Journal of Attention Disorders
1–15

DOI: 10.1177/1087054715608439
jad.sagepub.com
SAGE

Working Memory and Increased Activity Level (Hyperactivity) in ADHD: Experimental Evidence for a Functional Relation

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Abstract

Objective: Converging evidence indicates large magnitude deficits in the "working" component of working memory for children with ADHD. However, our understanding of the relation between these central executive deficits and ADHD behavioral symptoms remains limited due to problems with several commonly used working memory tests. Method: Children with ADHD (n = 25) completed a counterbalanced series of working memory tasks that differed only in memory set predictability. Results: Results indicated that central executive demands increased when memory set was unpredictable, as evidenced by moderate performance decreases (d = 0.22-0.56) and large changes in performance variability (d = 0.93-3.16) and response times (d = 1.74-4.16). Activity level remained relatively stable when memory set was unpredictable but decreased significantly over time when memory set was predictable. Conclusion: Results suggest that altering memory set predictability is a feasible method for increasing/maintaining central executive demands over time, and suggest a positive association between working memory demands and gross motor activity for children with ADHD. *(J. of Att. Dis. XXXX; XX(X) XX-XX)*

Keywords

ADHD, working memory, central executive, activity level, actigraph

The growing interest in treatments intended to ameliorate working memory deficits in ADHD parallels our increased understanding of the role of working memory in core ADHD behavioral symptoms and functional impairments (Chacko, Kofler, & Jarrett, 2014; Rapport, Orban, Kofler, & Friedman, 2013; Sonuga-Barke et al., 2013). Whereas early estimates suggested that approximately 50% of children with ADHD exhibit executive function deficits (Biederman et al., 2004; Willcutt, Pennington, Olson, Chhabildas, & Hulslander, 2005), emerging evidence indicates that working memory deficits—one of three primary executive functions (Miyake et al., 2000)—may be present in approximately 80% of children with ADHD based on meta-analytic best case estimation (Kasper, Alderson, & Hudec, 2012). This increased prevalence appears attributable to refined definitions and improved measurement of working memory (Conway et al., 2005; Shipstead, Redick, & Engle, 2012), such that most if not all "working memory" tests included in earlier meta-analyses indexed short-term memory (storage/rehearsal) more so than working memory (central executive) functioning (Engle, Tuholski, Laughlin, & Conway, 1999).

Working memory is a limited capacity, multicomponent system that serves a critical role in learning, comprehension, reasoning, planning, and guiding everyday behavior (Baddeley, 2007). The *working* component of working memory involves mental processing of internally held information, and is reified across neurocognitive models as the central executive, internal focus of attention, or secondary memory, among other terms (Baddeley, 2007; Cowan, 2011; Unsworth & Engle, 2007). This central executive is distinct from the more general executive functioning construct, and is a supervisory attentional controller responsible for monitoring, processing, reordering, and updating information held in short-term memory (Wager & Smith, 2003). No memory/storage functions are ascribed to the *working* components of working memory; instead, the central executive acts upon information currently held within the two, anatomically distinct, short-term storage/rehearsal (short-term memory) components: the *phonological* (PH; verbal) and *visuospatial* (VS; nonverbal) subsystems.

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Importantly, the magnitude of central executive working memory deficits are among the largest neurocognitive impairments associated with ADHD (Kasper et al., 2012), and these impairments do not appear to be attributable to low motivation (Dovis, Van der Oord, Wiers, & Prins, 2012, 2013), variability in responding (Kofler et al., 2014), disinhibition (Alderson, Rapport, Hudec, Sarver, & Kofler, 2010), or visual inattention during testing (Kofler, Rapport, Bolden, Sarver, & Raiker, 2010). In addition, recent experimental studies suggest that underdeveloped central executive processes may underlie ADHD behavioral symptoms (Kofler et al., 2010; Rapport et al., 2009), and cross-sectional mediation models further implicate central executive dysfunction in these children's impaired performance on tests of behavioral inhibition (Alderson et al., 2010), impulsivity (Raiker, Rapport, Kofler, & Sarver, 2012), response variability (Kofler et al., 2014), and Full-Scale IQ (Rapport et al., 2008). Furthermore, underdeveloped central executive abilities strongly predict social (Bunford et al., 2015; Kofler et al., 2011) and academic achievement problems (Gomez, Gomez, Winther, & Vance, 2014) for children with ADHD, suggesting a role of this cognitive ability in ecologically valid, functional outcomes for children with ADHD.

However, difficulties in experimentally manipulating central executive task demands have limited our understanding of the functional relation between central executive deficits and key ADHD behavioral and functional impairments. For example, Rapport and colleagues (2009) manipulated working memory stimulus set size and observed its effect on actigraph-measured activity level for children with and without ADHD. They found that activity level increased disproportionately for children with ADHD relative to a baseline task but did not change significantly despite increasing the number of to-be-recalled stimuli. Although manipulating set size reflects a face valid method for increasing working memory demands, converging evidence indicates that central executive demands remain relatively constant despite increasing storage/rehearsal demands (i.e., set size) and may decrease over time (Baddeley, 2007). In a follow-up study, Rapport and colleagues found that central executive performance on these tasks correlated .84 to .90 between adjacent set sizes (Kofler et al., 2010), suggesting potential multicollinearity and tempering conclusions regarding the effect of increasing central executive demands on hyperactivity in ADHD. A primary goal of the current study is to address this limitation, and test an alternate method for investigating the functional relation between central executive processes and activity level in ADHD.

Two other commonly used methods for experimentally manipulating working memory demands appear to have similar flaws. In the clinical literature, digit/location simple span tasks have been used traditionally (Martinussen, Hayden, Hogg-Johnson, & Tannock, 2005), wherein performance on forward and backward spans have been interpreted as reflecting short-term memory (storage/rehearsal processes) and working memory (central executive) processes, respectively. However, converging evidence in the cognitive sciences indicates that forward and backward versions of simple span tasks both reflect primarily short-term memory rather than central executive processes. For example, factor analytic and structural equation studies indicate that forward and backward span tasks load together, and load separately from established measures of working memory (e.g., complex span tasks). In addition, short-term memory (forward/backward span) and working memory (complex span) constructs predict nonoverlapping variance in outcomes such as intellectual functioning (Colom, Abad, Rebollo, & Chun Shih, 2005; Unsworth & Engle, 2007). Taken together, these converging findings indicate that, "a simple transformation of order [from forward to backward] would be insufficient to move a task from the short-term memory storage category to the working memory category" (Engle et al., 1999, p. 314). As such, it is unsurprising that children with ADHD do not perform comparatively worse than non-ADHD children on backward digit ($d = 0.43$) than forward digit ($d = 0.47$) span tasks based on meta-analysis (Martinussen et al., 2005).

