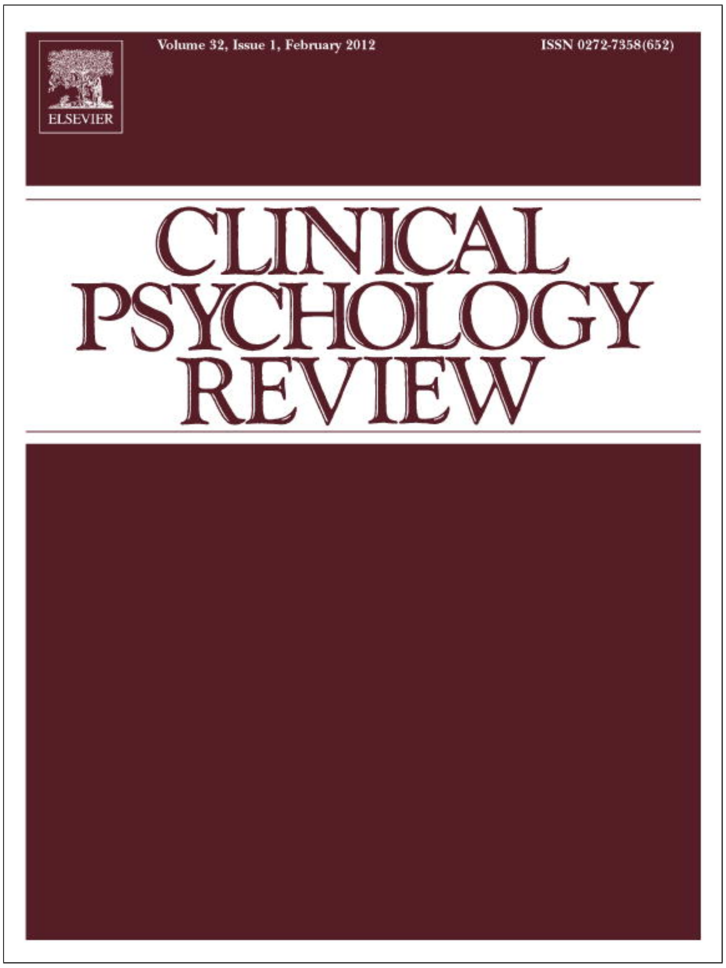
Volume 32, Issue 1, February 2012
ISSN 0272-7358(652)
ELSEVIER
CLINICAL
PSYCHOLOGY
REVIEW

Clinical Psychology Review 32 (2012) 605–617

Contents lists available at SciVerse ScienceDirect

Clinical Psychology Review

Moderators of working memory deficits in children with attention-deficit/hyperactivity disorder (ADHD): A meta-analytic review

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HIGHLIGHTS

- ► ADHD-related working memory (WM) deficits serve as a potential endophenotype of the disorder.
- ► Meta-analytic techniques examined the magnitude of ADHD-related WM deficits.
- ► Meta-regression revealed statistically significant moderators of effect size variability across WM tasks.

ARTICLE INFO

Article history:
Received 11 October 2011
Received in revised form 2 July 2012
Accepted 7 July 2012
Available online 17 July 2012

Keywords:
ADHD
Working memory
Attention
Meta-analysis

ABSTRACT

Working memory has assumed a prominent role as a primary neurocognitive deficit or endophenotype in extant models of attention-deficit/hyperactivity disorder (ADHD). The current study updated previous reviews and employed meta-analytic techniques to examine a broad range of moderating variables of effect size heterogeneity across phonological and visuospatial working memory tasks. Collectively, results revealed large between-group effect sizes across both working memory domains. In addition, several sample (percent female) and task (number of experimental trials, recall vs. recognition tasks, and demands on the central executive) moderating variables explained significant effect size variability among phonological and visuospatial studies. These findings suggest that children with ADHD exhibit statistically significant, large magnitude working memory deficits relative to their typically developing peers.

