter that occur 0.5-s apart. The letter is counterbalanced across trials to appear an equal number of times in other serial positions and never appears in the first or last position of the sequence to minimize potential primacy and recency effects. Each task contains 24 unique trials using the set size determined by the complex span task (OST) described previously and administration of the four experimental conditions was counterbalanced across the four testing sessions to control for order effects (Conway et al., 2005). The maximum task duration for each of the four experimental tasks was 12-m; children were allowed a maximum of 30-s to respond following the presentation of stimuli during each trial. Two trained research assistants, shielded from the participant's view, listened to the vocalizations through headphones in an adjoining room and independently recorded oral responses (interrater

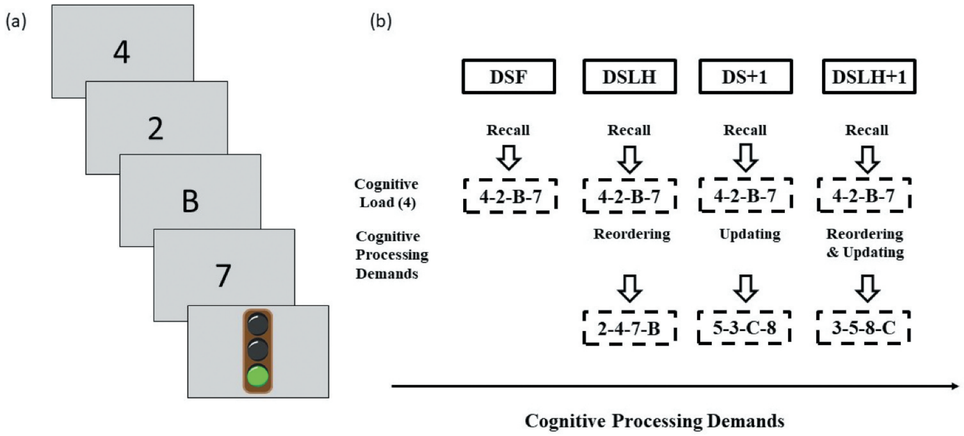

Figure 1. Example of stimuli presented in experimental tasks (a); and correct responses (dash line boxes) for each of the experimental tasks [DSF = digit span forward; DSLH = digit span low to high; DS +1 = digit span +1; DSLH+1 = digit span low to high +1]; with tasks increasing in cognitive processing demands from left to right while keeping cognitive load (i.e. number of stimuli) constant (b).

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[6] Requiring children to engage in brief math problems in-between remembering word sets reduces the potential buildup of proactive interference (i.e. interference by previous stimuli that may impede performance on subsequent trials) by engaging the short-term memory store with an unrelated category of items (Darling & Valentine, 2005; Gardiner et al., 1972).

reliability = 99.4% agreement). The number of stimuli presented to each child differed based on their WM capacity (see OST procedure, above). Consequently, the percentage of stimuli recalled correctly rather than the number of stimuli correct was used as an outcome. All tasks were programmed using SuperLab Pro 2.0 (Cirino et al., 2002).

Short-term memory (STM) task. Children completed a *Digit Span Forward* (DSF) task and were instructed to recall the numbers and single letter in the presented order (e.g. 5-9-B-1, is correctly recalled as 5-9-B-1). This task requires no additional processing of the presented digits – only maintenance of the information in STM until signaled to recall the information. Both groups of children were expected to perform with a high degree of accuracy on the task because the number of stimuli to be recalled was based on their OST performance (see OST, above) – which requires the ability to maintain *and* stabilize relevant information in focal attention for further processing and serves as a more appropriate control for the more cognitively demanding tasks described below.

Working memory central executive (CE) tasks. Three WM tasks were administered that additionally required increasing levels of CE related higher-order processing of the stimuli: the Digit Span Low/High (DSLH) task; the Digit Span Plus 1 (DS+1) task; and the Digit Span Low/High Plus 1 (DSLH+1) task.