Similarly, many studies investigating working memory in ADHD have relied on *n*-back tasks (McCarthy, Skokauskas, & Frodl, 2014). *N*-back tasks require participants to monitor a series of consecutively presented stimuli and respond when a stimulus matches a previous stimulus, *n* back in the series. Increasing the number of stimuli between the target and current stimulus (n) is intended to increase working memory demands. Similar to findings regarding backward digits, however, recent experimental (Jaeggi et al., 2010; Kane, Conway, Miura, & Colflesh, 2007) and meta-analytic (Redick & Lindsey, 2013) studies indicate that these recognition-based *n*-back tasks are minimally correlated with, and explain different variance in outcome measures than, established working memory tasks. As such, increasing the size of n appears to function similarly to moving from forward to backward digit recall—that is, it increases storage/rehearsal demands with minimal changes in central executive demands.

Collectively, it is becoming increasingly evident that our most commonly used experimental manipulations primarily, if not exclusively, affect storage and/or rehearsal demands (Bolden, Rapport, Raiker, Sarver, & Kofler, 2012) rather than the intended manipulation of the working components of working memory (i.e., central executive). A parsimonious solution to this difficulty may be to modify existing working memory tasks (Conway et al., 2005; Rapport et al., 2008) by randomizing the number of stimuli per trial within and across experimental blocks. This design differs from the more common application of sequentially presented, ordered blocks of increasingly larger memory sets (e.g., standardized digit span tasks). Outcomes of interest (e.g., activity level) can then be compared across methods using temporally matched blocks. As argued by Conway and colleagues (2005), mixing set sizes within experimental blocks is expected to maximize central executive demands by disallowing participants to anticipate the number of stimuli that they will be asked to remember on any given trial (Engle, Cantor, & Carullo, 1992). This in turn increases demands on working memory updating and monitoring processes—two of the three principal central executive responsibilities (Baddeley, 2007)—to respond to continuously changing task demands (Conway et al., 2005). Additional advantages include de-confounding set size and buildup of proactive interference across trials and increasing between-participant variability (Conway et al., 2005).

Thus, randomizing the number of stimuli per trial within and across blocks is expected to increase task difficulty relative to traditional, sequential (predictable) presentation. This increased difficulty, despite equivalent cognitive load (e.g., equal number of trials at each set size/cognitive load), is expected to reflect increased central executive demands. In particular, memory set unpredictability is expected to maintain higher central executive demands over more trials, given the expected decrease in executive demands associated with strategy use and developing task expertise over time (Baddeley, 2007). Although consistent with recommended best practices for working memory measurement (Conway et al., 2005) and face valid for increasing working memory central executive demands (Engle et al., 1992), this contention has never been tested empirically to our knowledge.[1] If successful, this manipulation would allow researchers to more precisely isolate behavior associated with central executive functioning and provide a powerful, experimental test of the role of central executive deficits in key ADHD behavioral symptoms.

Thus, the purpose of the current study is to (a) examine the feasibility of a proposed method for experimentally manipulating central executive demands by testing the extent to which randomizing the number of stimuli per trial increases central executive demands relative to sequential (ordered) memory set size presentation, and (b) if successful, examine the effect of increasing central executive demands on objectively measured activity level for children with ADHD. Following Conway and colleagues (2005), we hypothesized that randomizing stimulus set size during working memory tasks would result in increased central executive demands relative to equivalent forms with sequentially ordered set size presentation, as evidenced by poorer performance, increased variability in performance, and/or increased response times. We further hypothesized that this manipulation would increase objectively measured activity level for children with ADHD (Rapport et al., 2009).

Method

Participants

The sample initially comprised 29 children aged 8 to 13 years (M = 10.46, SD = 1.49; 18 boys, 11 girls) from the Mid-Atlantic United States, who were consecutive referrals to a children's learning clinic (CLC) through community resources to participate in a larger study examining predictors of behavioral treatment response for ADHD. None of the children participated in previous studies published by our group. Psychoeducational evaluations were provided to the parents of all participants. All parents and children gave informed consent/assent, 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, semistructured clinical interview using the Kiddie Schedule for Affective Disorders and Schizophrenia for School-Age Children (K-SADS; Kaufman et al., 1997). The K-SADS assesses onset, course, duration, severity, and impairment of current and past episodes of psychopathology in children and adolescents based on *Diagnostic and Statistical Manual of Mental Disorders* (4th ed.; *DSM-IV*; American Psychiatric Association, 1994) criteria. Its psychometric properties are well established, including interrater agreement of .93 to 1.00, test–retest reliability of .63 to 1.00, and concurrent (criterion) validity between the K-SADS and psychometrically established parent rating scales (Kaufman et al., 1997).

In addition, all children's K-SADS interviews were supplemented with parent and teacher ratings scales from the Behavior Assessment System for Children, 2nd edition (BASC-2; Reynolds & Kamphaus, 2004) and Child Symptom Inventory (CSI-IV; Gadow, Sprafkin, Salisbury, Schneider, & Loney, 2004). Children with all ADHD current presentations were eligible given evidence of the instability of ADHD subtypes (Nigg, Tannock, & Rohde, 2010; Valo & Tannock, 2010), previous research implicating central executive processes in both inattentive (Kofler et al., 2010) and hyperactive (Rapport et al., 2009) symptom clusters, and previous findings of increased actigraph-measured gross motor activity in both Inattentive and Combined subtypes of ADHD (Dane, Schachar, & Tannock, 2000).

Twenty-five children met the following criteria and were included in the ADHD group: (a) an independent diagnosis by the CLC's directing clinical psychologist using *Diagnostic and Statistical Manual of Mental Disorders* (5th ed.; *DSM-5*; American Psychiatric Association, 2013) criteria for ADHD based on K-SADS semistructured interview with parent and child; (b) parent ratings of at least 1.5 *SD*s above the mean on the Attention Problems and/or Hyperactivity clinical syndrome scale of the BASC-2 parent form, or exceeding the criterion score for the parent version of the ADHD-Inattentive and/or ADHD-Hyperactive/Impulsive subscales of the CSI; and (c) teacher ratings of at least 1.5 *SD*s above the mean on the Attention Problems and/or Hyperactivity clinical syndrome scale of the BASC-2 teacher form, or exceeding the criterion score for the teacher version of the ADHD-Inattentive and/or ADHD-Hyperactive/Impulsive subscales of the CSI.[2]

Of the 25 children with ADHD (10 girls), 14 met criteria for Combined, 8 for Inattentive, and 3 for Hyperactive/Impulsive Presentation. Given generalizability concerns (Wilens et al., 2002), children with comorbidities were included. In all cases, the K-SADS interview indicated that the onset of ADHD symptoms preceded the onset of comorbid symptoms, and that the child's inattention and/or hyperactive/impulsive symptoms could not be better accounted for by the comorbid condition. Comorbidities included oppositional defiant disorder (20%), depressive disorders (20%), and anxiety disorders (8%). Sample ethnicity was representative of the region and included children of Caucasian non-Hispanic (80%), mixed racial/ethnic (12%), Hispanic English-speaking (4%), and Asian (4%) backgrounds.

