The Functional Relationship Between Working Memory and Objectively Measured Activity Level in Boys with Attention-Deficit/Hyperactivity Disorder (ADHD)

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INTRODUCTION

The significance of excessive motor activity or hyperactivity has varied considerably in the conceptualization of attention-deficit/hyperactivity disorder (ADHD) during the past century. Hyperactivity, initially considered the disorder's dominate feature in early clinical and theoretical descriptions, is currently viewed as ubiquitous behavior secondary to pervasive cognitive deficits (Barkley, 1997). No study to date has empirically investigated the relationship between model-implied deficits and objective measures of children's activity level.

The nascent working memory (WM) model (Rapport et al., 2007), however, postulates that activity level is functionally related to challenges to underlying WM systems. Specifically, the model proposes that challenges to underlying WM systems engender increased movement in all children as a process that augments arousal necessary for task performance. Higher rates of movement are predicted to occur under identical WM experimental conditions in children with ADHD relative to typically developing (TD) children to compensate for the chronic cortical under-arousal associated with the disorder.

The present study examines whether objectively measured activity level is functionally related to children's WM performance when assessed in a controlled setting under identical, systematically manipulated experimental parameters. A series of experimental paradigms – designed to assess phonological and visuospatial WM based on Baddeley's (2007) model – was used to examine the relationship between children's WM performance and their actigraph measured activity level. A visual schematic of Baddeley's model is depicted in Figure 1.

Baddeley's (2007) model views WM as a multi-component system consisting of two independent subsystems – phonological (PH) and visuospatial (VS) – that are each equipped with a unique input processor, buffer for the temporary store of modality specific information (PH, VS), and rehearsal mechanism. The domain general central executive (CE) provides oversight and coordination of the two subsystems, reacts to changing experimental/multi-task demands, and provides a link between WM and long-term memory. The distinct functioning of the two subsystems and their buffer-rehearsal components are supported by extensive neuropsychological (Baddeley, 2003), neuroanatomical (Smith, Jonides, & Koeppe, 1996), neuroimaging (Fassbender & Schweitzer, 2006), and factor analytic (Alloway, Gathercole, & Pickering, 2006) investigations.

Children with ADHD and TD children were both expected to exhibit increased motor activity while performing WM tasks relative to a control condition as predicted by the WM model (Rapport et al., 2001; Rapport et al., 2008). No predictions were offered concerning whether motor activity would increase to some minimal threshold level to reflect general WM task demands (i.e., reflecting primarily CE processing and focused attention), or rise incrementally in response to the greater number of stimuli to be recalled (i.e., reflecting storage-rehearsal loop processes). The issue was addressed statistically, however, by isolating and subsequently comparing activity level associated with the domain general CE and subsystem (PH, VS) processes. Children with ADHD were also predicted to exhibit significantly increased motor activity relative to TD children across both WM modalities (PH, VS). Finally, the two groups were compared under minimal WM control conditions and after removing variance associated with WM performance to address the conventionally held belief that hyperactivity in children with ADHD is ubiquitous and unrelated to setting/task variables (Porrino et al., 1983).

METHOD

Participants
Twenty-three children (11TD and 12 children with ADHD) between the ages of 8 and 12 years (M = 9.04, SD = 1.36) participated in the study. All children and their parents participated in a detailed, semi-structured clinical interview using the K-SADS. Children with ADHD met diagnostic criteria for ADHD-combined type and stringent rating scale cutoff criteria (>2 SD) on the Child Behavior Checklist (CBCL), Teacher Report Form (TRF), and Child Symptom Inventory (CSI); TD children scored within the normal range on these instruments. Six of the children diagnosed with ADHD were comorbid for Oppositional Defiant Disorder (ODD); none were receiving medication during the study. Children that presented with (a) gross neurological, sensory, or motor impairment, (b) history of a seizure disorder, (c) psychosis, or (d) Full Scale IQ score less than 85 were excluded from the study.

Measures
MicroMini Motionlogger® (Ambulatory Monitoring Inc., 2004) actigraphs were used to measure children's activity level (see figure 2). The acceleration-sensitive devices resemble a wristwatch and were set to Proportional Integrating Measure (low-PIM) mode, which measures the intensity of movement (i.e., quantifies gross activity level). A histogram of measured voltage over time is depicted in figure 2. 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 Inc., 2004) to calculate mean activity frequencies for each child during the control and WM tasks described below.

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 using Velcro watch bands. Ankle placement was used in lieu of trunk placement due to the improved sensitivity of the former for detecting movement (Eaton, McKeen, & Saudino, 1996). A third actigraph was placed on children's non-dominant wrist only, because the visuospatial and both control tasks required hand movement (using the preferred hand), which would have confounded measured activity level across tasks.