For the *Digit Span Low/High* (DSLH) task, children recalled the numbers and the letter aloud in the exact same order in which they are presented initially, and immediately afterward, used a CE serial reordering process to recall the numbers in order from smallest to largest and the letter last (e.g. 7-D-4-2, is correctly recalled as 2-4-7-D).

For the *Digit Span Plus 1* (DS+1) task, children recalled the numbers and the letter in the exact same way in which they are presented initially, and immediately afterward, used a CE updating process to recall the next highest number and ensuing letter appearing in the alphabet (e.g. 2-B-8-4, is correctly recalled as 3-C-9-5).

Finally, for the *Digit Span Low/High Plus 1* (DSLH+1) task, children (a) recalled the numbers and letter aloud in the same order in which they are presented initially; (b) used a CE reordering process to recall the numbers from smallest to largest and the letter last immediately afterward; and (c) used a second CE process (updating) to recall the next highest number and ensuing letter appearing in the alphabet (e.g. 3-2-A-5, is recalled initially as 2-3-5-A using the reordering process, then as 3-4-6-B using the updating process).

The tasks were designed to place incremental demands on children's cognitive processing abilities, ranging from no upper level cognitive processing (i.e. DSF), to a single upper level processing demand (either reordering or updating; DSLH and DS+1, respectively), to dual processing demands involving both reordering and updating (i.e. DSLH +1). The DS+1 task was presumed more difficult than the DSLH task because it requires the digits and letter to be transformed to a different set of digits and letter rather than simply reordering them (note: the validity of this assumption was examined in the preliminary analyses section below).

A partial credit scoring procedure was used to calculate the percent of stimuli correct for each recall trial administered based on extant evidence that it represents a more reliable scoring method relative to using a correct/incorrect trial approach (Conway et al., 2005). Information had to be recalled in the correct order to count as correct (e.g. 7, 3, S, 5 recalled as 7, S, 5 would count as 3 stimuli recalled correctly). The number of correct stimuli on each of the 24 trials for each of the four experimental conditions was calculated and divided by the total number of possible stimuli correct (i.e. out of 24) for a given experimental condition for each child. If a child *incorrectly* recalled the initial presentation of the stimuli but *correctly* processed the incorrectly ordered stimuli, only correct stimuli in the correct order (i.e. partial correct) were counted as correct.

Control Condition Tasks. Children's activity level was assessed via actigraphs while interacting with the Microsoft® Paint program for five minutes at the beginning and end of each day's session. Control conditions were used to estimate children's activity level while engaged in a task with negligible cognitive demands (i.e. the Paint program allows children to draw/paint on the monitor using a variety of interactive tools) and control for potential setting/demand characteristics (i.e. children were situated in the same room, sat in the same chair, and interacted with the same computer used for the cognitive tasks). The four pre- and post-activity level control condition scores were averaged for each child to form a total extremity score (TES) score.[7] These scores were combined subsequently to form TES composite scores for the two groups (ADHD, TD), and used to estimate the extent to which each group's activity level changed relative to the control conditions while completing the four experimental tasks described above.

Procedures

Children completed the Operation Span Task (OST) to establish WM capacity during the first assessment session, and the short-term memory and three CE WM tasks across four assessment sessions (one per week, in counterbalanced order). Children completed all tasks while seated alone, approximately 0.66 m from the monitor, in an assessment room. Performance was monitored at all times by the examiner, who was stationed just outside the child's view to provide a structured setting while minimizing performance improvements associated with examiner demand characteristics (Power, 1992). All children received brief (2–3 min) breaks following each task, longer (10–15 min) breaks after every two to three tasks to minimize fatigue, and small prizes at the conclusion of each session that were non-contingent upon task performance. The total duration of each assessment session was approximately three hours.