Children who presented with (a) gross neurological, sensory, or motor impairment; (b) history of a seizure disorder; (c) psychosis; or (d) Wechsler Abbreviated Scale of Intelligence (WASI-2) verbal comprehension index (VCI) IQ score less than 85 were excluded from the study. Four of the 29 children were excluded from the study due to failing to meet diagnostic criteria for ADHD,[3] resulting in a final *N* of 25. Fourteen of these 25 children with ADHD had previously received psychostimulant trials or were currently prescribed psychostimulants (which were withheld for a minimum of 24 hr prior to each testing session). Demographic data for the ADHD sample are provided in Table 1.

Table 1. Sample and Demographic Variables.

Variable	*M* (*SD*)
Age	10.46 (1.49)
WASI-2 IQ	110.44 (14.62)
Hollingshead SES	47.00 (10.68)
BASC-2 parent	
Hyperactivity	72.75 (13.81)
Attention problems	68.50 (7.90)
BASC-2 teacher	
Hyperactivity	61.00 (12.70)
Attention problems	63.92 (8.49)
ADHD current presentation	*N* (%)
Combined	14 (56%)
Inattentive	8 (32%)
Hyperactive/impulsive	3 (12%)
Gender	
Male	15 (60%)
Female	10 (40%)

Note. WASI-2 = Wechsler Abbreviated Scale of Intelligence–Second Edition; SES = socioeconomic status; BASC-2 = Behavior Assessment System for Children–Second Edition; IQ = Intelligence Quotient.

Measures

Working memory

Phonological working memory task. The phonological working memory task is similar to the Letter-Number Sequencing subtest on the Wechsler Intelligence Scale for Children, 4th Edition (WISC-IV)and assesses phonological working memory based on Baddeley's (2007) model. Children heard a series of jumbled numbers and a letter via computer speakers. All stimuli were recorded using AT&T Natural Voices® Text-to-Speech speech synthesis system and presented aurally at 1 s intervals. Auditory rather than visual presentation was used to more precisely isolate phonological task demands by minimizing visuospatial influences (Alderson et al., 2015). The letter was never presented in the first or last position of the sequence to minimize potential primacy and recency effects, and was counterbalanced across trials to appear an equal number of times in the other serial positions (i.e., position 2, 3, 4, or 5). Children were instructed to recall the numbers in order from smallest to largest, and to say the letter last (e.g., 4 H 6 2 is correctly recalled as 2 4 6 H). Two trained research assistants, shielded from the participant's view, listened to the children's vocalizations and recorded oral responses independently (interrater reliability was 99.50%).

Visuospatial working memory task. Children were shown nine squares arranged in three offset vertical columns on a computer monitor. The columns were offset from a standard 3 × 3 grid to minimize the likelihood of phonological coding of the stimuli (e.g., by equating the squares to numbers on a telephone pad). A series of 2.5 cm diameter dots (3, 4, 5, or 6) were presented sequentially in one of the nine squares during each trial such that no two dots appeared in the same square on a given trial. All but one dot was black; the exception being a red dot that never appeared as the first or last stimulus in the sequence. Each dot was displayed for 800 ms followed by a 200 ms interstimulus interval. Children were instructed to respond by pressing the corresponding squares on a modified computer keyboard and to reorder the dot locations by indicating the serial position of the black dots in the order presented followed by the serial position of the red dot last.

Parallel forms for ordered and mixed conditions. The working memory tasks developed by Rapport et al. (2008) and described above were used to create two parallel forms of each modality (visuospatial, phonological) for the current study. Evidence for reliability and validity of these working memory tasks includes high internal consistency ($\alpha = .82$ to .97) and demonstration of the expected magnitude of relations (Swanson & Kim, 2007) with an established measure of short-term memory (WISC-IV Digit Span raw scores: $r = .50$ to .66; Raiker et al., 2012). Two, 12-trial versions of each set size were created for each modality by constructing split-half versions of the original 24-trial versions developed by Rapport et al. (2008). Twelve trials were selected based on reanalysis of data provided by the task developers demonstrating that all 12-trial versions correlate ≥ .90 with their corresponding full, 24-trial version. These split-half versions were then randomly assigned to the Ordered and Mixed conditions to create parallel forms.

For the *Ordered* condition, the trials were presented sequentially in four blocks, with each block containing 12 unique trials of the same stimulus set size (48 total trials comprising 216 total stimuli). Children completed the Set Size 3 block first (12 trials), followed by Set Size 4 (12 trials), and so on, with short breaks in between each block (approximately 1-2 min). Task duration ranged from 2 to 5 min each for the phonological blocks, and 2 to 3 min each for the visuospatial blocks.

For the *Mixed* condition, the 48 trials (12 trials at each set size) were randomized, and then grouped into four blocks of 12 trials each, such that the stimulus set size (3, 4, 5, or 6 stimuli) for a given trial was not predictable based on the preceding trial. The Mixed condition was identical to the Ordered condition in all other aspects, including the total number of unique trials in each block (12), number of total trials at each set size across the task, total number of stimuli in the task, and provision of short breaks between each 12-trial block (approximately 1-2 min). Chi-square analysis revealed no significant differences in the number of stimuli randomized to each Mixed block for the phonological, $\chi^2(3) = 2.70$, $p = .44$, *ns*, or visuospatial, $\chi^2(3) = 1.22$, $p = .75$, *ns*, mixed conditions. Task duration was approximately 2.5 (visuospatial) to 3.5 (phonological) min per block.

Dependent variables: Working memory task performance. Three metrics were used to examine the impact of randomizing stimulus set size on central executive demands: (a) percentage of stimuli correct per trial, using partial credit scoring as recommended to index overall working memory performance at each set size (Conway et al., 2005); (b) *SD* of stimuli correct per trial, to index performance variability at each set size; and (c) response time, to index expected increases in response time associated with the unpredictable response set. For the visuospatial conditions, response time was indexed as latency to first response for each trial; for the phonological task, response time reflected the total response time for each trial. The difference was due to differences in task requirements. The visuospatial task required a motor response for each dot location (response time = first dot location pressed), while the phonological task required a motor response at the end of the verbal response (response time = completion of the trial).