Multi-site actigraph measurements were obtained as participants completed phonological (verbal) and visuospatial (nonverbal) WM tasks across four memory set size conditions based on Baddeley's (2007) WM model. Children with ADHD were previously shown to exhibit significant WM deficits relative to TD children in both WM subsystems using these paradigms (Rapport et al., 2008). The VS and PH WM tasks are identical to those described by Rapport et al. (2008), and are depicted in Figure 4.

Control 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 PH and VS WM tasks during each of the four consecutive Saturday assessment sessions. The Paint program served as pre and post conditions 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 WM tasks while interacting with a program that placed relatively modest demands on WM (i.e., the Paint program allows children to draw/paint anything they like on the monitor using a variety of interactive tools). The 4 pre and 4 post conditions were separately averaged to create pre and post composite scores due to preliminary analyses finding no differences in children's activity level across days (all $p > .10$). Successful interaction with the Paint program requires central executive processes such as focused attention and interaction with long-term memory, as well as limited PH and VS buffer/loop processes.

Figure 1. Adapted and expanded version of Baddeley's (2008) working memory model and associated anatomical loci.

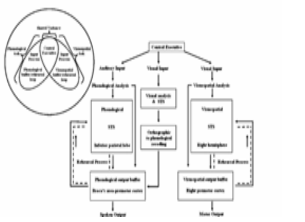


Figure 3. Visuospatial (top) phonological (bottom) tasks.

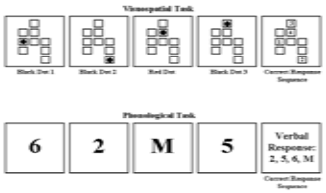


Figure 4. Motor activity during phonological tasks.

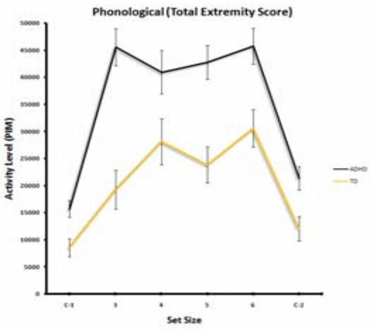


Figure 2. Motionlogger® (Ambulatory Monitoring Inc., 2004) and histogram of measured voltage over time.

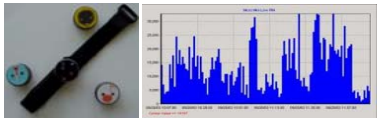


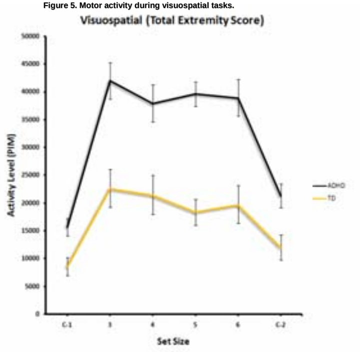
Table 1. Sample and demographic variables

Variable	ADHD		TD Children		
	$\bar{X}$	SD	$\bar{X}$	SD	F (1,21)
Age	8.75	1.29	9.36	1.43	1.17
FSIQ	100.92	15.22	110.18	13.11	2.43
SES	43.46	12.25	52.50	7.57	6.13*
CBCL					
Attention Problems	78.50	10.53	55.64	7.06	36.68***
TRF					
Attention Problems	66.25	8.83	48.73	16.92	9.94**
CSI-Parent					
ADHD, Combined	77.75	9.92	48.73	11.11	9.29**
CSI-Teacher					
ADHD, Combined	63.08	11.05	49.50	9.57	43.83***

† $p = .06$, * $p \le .05$, ** $p \le .01$, *** $p \le .001$

Note: ADHD = attention deficit/hyperactivity disorder – combined type; 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.

Figure 5. Motor activity during visuospatial tasks.



RESULTS

Data Screening
An average effect size of 0.77 was calculated from three studies providing actigraph means and SDs for children with ADHD and TD children during academic (McGrath et al., ref) and laboratory (Dane, Schachar, & Tannock, 2000; Halperin, Matier, Bedi, & Sharma, 1992) tasks. GPower software version 3.0.5 (Faul, Erdfelder, Lang, & Buchner, 2007) was used to determine needed sample size using this ES, with power set to .80 as recommended by Cohen (1992). For an ES of 0.77, $\alpha = .05$, power $(1 - \beta) = .80$, 2 groups, and 6 repetitions (C1, C2, PH 3-6), 16 total subjects are needed for a repeated measures ANOVA to detect differences and reliably reject H_0. Table 1 depicts sample and demographic variables.

Tier I. Composite Scores
A 2 (group: ADHD, TD) by 2 (modality: VS, PH) mixed-model ANOVA revealed significant main effects for WM system ($p < .005$) and group ($p < .001$). All children with ADHD moved more during the PH task relative to the VS task. Children with ADHD moved more than TD children during both the PH and VS condition. The system by group interaction was not significant ($p > .05$).