Results

Power analysis

A priori power analysis performed using G*Power (Faul et al., 2007) indicated that 46 participants were needed to detect between-subjects effects using a repeated measures ANOVA with 4 task conditions (DSF, DSLH, DS+1, DSLH+1), 2 groups (ADHD, TD) .80 power (1-β), $\alpha = .05$, an estimated effect size of $d = .69$ based on CE/WM differences between children with ADHD and TD children in a recent meta-analysis (Kasper et al.,

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[7] Note: Marginally higher levels of movement occurred at the conclusion relative to the beginning of assessment sessions for both groups (i.e., $F(1,58) = 9.05$, $p = .004$; non-significant group-by-time interaction, $F(1,58) = 2.35$, $p = .13$), but considered non-meaningful based on the significant overlap of 95% confidence intervals (pre-session 5826.16–-27,966.24; post-session 6917.66–29,918.50).

2012), and estimated correlation of $r = .50$ between measures. A smaller sample ($N = 28$) was required for gross motor activity, as the estimated effect size difference between children with ADHD and TD children for activity level during WM tasks is robust, $d = .86$ (Kofler et al., 2016). Similar sample sizes are sufficient for detecting group by cognitive demand interactions on activity level, based on the difference in effect sizes between low and high cognitive demand conditions in the most recent meta-analysis (high cognitive demands: $d = 1.14$, low cognitive demands: $d = 0.36$; Kofler et al., 2016).

Outliers and missing data

DSF task scores for two children were identified as univariate outliers, and replaced by a value that was 1% lower than the lowest value within the group of the particular child (cf. Tabachnik & Fidell, 2007). No univariate outliers were identified for the other tasks or the activity level data. No multivariate outliers were detected.

Actigraph assessed activity level was unavailable for two children for the DSF task, and for one child for the DSLH+1 task, and performance data was unavailable for one child on the DSF task, all due to unexpected technical problems. In these cases, the group mean for the particular group the child was assigned to was used (Tabachnik & Fidell, 2007). Overall, data was missing on 0.67% of the data points.

Preliminary analyses

Demographic analysis

Demographical sample characteristics are depicted in Table 1. Groups did not differ in age, sex distribution, IQ, or socioeconomic status. Scores were significantly higher for children with ADHD relative to TD children on all parent- and teacher-rating scales, as expected (see Table 1). The use of covariates was not warranted in any of the foregoing analyses due to the non-significant between-group differences for age, SES and FSIQ.[8] All independent and dependent variables were screened for multivariate outliers using

Table 1. Sample characteristics.

	ADHD (n = 36)	TD (n = 24)	
Age	9.57 (1.40)	9.77 (1.25)	$t(58) = .56$, n.s.
Sex (% boys)	92%	92%	$\chi^2(1) = .00$, n.s.
FSIQ	104.89 (10.41)	108.25 (11.86)	$t(58) = 1.16$, n.s.
SES	50.63 (9.50)	54.15 (9.02)	$t(58) = 1.43$, n.s.
CBCL Attention problems	71.89 (6.01)	50.91 (4.62)	$t(56.7) = -13.85$***
TRF Attention problems	67.81 (6.49)	50.91 (1.90)	$t(44.1) = -14.62$***
CSI-parent ADHD, combined	77.83 (8.69)	47.13 (6.48)	$t(57) = -12.88$***
CSI-teacher ADHD, combined	71.28 (8.06)	45.68 (4.61)	$t(55.8) = -15.38$***

Note: Cells represent means (with standard deviations in parentheses), unless otherwise indicated. TRF and CSI (teacher version) scores were not collected for two home-schooled children (they would have been redundant with the parent scale), and one parent did not return the CSI (parent version). Abbreviations: ADHD attention-deficit/hyperactivity disorder, CBCL Child Behavior Checklist, CSI Child Symptom Inventory, FSIQ Full Scale IQ, SES socioeconomic status, TRF Teacher Report Form. *p <.05, **p <.01, ***p <.001.