Performance data were collected for each trial for each participant. The randomized trials in the Mixed condition were collated during postprocessing to allow direct comparison of performance at each set size between the Ordered and Mixed conditions. Estimates of task performance associated with central executive (CE) working memory were computed at each set size for each of the three performance metrics (performance, performance variability, response time) using the regression approach described by Rapport et al. (2008) as recommended (Swanson & Kim, 2007). Briefly, this approach calculates a predicted score by regressing the PH and VS working memory subsystem processes onto each other based on the assumption that shared variance between the measures reflects the domain-general, higher order supervisory mechanism of the two processes. The approach is valid to the extent that the higher order central executive is domain-general rather than domain-specific—that is, that there is a single higher order system or mechanism responsible for the subsidiary systems rather than a separate controller unique to each subsystem. Studies examining Baddeley's (2007) working memory model uniformly support a domain-general central executive (e.g., Alloway, Gathercole, & Pickering, 2006) that provides oversight for the distinct PH and VS working memory subsystems (Smith, Jonides, & Koeppe, 1996). Contemporary studies have adopted this approach to partition and examine storage (buffer/loop) and processing (central executive) components of working memory using PH storage and PH storage + processing tasks (e.g., Colom et al., 2005; Engle et al., 1999; Swanson & Kim, 2007), as well as PH and VS working memory tasks (e.g., Kane et al., 2004; Rapport et al., 2008). The extraction of "common and perfectly reliable variance" (Swanson & Kim, 2007, p. 158) between working memory tasks using regression or structural equation model-based techniques has the additional benefit of reducing or eliminating variance related to non-working memory processes and measurement error (Miyake, Friedman, Rettinger, Shah, & Hegarty, 2001).[4] Unstandardized predicted scores were used to estimate performance attributable to central executive functioning because they retain the original metric (e.g., percentage of stimuli recalled), thus allowing comparisons within and across the Mixed and Ordered conditions.

Activity level

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, Pinto, & Morrison, 1991). Basic Motionlogger® (Ambulatory Monitoring, 2004) actigraphs were used to measure children's activity level. The acceleration-sensitive devices 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-s epochs. Data were downloaded via a hardware interface and analyzed using the Action-W4 software program (Ambulatory Monitoring, 2004) to calculate mean activity rates for each child during the working memory tasks described above.

Children were told that the actigraphs were "special watches" that let them play the computer learning games. The Observer XT (Noldus Information Technology, 2012) 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 nondominant wrist only because the visuospatial tasks required dominant hand movement.

Dependent variables: Activity level. Following Rapport et al. (2009), we computed total extremity scores (TES) by summing activity level across the three actigraph sites (2 ankle, 1 nondominant hand) to index overall movement for each of the 16 blocks (ordered vs. mixed: VS Blocks 1-4, PH Blocks 1-4). Each block comprised 12 consecutively presented trials of a particular modality/condition as opposed to the performance analyses in which we were able to collate Mixed trials of the same stimulus set size during postprocessing. By design, the number of stimuli in each block differed across the Mixed and Ordered conditions. Although the number of stimuli/trial was not expected to influence activity level (Rapport et al., 2009), individual differences in the resultant task duration may introduce significant confounds for the critical Ordered versus Mixed comparisons (e.g., time on task effects). To control for intertask and intraindividual block duration differences, TES activity level was divided by block duration, individually for each child for each experimental block. Latent *Activity Level* variables were then created for each block by computing unstandardized predicted scores to provide estimates of overall activity level by capturing the shared variance across the phonological and visuospatial working memory conditions, separately for each block of each condition (Ordered, Mixed) based on the preceding methodological/statistical rationale. This approach has additional advantage of conserving power while providing the broader sampling of children's activity level needed to test hypotheses regarding the relation between overall activity level and working memory (Rapport et al., 2009).

Procedures

All children participated in two consecutive Saturday assessment sessions. The ordered and mixed, phonological and visuospatial task variants were administered as part of a larger battery of laboratory tasks that required the child's presence for approximately 3 h per session. Five practice trials were administered before each task; children were required to achieve 80% correct before advancing to the full task. All tasks were counterbalanced across testing sessions to minimize order effects. Children were seated in a caster-wheel swivel chair approximately 0.66 m from the computer monitor for all tasks. Performance was monitored at all times by the examiner, who was stationed just out of the child's view to provide a structured setting while minimizing performance improvements associated with examiner demand characteristics (Gomez & Sanson, 1994). All children received brief (2-3 min) breaks following each task, and preset longer (10-15 min) breaks after every two to three tasks to minimize fatigue.

Data Analysis Overview

The current study used a two-tiered approach to examine the relation between central executive functioning and activity level in children with ADHD. In the first Tier, we tested the hypothesis that randomizing set size presentation would increase central executive demands (Engle et al., 1992). Support for this hypothesis would include evidence that children recalled fewer stimuli, were more variable in performance, and took longer to respond during the Mixed relative to the Ordered condition (Conway et al., 2005).

In the second Tier, we examined the impact of the Mixed versus Ordered manipulation on objectively measured activity level. TES activity level was expected to be significantly higher during the Mixed relative to the Ordered condition, to the extent that the former is associated with increased central executive demands. This effect was expected to be particularly evident during later blocks when central executive demands are expected to attenuate somewhat in the Ordered but not the Mixed condition due to developing task expertise (Baddeley, 2007). This finding would be consistent with previous comparisons of activity level during working memory relative to control tasks (Rapport et al., 2009), and suggest that a functional relation between central executive demands and gross motor activity is observable at the within-subjects level for children with ADHD. In contrast, finding that activity level is unchanged despite Tier I evidence for increased central executive demands would be consistent with previous experimental manipulations of short-term memory demands, and suggest that previous findings regarding the link between working memory and hyperactivity are likely attributable to non-central executive processes.