Tier II: Set Size
Phonological. A 2 (group) by 6 (C1, C2, PH set sizes 3-6) mixed model ANOVA revealed significant main effects for condition ($p < .0001$) and group ($p < .0001$). Children with ADHD moved significantly more than TD children on all conditions. The group by condition interaction was significant ($p < .0005$). Post hoc tests for the interaction revealed that children with ADHD moved more during all PH set sizes (set sizes 3-6) compared to TD children (all $p \le .04$). The pattern of activity level across the PH conditions (set sizes 3-6) differed between the groups. Activity level for children with ADHD did not differ significantly across the PH conditions (set sizes 3-6)(all $p > .05$). Activity level for TD children, in contrast, was not statistically different under PH set size 3 and 5 ($p > .05$) but was significantly less under PH set size 3 relative to PH set sizes 4 and 6 (all $p \le .05$). Figure 4 depicts activity level measured as children completed the PH task.

Visuospatial. A 2 (group) by 6 (C1, C2, VS set sizes 3-6) mixed model ANOVA revealed significant main effects for condition ($p < .0001$) and group ($p < .0001$). Children with ADHD moved significantly more than TD children under all conditions (C1, C2, VS set sizes 3-6). The group by set size interaction was significant ($p < .0001$). Post hoc tests for the interaction revealed that children with ADHD moved more under all VS set sizes conditions (3-6) relative to TD children (all $p \le .01$). The pattern of activity level for children with ADHD and TD children was not significantly different under the VS and control conditions (C1, C2, VS set sizes 3-6). All children moved more under the VS conditions (set sizes 3-6) relative to control conditions (C1, C2) (all $p \le .006$). The activity level for both groups of children (ADHD, TD) did not differ significantly across all VS set sizes (3-6) (all $p > .05$). Figure 5 depicts activity level measured as children completed the VS task.

Tier III: Latent variable analysis
The extent to which group differences in PH and VS activity level were associated with the domain general central executive relative to the two subsidiary systems (VS and PH buffer/loops) were examined. Statistical regression techniques were used to partial activity level related to three variables of interest: phonological buffer/rehearsal loop (PHBL), visuospatial buffer/rehearsal loop (VSBL), and the central executive (CE). This process is described in detail elsewhere (Rapport et al., 2008; Swanson & Kim, 2007). The three derived variables were subjected to an independent samples *t*-test to determine whether children with ADHD and TD children differed in the quantity of activity level related to central executive and storage/rehearsal loop processing. An independent samples *t*-test on the three derived variables indicated significant between-group differences in activity level associated with the CE, VS and PH performance, with children with ADHD evincing higher levels of activity level associated with WM performance (all $p < .05$).

Tier IV: Control Condition
Latent variable analysis was used in the final tier to examine the extent to which between-group activity level differences during the pre and post control conditions (C1, C2) represent ubiquitous hyperactivity in children with ADHD or the influence of minimal WM demands associated with the Paint program. This procedure involved deriving residual scores from linear regression analyses, with residual scores reflecting activity level that is *unrelated* to WM. An independent sample *t*-test on the derived variable did not indicate a significant between group difference in the control condition after removing variance in activity level associated with children's WM ($p > .05$).

DISCUSSION

Measurement of activity level while children performed working memory tasks allowed direct examination of the relationship between working memory and hyperactivity, providing incremental benefit beyond the correlational studies described above.

The current study demonstrates a functional relationship between WM and activity level in children. Children with ADHD and typically developing children exhibited increased motor activity while performing WM tasks relative to a control condition as predicted by the working memory model (Rapport et al., 2001; Rapport et al., 2008). Children with ADHD exhibited significantly increased motor activity relative to TD children across both working memory modalities (PH, VS). This finding is consistent with recent experimental (Rapport et al., 2008) and meta-analytic (Martinussen, Hayden, Hogg-Johnson, & Tannock, 2005) findings demonstrating deficient CE, PH, and VS WM processes relative to typically developing children.

Activity level for children with ADHD was not significantly different across the PH and VS set size conditions. This finding suggests that motor activity increases to a minimal threshold level to reflect primarily CE processing and focused attention. Activity level for TD children rose incrementally in response to the number of stimuli to be recalled on the VS task which suggests that motor activity for TD children during the VS task partly reflects storage-rehearsal loop processing. Examination of activity level associated with the two-independent subsystems and central executive revealed that children with ADHD evinced higher levels of activity level associated with WM relative to TD children of similar age and intelligence.

Collectively, these results demonstrate a functional relationship between WM and activity level in children. The results of the present study challenge prevailing beliefs concerning the ubiquitous nature of hyperactivity (Porrino et al., 1983).

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