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[8] IQ is inherently an unsuitable covariate even when significant between-group differences emerge because WM shares considerable variance (~57%) with FSIQ and would result in extracting WM from WM (Calub et al., 2019; Dennis et al., 2009).

Mahalanobis distance tests ($p < .001$) and univariate outliers as reflected by scores exceeding 3.5 standard deviations from the mean (Tabachnik & Fidell, 2007).

WM capacity

An independent t-test demonstrated that the WM capacity of children with ADHD (mean set size = 3.53) was significantly lower than in the TD group (mean set size = 3.92, $t(52.91) = 2.80$, $p = .007$), as expected.

Internal validity of IV analysis (central executive demands on task performance)

A 2 (groups: ADHD, TD) by 4 (tasks: DSF, DSLH, DS+1, DSLH+1) repeated-measures ANOVA was performed to examine the internal validity of the independent variable (% stimuli correct). The performance of all children was predicted to worsen as a function of imposing increasingly more difficult processing demands across experimental conditions.

This analysis, using Huynh-Feldt[9] corrections, revealed a significant main effect for group, $F(1,58) = 8.77$, $p = .004$, $\eta_p^2 = .131$, and task condition, $F(2.80, 162.27) = 48.20$, $p < .001$, $\eta_p^2 = .454$, and a significant group-by-condition interaction, $F(2.80, 162.27) = 3.65$, $p = .016$, $\eta_p^2 = .059$. The group-by-condition interaction effect was characterized by a steeper linear decline in performance for the ADHD relative to the TD group across the four task conditions as a function of increasing cognitive processing demands, which was confirmed by polynomial contrasts revealing a significant linear effect of condition and a significant linear group-by-condition interaction ($F(1,58) = 112.93$, $p < .001$, $\eta_p^2 = .661$ for condition; $F(1,58) = 8.39$, $p = .005$, $\eta_p^2 = .126$ for group-by-condition; see Table 2).

Total task duration – preset at a 12-m maximum for each of the four experimental tasks – was examined to determine whether (a) differences occurred in the allotted 30-s response interval following each stimulus array presentation as a function of increasing task processing demands, and (b) task duration influenced between-group actigraph scores. Task duration was significantly longer as a function of increasing processing demands as expected (DSF<DSLH<DS+1< DSLH+1; all contrasts at $p = .001$), did not differ between groups (independent t-test for all conditions: all p's > .10), and was non-significantly (DSF $r = .03$, DS+1 $r = .03$, DSLH+1 $r = .18$) or weakly (DSLH $r = -.36$) correlated with children's actigraph scores. Collectively, the preliminary analysis revealed

Table 2. Group × task condition accuracy.

	ADHD ($n = 36$)	TD ($n = 24$)	
DSF	96.14 (5.27)	95.46 (3.42)	$t(58) = -.56$, $p = .09$
DSLH	79.21 (16.13)	86.70 (11.48)	$t(58) = 1.97$, $p = .05$
DS+1	69.38 (19.73)	79.72 (13.90)	$t(58) = 2.38$, $p = .02$*
DSLH+1	59.28 (23.42)	74.84 (16.69)	$t(58) = 3.00$, $p = .004$**

Means and standard deviations of stimuli (percentage correct) for children with ADHD and Typically Developing (TD) children across the four cognitive processing task conditions. DSF = Digit Span Forward task, DSLH = Digit Span Low to High task, DS+1 = Digit Span +1 task, DSLH+1 = Digit Span Low to High +1 task. * $p < .05$, ** $p < .01$.

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[9] A Huynh-Feldt correction was applied as recommended by Field (2013) because the Greenhouse-Geisser estimate of sphericity was >.75.

robust support for the internal validity of the IV, and a noncontributory role for task response time on children's activity level.