Results

Preliminary Analyses

All variables were screened for univariate/multivariate outliers and tested against $p < .001$. No significant outliers were found. One-sample t tests revealed that the BASC-2 parent and teacher Attention Problems and Hyperactivity subscale scores were significantly elevated for the ADHD group relative to the scale's T-score mean of 50 as expected (all $p < .0005$; Table 1). In addition, the current sample was

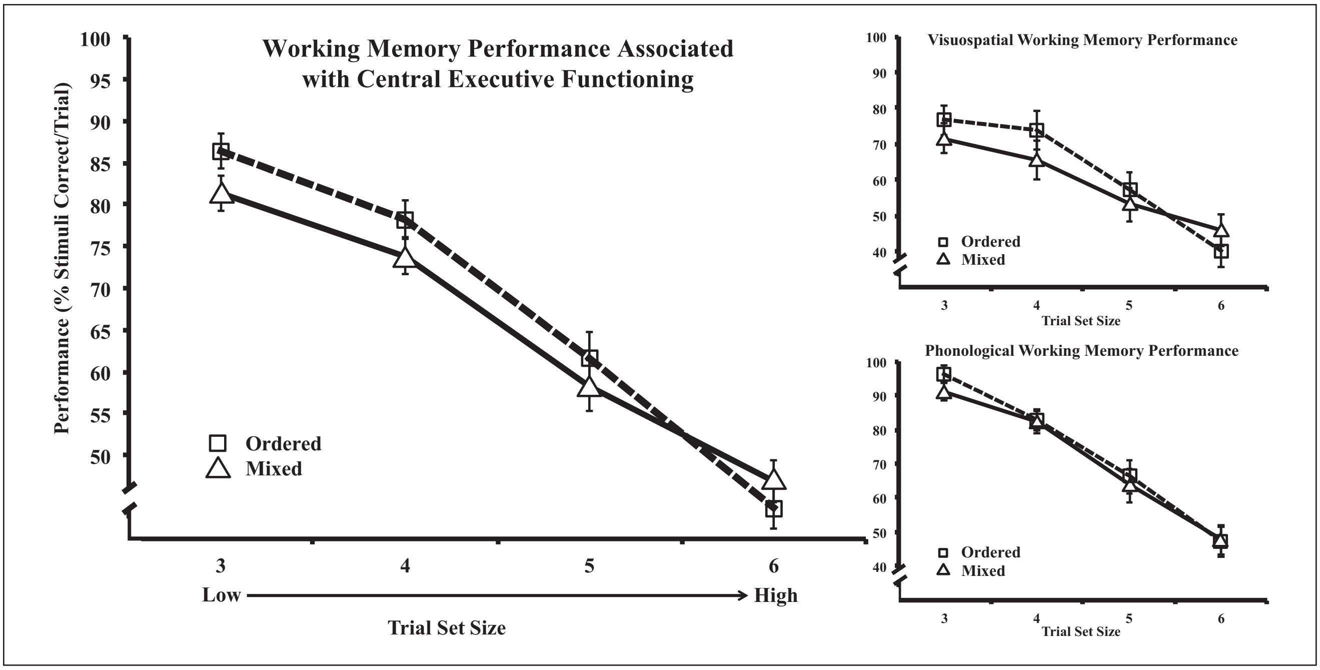

Figure 1. Task performance across the Mixed and Ordered presentation conditions. The randomized trials in the Mixed condition were collated during postprocessing to allow direct comparison of performance at each memory set size between the Ordered and Mixed conditions. Error bars reflect standard error.

somewhat higher than the test mean of 100 in terms of WASI-2 IQ, one-sample $t(24) = 4.01$, $p < .0005$, potentially reflecting the relatively higher socioeconomic status (SES) of the area from which the sample was recruited (Table 1). IQ was not analyzed as a covariate, however, because it shares significant variance with working memory ($r = .75$ to .79), which would result in removing substantial variance associated with working memory from working memory (Ackerman, Beier, & Boyle, 2005; Dennis et al., 2009). Age, SES, and gender were not significant covariates of any of the analyses (all $p > .10$) and did not interact with any variables of interest, with one exception.[5] We therefore report simple model results with no covariates.

Tier I: Integrity of the Experimental Manipulation for Increasing Central Executive Demands

A series of 2 (Task version: Ordered vs. Mixed) × 4 (set sizes 3-6) mixed-model ANOVAs were conducted to examine the impact of set size randomization on mean performance, performance variability, and response time associated with central executive functioning.

Task performance associated with central executive functioning. The mixed-model ANOVA for central executive task performance was significant for task version ($p = .018$), set size ($p < .0005$), and the Task version × Set size interaction ($p = .02$; Figure 1, Table 2). Post hoc tests revealed that children with ADHD recalled fewer stimuli correctly during the Mixed relative to Ordered condition ($p = .02$) and that the percentage of stimuli correctly recalled decreased significantly as the number of stimuli increased across all set sizes for both Mixed and Ordered conditions as expected (all $p < .0005$). The significant interaction was due to the pattern of between-condition performance differences across set sizes. Specifically, children's performance was significantly worse during the Mixed relative to Ordered condition for Set Size 3 ($p = .001$), Set Size 4 ($p = .004$), and Set Size 5 ($p = .019$), whereas performance did not differ significantly at Set Size 6 ($p = .067$).

Performance variability associated with central executive functioning. The mixed-model ANOVA for central executive performance variability (*SD* of stimuli correct per trial) was significant for task version, set size, and the Task version × Set size interaction (all $p < .0005$; Table 2). Post hoc tests revealed that children with ADHD were more variable during the Mixed relative to Ordered condition ($p < .0005$) and that children's performance became more variable with each increase in set size (all $p < .0005$). Post hocs for the interaction revealed increased performance variability at the lowest and highest Mixed set sizes (both $p < .001$) but not during Set Sizes 4 ($p = .12$) or 5 ($p = .09$).

Response time associated with central executive functioning. The mixed-model ANOVA for response times associated with central executive functioning was significant for task

Table 2. Task Performance and Activity Level Associated With Central Executive Demands.

	Condition			
	Mixed	Ordered		
Task	*M* (*SD*)	*M* (*SD*)	Contrast	Cohen's *d*
Performance (% stimuli correct/trial)				
Set Size 3	81.33 (10.53)	86.44 (7.03)	ORD > MIX**	−0.56
Set Size 4	73.79 (10.98)	78.29 (10.63)	ORD > MIX**	−0.41
Set Size 5	58.30 (15.21)	61.63 (15.02)	ORD > MIX*	−0.22
Set Size 6	46.86 (12.38)	43.64 (13.12)		0.25
Performance variability (*SD* stimuli correct/trial)				
Set Size 3	0.68 (0.18)	0.55 (0.04)	MIX > ORD**	0.93
Set Size 4	1.05 (0.17)	1.10 (0.03)		−0.41
Set Size 5	1.44 (0.11)	1.41 (0.09)		0.36
Set Size 6	1.69 (0.10)	1.46 (0.01)	MIX > ORD***	3.16
Response time (ms)				
Set Size 3	4,041.61 (952.39)	2,750.71 (401.30)	MIX > ORD***	1.74
Set Size 4	5,332.37 (438.84)	5,253.92 (555.66)		0.15
Set Size 5	6,321.25 (111.52)	6,654.71 (37.13)	ORD > MIX***	−3.95
Set Size 6	6,885.52 (316.86)	8,388.21 (391.19)	ORD > MIX***	−4.16
Activity level/second (TES)				
Block 1	1.10 (0.24)	1.82 (0.50)	ORD > MIX***	−1.84
Block 2	1.17 (0.22)	1.29 (0.18)	ORD > MIX**	−0.61
Block 3	1.26 (0.18)	1.01 (0.16)	MIX > ORD***	1.46
Block 4	1.06 (0.17)	0.88 (0.15)	MIX > ORD***	1.07