Primary data analysis

A 2 (groups: ADHD, TD) by 5 (tasks: baseline control, DSF, DSLH, DS+1, DSLH+1) repeated-measures ANOVA on activity level using a Huynh-Feldt correction revealed a significant main effect for group, $F(1,58) = 9.09$, $p = .004$, $\eta_p^2 = .135$, and task condition, $F(3.57, 206.97) = 73.62$, $p < .001$, $\eta_p^2 = .559$, and a nonsignificant group-by-condition interaction effect, $F(3.57, 206.97) = 1.21$, $p = .306$, $\eta_p^2 = .021$.

Polynomial contrasts of the task effect revealed a significant quadratic trend, $F(1,58) = 146.78$, $p < .001$, $\eta_p^2 = .717$, characterized by an immediate increase from the baseline control condition to the DSF task condition, and stabilization of both group's gross motor activity thereafter across the three cognitive processing task conditions (also see Figure 2).

Post-hoc independent *t*-tests revealed that activity level was higher in children with ADHD relative to TD children under all conditions (see Figure 2), and significant for three of the four STM/WM conditions: DSF ($t(58) = -3.03$, $p = .004$), DS+1 (*t*

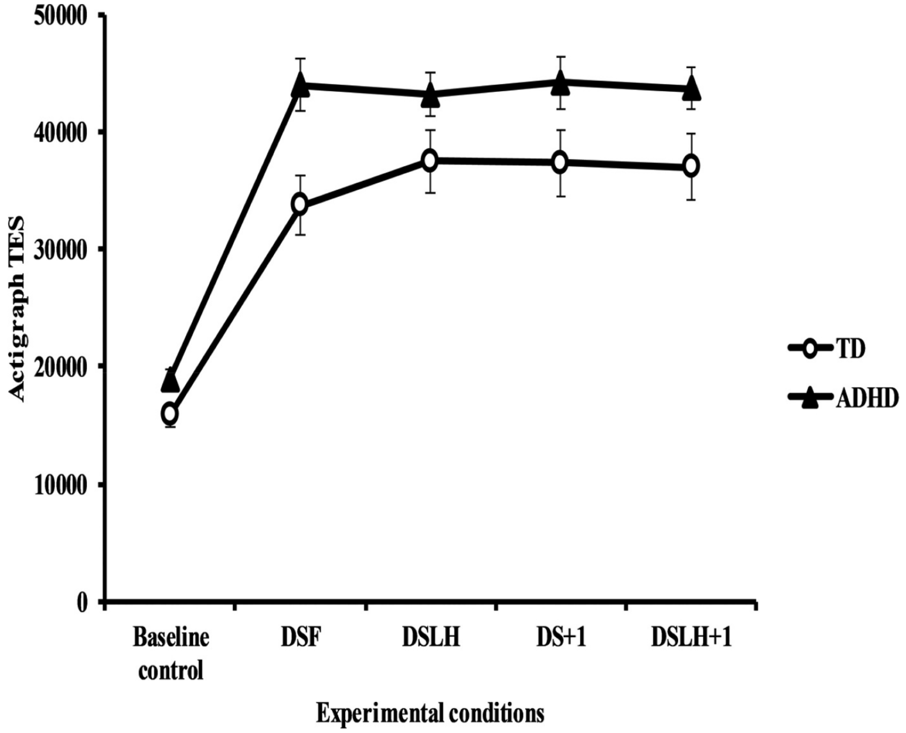

Figure 2. Children's actigraph measured activity level during baseline and cognitive task conditions displayed as a total extremity score (TES); Error bars represent the standard error of the mean. DSF = Digit Span Forward task; DSLH = Digit Span Low to High task; DS+1 = Digit Span +1 task; DSLH+1 = Digit Span Low to High +1 task.

(58) = −1.95, p = .054), DSLH+1 (t(58) = −2.14, p = .037), and DSLH (t(58) = −1.77, p = .081).

Planned contrasts examining the main task effect revealed that (a) actigraph measured activity level was higher under all cognitive task conditions relative to the baseline control condition (all p's < .001); and (b) none of the within group comparisons of activity level among any of the STM/WM task conditions were significant.

Discussion

The rudimentary nature of gross motor activity and its relation with cognitive performance in children with ADHD relative to typically developing (TD) children is reasonably well established – nearly all children display higher levels of gross motor movement while engaged in cognitively demanding activities, children with ADHD display disproportionately higher levels relative to same age peers (Alderson et al., 2012; Rapport et al., 2009; Hudec et al., 2015; Kofler et al., 2016; Orban et al., 2018; Sarver et al., 2015), and activity level may vary depending on the predictability of information to be processed (Kofler et al., 2020). The underlying dynamics of this relation, however, remains speculative based on the scant experimental literature available, limited range of task related processing demands employed systematically, and uncontrolled influences of preexisting differences in children's WM capacity.

The present investigation is the first to examine whether children's gross motor activity rises to an absolute level or accelerates incrementally as a function of increasingly more difficult cognitive processing demands imposed on the limited capacity WM system while controlling for past methodological shortcomings and preexisting differences in WM capacity. Children completed a series of experimental tasks that required short-term storage only and increasing higher upper level cognitive processing demands on WM while monitoring their gross motor activity via actigraphs relative to a baseline (non STM/WM task) condition to address the phenomenon.

Our initial set of analyses revealed that imposing higher cognitive processing demands engendered *decreases* in the performance accuracy of all children in a linear fashion, as expected, and substantiated the internal validity of the experimental tasks. Of particular note was the significant interaction effect, wherein the performance of children with ADHD decreased disproportionately relative to TD children as a function of increasing cognitive processing demands. The lack of between-group differences under the simple span (DSF) task condition was expected because the stimulus set size to be recalled by children was individualized based on their pre-determined WM capacity, but without the added burden of an interleaved cognitive process that interferes with covert rehearsal. All children were set at their WM capacity to enable a clearer picture of the impact of imposing increasingly difficult cognitive processing demands on activity level.

The rapid deterioration in performance observed in all children associated with the imposition of more difficult cognitive processing demands was expected due to the increasingly heavy burden placed on children's ability to not only keep information within the focus of attention, but also to utilize additional resources to stabilize, process, and update the information (Cowan et al., 2006; Shipstead et al., 2015). Collectively, these findings corroborate the results of previous experimental studies

(Alderson, Hudec, Patros & Kasper, 2013; Rapport et al., 2008; Dovis et al., 2013; Kofler et al., 2010) and meta-analytic reviews (Kasper et al., 2012; Martinussen et al., 2005; Willcutt et al., 2005) in demonstrating ADHD-related large magnitude deficits on tasks requiring upper level cognitive processes, and extend these findings by exemplifying the negative impact on children's performance when faced with a task that requires them to employ multiple cognitive processes sequentially. The disproportionate decline in the ADHD group's performance is also consistent with brain imaging findings that reveal underdeveloped frontal/prefrontal brain regions that support higher-order executive functions such as WM for information processing in children with ADHD (Shaw et al., 2007, 2018).

The central finding of the study – viz., that children's gross motor activity more than doubled from the baseline control condition to an absolute level under the four cognitive task conditions – was consistent with an all-or-nothing explanation. The overall magnitude of the gross motor activity increase was remarkably similar for both groups, albeit children with ADHD consistently displayed higher levels of movement relative to TD children. Finding that the upregulation of physical movement is not significantly different following the imposition of general (e.g. encoding/briefly retaining task-related information) and upper level cognitive processing demands (i.e. stabilizing, updating, and acting on the information) suggests that a moderate level of physical movement is needed to promote arousal related mechanisms when engaged in cognitive activities related to the WM system, and that once this level is obtained, additional movement is superfluous (Hebb, 1955; Yerkes & Dodson, 1908). The underlying dynamics of this proposed relation, however, remains speculative and requires empirical scrutiny involving the imposition of cognitive demands and simultaneous measurement of activity level and brain-related arousal mechanisms.