Note. TES = total extremity score; ORD = ordered; MIX = mixed.
Mixed and ordered conditions differ at $^{*}p < .05$. $^{**}p < .01$. $^{***}p < .001$.

version ($p = .03$), set size ($p < .0005$), and the Task version × Set size interaction ($p < .0005$; Table 2). Post hoc tests indicated that the Mixed condition was associated with significantly longer response times across the set sizes, as expected, but that response times in the Ordered condition increased at a faster rate. Consequently, the Mixed condition was associated with significantly longer response times during the lowest set size ($p < .001$) and significantly shorter response times during the highest two set sizes (both $p < .001$); response times did not differ for Mixed and Ordered trials at Set Size 4 ($p = .48$).

Collectively, the preceding analyses suggest that randomizing memory set is a feasible method for increasing central executive demands. Specifically, randomizing memory set differentially affected all three performance metrics for children with ADHD, with overall decreased performance, increased performance variability, and changes in response time (dependent on cognitive load) during the Mixed relative to Ordered tasks.

Tier II: Effect of Increasing Central Executive Demands on Objectively Measured Activity Level

In the preceding Tier, we found evidence supporting the validity of experimentally manipulating central executive demands by randomizing the memory set within and across blocks, with this effect particularly apparent when examining performance metrics during trials of the highest and lowest set sizes. Thus, in Tier II, we examine the impact of these increased central executive demands on the objectively measured activity level of children with ADHD, with the lower and higher set size trials necessarily interspersed within each Mixed block to elicit this effect. In other words, the Tier II analyses examine activity level during consecutive *blocks* of 12 trials across the Mixed and Ordered conditions, as opposed to the performance analyses in which we were able to collate Mixed trials of the same stimulus set size during postprocessing.

Activity level associated with central executive processes: Ordered versus mixed manipulation. The mixed-model ANOVA for activity level (TES/Second) was significant for task version ($p = .01$), block ($p < .0005$), and the Task × Block interaction ($p < .0005$).[6] As shown in Figure 2, children with ADHD were significantly less active during Mixed Blocks 1 and 2 (first 24 trials administered; both $p < .005$), and significantly more active during Mixed Blocks 3 and 4 (last 24 trials administered; both $p < .0005$), relative to their temporally matched Ordered blocks (Figure 2). This pattern was attributable to a pattern of stable or increasing activity level across the Mixed blocks, with increased activity level per second during Blocks 2 and 3 relative to Blocks 1 and 4

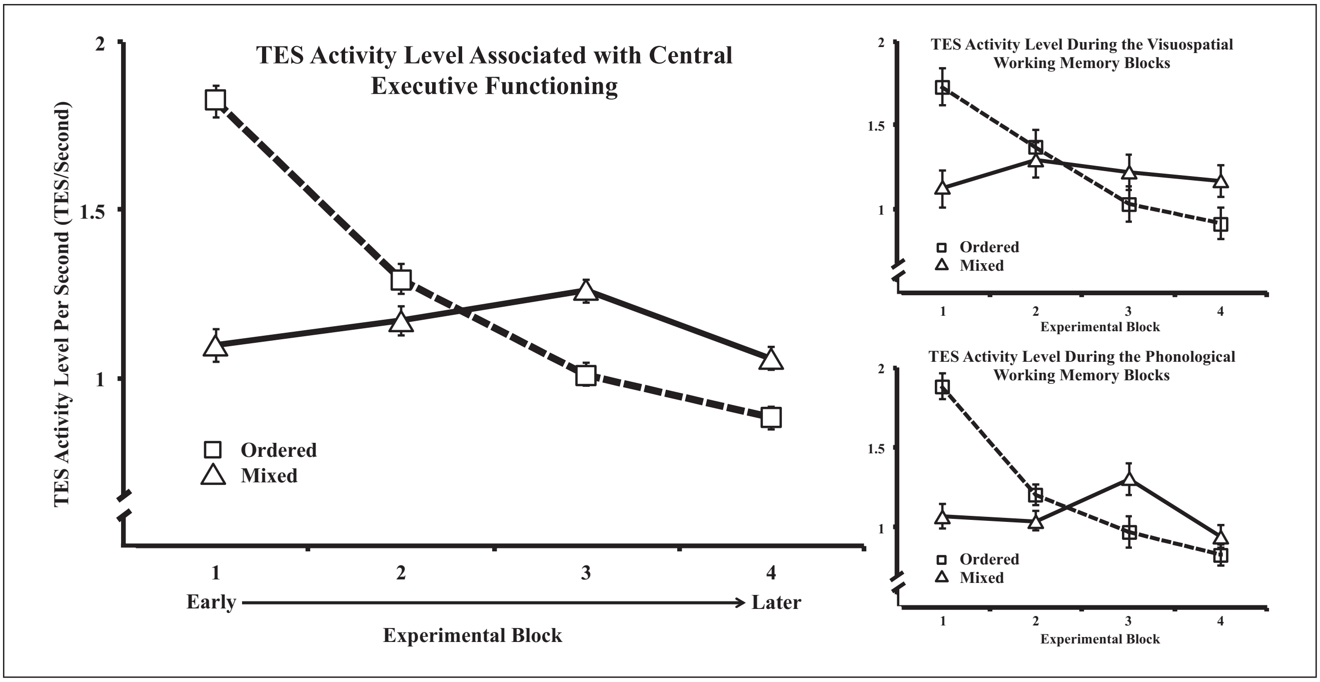

Figure 2. Actigraph-measured gross motor activity per second (TES/Second) during each temporally matched Mixed and Ordered block. Each block comprised 12 unique trials. Ordered Blocks 1, 2, 3, and 4 presented 3, 4, 5, and 6 stimuli per trial, respectively. Mixed blocks presented a random number of stimuli per trial across all four blocks. Error bars reflect standard error.
Note. TES = total extremity scores.