The central finding of the current investigation seems at odds with a previous study investigating the link between motor activity and cognitive processing demands, which indicated that children with ADHD moved more under higher (1-back/2-back tasks) relative to lower cognitive processing demand conditions (simple/choice reaction time tasks) (Hudec et al., 2015). The tasks with the lowest cognitive processing demands in the Hudec et al. (2015) study (i.e. reaction time tasks), however, required substantially less demanding upper level processes relative to the task with the lowest cognitive demands in the current study (digit span forward), and may account for the discrepant findings. In contrast, the central findings of the current study are consistent with a recent meta-analysis that examined the relation between cognitive demand and activity level in ADHD, and reported that higher activity levels occurred during high cognitive demand tasks (e.g. executive functioning tasks such as the experimental tasks in the current investigation) relative to low cognitive demand tasks such as painting, free play and watching television (i.e. similar to the drawing activities the children engaged in during the current investigation) (Kofler et al., 2016).

Despite the multiple strengths of the study – e.g. well-defined ADHD-combined presentation phenotype; tasks designed to approximate the upper level cognitive processes required in foundational learning environments; pre-establishing children's WM capacity prior to assessing cognitive processing demand outcomes; use of high precision actigraphs – potential limitations of the current investigation warrant mention. For example, it is unknown to what extent the results generalize to other types of tasks or settings that require upper level cognitive processing. Tasks designed to explore other types of upper level cognitive processing demands, such as set shifting and dual processing, are recommended to address task generalization effects, whereas measuring gross motor activity level (e.g. via actigraphs) in classroom settings while children perform foundational learning activities that require upper level cognitive processing such as math and reading, could be used to assess the ecological validity of the current findings. A second potential limitation concerns the sample composition, which was comprised of children (mostly boys) meeting ADHD-combined presentation diagnostic criteria. Independent and preferably preregistered replications in samples with more girls and more children with ADHD-inattentive presentation are recommended. It would also be prudent to examine the relation between gross motor activity and cognitive processing demands in other populations with established executive functioning deficits, such as children with intellectual disabilities (Hartman et al., 2010) and pervasive developmental disability (Geurts et al., 2004), in line with current recommendations to investigate underlying mechanisms of psychopathology above and beyond the boundaries of categorical classification systems (e.g. Research Domain Criteria; Insel et al., 2010).

Finally, further explication and extension of the current findings that gross motor activity increases in children with ADHD and TD children while engaged in higher cognitive processing could be accomplished by examining the relation between gross motor activity and frontal/prefrontal mediated blood flow oxygenation during cognitive processing using a noninvasive neuroimaging technique such as functional near-infrared spectroscopy (fNIRS). Unlike other imaging techniques such as functional Magnetic Resonance Imaging, fNIRS allows considerable motor movement with minimal influence on the imaging quality while assessing the extent of neurovascular coupling (Kamran et al., 2015).

Educational and treatment-related implications for children with ADHD based on the study’s results also warrant mention. Finding that gross motor activity is higher in all children when engaged in cognitively demanding relative to undemanding tasks, combined with earlier findings that movement is positively related to WM performance in children with ADHD (Sarver et al., 2015), suggests that overly restricting movement via behavioral classroom management programs may be counterproductive for some children while engaged in learning activities, but awaits empirical scrutiny. Future investigations can address this issue by examining whether enabling higher levels of gross motor activity that do not disrupt on-going classroom academic learning – such as pedaling a stationary bicycle relative to sitting at a conventional classroom desk – result in increased academic productivity and/or reduced inappropriate classroom deportment. Given the heterogeneous nature of ADHD and extant findings suggesting that only a subgroup demonstrates arousal regulation deficits and executive functioning problems (Dovis et al., 2015; Wåhlstedt et al., 2009), children with both arousal regulation and executive functioning deficits may derive the most benefit from these types of activities.

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