(all $p < .003$; that is, Block 1 < 2 < 3 > 4; 1 = 4). In contrast, activity level decreased significantly across all Ordered blocks (Block 1 > 2 > 3 > 4; all $p < .0005$). This pattern of results suggests that activity level decreases for children with ADHD as set size increases when presented sequentially but remains stable and high across at least 48 trials when central executive demands are increased through random presentation of memory set sizes.

Discussion

The current study was the first to test a novel method for manipulating central executive working memory demands and examine the utility of this manipulation for testing model-driven predictions regarding the functional relation between working memory deficits and ADHD hyperactive behavior. Overall, results supported the integrity of the tasks' parallel forms, wherein the Mixed and Ordered versions demonstrated the expected patterns of decreasing performance, increasing performance variability, and increasing response times for both modalities (phonological, visuospatial) as set size increased. Importantly, children with ADHD recalled fewer stimuli and demonstrated more variable performance for randomized trials (Mixed) relative to matched trials for which the memory set could be anticipated (Ordered). Given the equivalence in cognitive load (set size) between the Mixed and Ordered conditions, this increased task difficulty suggests that central executive updating and monitoring demands increased when memory set was unpredictable as hypothesized, and provides the first empirical support for the cognitive literature's recommendation to randomize memory load within and across experimental blocks to maximize central executive working memory demands (Conway et al., 2005; Engle et al., 1992).

Interestingly, the evidence supported our hypothesis that an unpredictable memory set would increase central executive demands, but this support varied somewhat across the three performance metrics. With regard to recall accuracy, small to medium performance decrements were detected during trials of all but the highest set size (d = −0.22 to −0.56). In contrast, large effects on performance variability and response times were detected at the highest (d = 3.16 to 4.16) and lowest set sizes (d = 0.93 to 1.74). The finding that response times were longer during Mixed trials of 3 stimuli was consistent with predictions; however, this pattern reversed for trials of the highest cognitive loads. This latter finding—that children with ADHD responded more quickly to higher set size trials when they were interspersed with lower set size trials—may be parsimoniously explained by the increased order effects and associated buildup of proactive interference for the higher set size trials in the Ordered condition. That is, these trials always occurred as the final 24 trials in the Ordered (but not Mixed) condition, during which time the cognitive sequelae of order effects are most potent.

Alternatively, when considered in the broader context of children's performance across metrics, we propose that children with ADHD in the current sample may have anticipated a memory set of approximately four stimuli when trial length was unknown. That is, response times and performance variability were highly consistent during trials of four stimuli regardless of whether memory set was predictable, whereas the Mixed condition produced reliable differences in these metrics during the higher and lower set sizes. If correct, this interpretation suggests that an unpredictable memory set increases central executive demands by intensifying monitoring and memory updating processes and that this effect is most apparent when the number of stimuli presented is higher or lower than anticipated (Conway et al., 2005; Engle et al., 1992). This conceptualization may account also for the lack of performance differences at the highest set sizes, such that increasing central executive demands may exert a detectable effect on performance only when other working memory subcomponents (i.e., storage/rehearsal capacity) are not already overwhelmed (Cowan, Morey, AuBuchon, Zwilling, & Gilchrist, 2010; Kofler et al., 2010). Interestingly, however, this hypothesized strategy was not successful at ameliorating performance deficits—children with ADHD continued to demonstrate performance decrements during Mixed trials with four stimuli that were similar in magnitude to their performance decrements during Mixed trials with fewer stimuli ($d = -0.41$ vs. -0.56).

After demonstrating that randomizing the memory set increased central executive demands as predicted, we turned to the critical issue regarding the relation between central executive functioning and gross motor activity. Examination of activity level across the Ordered blocks revealed an unexpected but modestly higher initial rate of activity level compared with the Mixed condition, coupled with a consistent pattern in which gross motor movement decreased over time as storage/rehearsal demands increased and central executive demands attenuated as a function of task predictability (Baddeley, 2007; Engle et al., 1992). In contrast, children with ADHD evinced relatively stable, high levels of gross motor movement when central executive demands were kept high by making stimulus set size unpredictable from trial to trial. As a result, activity level was significantly higher for the Mixed relative to the Ordered condition, particularly during the final 24 trials (d = 1.07 to 1.46). Given this performance pattern, the current findings suggest that central executive demands reliably evoke high levels of gross motor activity in children with ADHD, regardless of stimulus modality (Figure 2) and that their motor activity remains high to the extent that task demands prevent decreases in central executive demands over time. It suggests also that randomizing the memory set may maintain a working memory task's central executive demands across a larger number of trials, rather than increase central executive demands per se. This interpretation is consistent with the convention in the cognitive literature of randomizing memory set to maximize working memory demands (Conway et al., 2005), as well as research indicating that central executive demands attenuate when task demands are predictable due to developing task expertise (Baddeley, 2007). The current results extend this literature by providing the first demonstration of this phenomenon in a clinical child population.

The positive association between central executive demands and activity level observed in the present study is consistent with previous investigations comparing actigraph-measured activity level for children with ADHD during tasks with high relative to minimal working memory demands (Rapport et al., 2009) and provides new data linking activity level with central executive processes specifically rather than working memory in general. Furthermore, this pattern is unlikely to be attributable to time-on-task effects because we controlled for task duration differences and found differential performance patterns across the two task variants despite an equivalent number of total trials. Taken together, the current findings provide experimental support for models of ADHD that propose a functional relation between working memory and motor activity (Killeen, Russell, & Sergeant, 2013; Rapport et al., 2008, 2013), and contradict models describing hyperactivity as a ubiquitous deficit that is unrelated to cognitive demands imposed by the environment. It will be important for future investigations to extend these cross-sectional findings by documenting the extent to which developmental changes in working memory and activity level interact to affect the remission of ADHD symptomology (Halperin & Schulz, 2006; Trampush, Jacobs, Hurd, Newcorn, & Halperin, 2014).

Despite the current study's experimental design, our understanding of the directional relation between central executive demands and gross motor activity remains limited. This relation is likely transactional, and key third variables are likely involved in the functional relation we observed. For example, the Rapport et al. (2009) model proposes that hyperactivity, or excess gross motor activity, facilitates working memory processing by increasing cortical arousal to help compensate for the ontogenetically underdeveloped cortical structures underlying working memory abilities (Shaw et al., 2007) and associated chronic cortical underarousal (Barry, Clarke, McCarthy, Selikowitz, & Rushby, 2005; Zentall & Zentall, 1983). In other words, the relation between gross motor activity and central executive functioning is expected to be indirect, whereby the central executive monitors environmental demands and signals the need to up-regulate gross motor activity in response to these demands. This increased gross motor activity increases cortical arousal, which in turn facilitates working memory processing (Rapport et al., 2009).[7] This hypothesis is consistent with an emerging literature demonstrating improvements in some aspects of behavior and cognitive test performance following physical exercise (Hoza et al., 2015). However, no study of ADHD children to date has examined the impact of increasing (or rarefying) activity level on central executive working memory performance, and the cognitive-enhancing benefits of acute physical exercise for children with ADHD may be time limited (Pontifex, Saliba, Raine, Picchietti, & Hillman, 2013). In addition, future studies will benefit from inclusion of physiological measures to directly test the hypothesized mediation chain between central executive working memory, physiological arousal, and task performance.

The unique contribution of the current study was its experimental evaluation of the relation between central executive functioning and gross motor activity in a well-defined sample of children with ADHD. Several caveats merit consideration despite methodological refinements such as the validation of a novel experimental method for increasing central executive demands, objective measurement of gross motor activity, and use of multiple tasks of varying modalities to isolate performance and motor activity associated with central executive functioning. Generalization of findings from highly controlled laboratory experiments are always limited to some extent, and no conclusions regarding central executive *deficits* or *hyper*activity can be drawn due to the lack of a typically developing comparison group. However, ADHD-related impairments in central executive functioning (Kasper et al., 2012) and increased gross motor activity across all ADHD subtypes/current presentations (Dane et al., 2000) are well documented, and recruitment of a typically developing comparison sample was not feasible in the context of the larger treatment study. Furthermore, results were generally consistent with hypotheses generated from studies of healthy individuals (Conway et al., 2005), suggesting that the findings likely inform neuropsychology rather than reflecting a phenomenon unique to children with ADHD. Future research that includes typically developing and clinical comparison groups is clearly needed to determine the extent to which children with ADHD are differentially affected by the increased central executive demands associated with memory set unpredictability.

In addition, several of the children with ADHD met criteria for comorbid behavioral and mood disorders; thus, the extent to which the findings generalize to children with "pure" ADHD is unknown. The inclusion of these common comorbidities, however, is expected to improve generalizability of the findings given that the sample is more representative of the larger population of children with ADHD (for which the majority have at least one comorbid diagnosis; Wilens et al., 2002). The mean IQ of our sample was higher than the national average by approximately 2/3 *SD*. Although reflective of the higher SES of the region from which the sample was recruited and similar to the mean IQ reported in other relatively high SES ADHD samples (Abikoff et al., 2013), the extent to which the findings generalize to samples of children with ADHD, or children in general, with average or lower intellectual abilities remains unknown. Finally, third variable explanations cannot be ruled out conclusively, and future research is needed to disentangle the potentially interactive influences of motivational and affective systems, proactive interference, and arousal (Dovis et al., 2013).

Clinical and Research Implications

Collectively, the results underscore the importance of considering the influence of environmental cognitive demands on the gross motor behavior of children with ADHD and suggest that at least in some circumstances their increased gross motor activity may be functional (Hartanto, Krafft, Iosif, & Schweitzer, 2015; Sarver, Rapport, Kofler, Raiker, & Friedman, 2015). As such, the observed relation between central executive demands and ADHD-related gross motor behavior lends strong support to recent efforts to refine the specificity of cognitive interventions for children with ADHD (Chacko et al., 2014; Rapport et al., 2013). The current study also provides the first empirical support for the cognitive literature's convention of randomizing the memory set within and across blocks. Adopting this methodological approach appears to provide improved measurement of working memory relative to standardized assessments that utilize sequential presentation orders. In future studies, we recommend matching the total number of stimuli across each Mixed and Ordered block (rather than over the whole task), counterbalancing the Ordered blocks to disentangle set size/proactive interference buildup, and employing experiment presentation software that time-stamps each stimulus presentation to allow more direct comparison of ADHD-related behavior during individual trials. Overall, this refined measurement and manipulation of central executive working memory demands appears to provide a parsimonious method for furthering our understanding of the complex interrelations among cognitive, environmental, and behavioral sequelae of ADHD.

Acknowledgments

The authors thank Erin Lunsford, Paula Aduen, Dr. Hillary Schaefer, and the CLC-V undergraduate research assistants.

Authors' Note

All authors contributed substantially to the conceptualization and development of the study.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was supported by a UVa Curry School of Education Foundation grant (principal investigator [PI]: Kofler) from the Galant Family. Manuscript preparation was supported in part by a

National Institutes of Health (NIH) grant (R34 MH102499-01, PI: Kofler). The sponsors had no role in design and conduct of the study; collection, management, analysis, and interpretation of the data; or preparation, review, or approval of the manuscript.

Notes

1. Similar manipulations have been used to increase set shifting (cognitive flexibility) and inhibition demands, two of the other "Big 3" executive functions with working memory updating (Miyake et al., 2000). *Mixing costs* refer to increased set shifting demands when participants are required to switch between two competing task goals (Kray, Karbach, Haenig, & Freitag, 2012; Monsell, 2003) or increased inhibitory demands associated with mixing congruent and incongruent trials within an experimental block relative to their performance when separately completing the same two tasks. Mixing costs are postulated to reflect the added working memory demands associated with maintenance of two sets of task rules (set shifting) or an infrequently applied rule (inhibition) during mixed relative to nonmixed blocks (Monsell, 2003). In the current study, mixing costs are expected to reflect central executive instead of shifting/inhibitory processes because the task goal remains constant across trials despite differing number of stimuli. In other words, the current study's *Mixed* condition (see "Method" section) requires additional updating and monitoring processes attributed to the central executive (Baddeley, 2007), and disallows strategies intended to decrease central executive processes associated with knowing the memory set (Conway et al., 2005).
2. Two children with ADHD failed to meet the teacher cutoff criteria, likely due to behavior well controlled on medication. In both cases, previous psychoeducational evaluations were available that documented cross-setting behavioral symptoms and impairment.
3. Of these four children, two were diagnosed with an autism spectrum disorder, one with an anxiety disorder, and one with obsessive-compulsive disorder.
4. We acknowledge that some reliable, shared variance may be related to non-central executive and/or activity level shared method factors, as experimental conditions between our phonological and visuospatial tasks were as identical as possible by design. Based on the converging evidence above, however, we believe that a latent approach to isolating central executive performance and activity level provides more valid estimates than the use of any single task.
5. Age interacted with set size for the Response Time analysis ($p < .001$); the pattern of results was unchanged with age included in the analyses.
6. As shown in Figures 1 and 2, results were highly consistent when examining performance and activity level separately for the visuospatial and phonological tasks.
7. The Rapport et al. (2009) model specifies that this positive association occurs when task demands fall within a child's zone of proximal development and notes that activity level may function as escape behavior when task demands overwhelm the child's ability level.

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