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doi:10.1016/j.cpr.2012.07.001

1. Introduction

Attention-deficit/hyperactivity disorder (ADHD) is a pervasive childhood disorder that affects approximately 3% to 7% of the population (Ek et al., 2007; Lee, Oakland, Jackson, & Glutting, 2008; Polanczyk, de Lima, Horta, Biederman, & Rohde, 2007; Weyandt & DuPaul, 2006) and is characterized by difficulties with hyperactivity, impulsivity, and sustained attention (Barnett et al., 2001). Within the last several years, there has been increased interest in the identification of potential endophenotypes of ADHD (Castellanos & Tannock, 2002; Crosbie, Perusse, Barr, & Schachar, 2008). Endophenotypes underlie clinical symptoms, are less genetically complex, and are closer to the genome relative to the disorder's phenotype (Gottesman & Gould, 2003). Identification of potential endophenotypes is particularly advantageous to the examination of ADHD because it holds promise for the eventual development of more objective neurocognitive diagnostic procedures with improved predictive power relative to current best practices (Crosbie et al., 2008). Investigation of candidate endophenotypes may also lead to new treatment modalities that provide improved near- and long-term outcomes (Rapport et al., 2008).

ADHD-related working memory (WM) deficits have garnered particular attention as a potential endophenotype of the disorder, resulting in a considerable increase in published studies (Martinussen, Hayden, Hogg-Johnson, & Tannock, 2005; Pennington & Ozonoff, 1996; Willcutt, Doyle, Nigg, Faraone, & Pennington, 2005) of the construct, and its contribution to the ADHD phenotype (Castellanos & Tannock, 2002; Crosbie et al., 2008; Rapport, Chung, Shore, & Isaacs, 2001). While there are several theoretical models that describe working memory (e.g., Baddeley, 2007; Cowan, 1997; Engle, Kane, & Tuholski, 1999a; Miyake, Friedman, Emerson, Witzki, & Howerter, 2000), the current study's conceptualization of working memory is based on Baddeley's multi-component model since it is the most commonly referenced in ADHD research (Alderson, Rapport, Hudec, Sarver, & Kofler, 2010; Rapport et al., 2001). Baddeley's model describes working memory as a limited-capacity system that is responsible for producing, maintaining, and manipulating cognitive representations of stimuli, searching for same or similar stimuli in memory, and maintaining appropriate behavioral responses (Baddeley, 2003). The working memory system is comprised of the central executive (CE) that is primarily responsible for focusing and dividing controlled attention among concurrent tasks, and independent phonological (PH) and visuospatial (VS) storage/rehearsal subsystems (Baddeley, 2007). The storage/rehearsal components of the PH and VS subsystems are analogous to short-term memory (STM), which is not viewed as a separate process in Baddeley's model. A fourth component, the episodic buffer, is a relatively nascent structure, and primarily functions as a theoretical interface between the PH loop, VS sketchpad, CE, and long-term memory.

Working memory has assumed a prominent role in extant models of ADHD. For example, Barkley's inhibition model (Barkley, 1997) suggests that deficits of working memory reflect one of a number of executive function deficits that occur downstream from inhibitory impairments. The working memory model of ADHD (Rapport et al., 2001), in contrast, suggests that working memory deficits serve as a potential core component or endophenotype of the disorder that is upstream of inhibitory deficits and other executive functions, as well as DSM-IV-TR (American Psychiatric Association, 2000) defined core features such as inattention, hyperactivity, and impulsivity. Elucidating the effect-size magnitude of working memory deficits in children with ADHD, as well as variables that moderate between-study performance variability, will both inform these mechanistic theories and further the development of future genetic and etiological studies (Castellanos & Tannock, 2002).

Two previous meta-analytic reviews have examined working memory deficits in children with ADHD. The first review examined 17 studies published between 1980 and 2004 (Willcutt et al., 2005). The majority of reviewed studies (77% of VS and 55% of PH) found statistically significant between-group differences among children with ADHD and typically developing controls, with a large magnitude VS effect size (ES) of 0.75 and a medium PH effect size of 0.59. The review also examined potential moderating variables of between-group working memory differences, including sample source (community vs. clinic) and diagnostic classification (DSM-III, DSM-IV, DSM-IV-TR), and found that neither moderator predicted between-study variability (Willcutt et al., 2005). Overall, the authors suggested that the lack of universal executive function deficits in children with ADHD, as indicated by small effect sizes and inconsistent results among some studies, did not support a neurocognitive (e.g., working memory) deficit central to the disorder. Conclusions from this study may be premature, however, since only two moderating variables were included, neither of which were statistically significant predictors of between-study variability.

A more recent meta-analytic review of 26 studies examined working memory in ADHD by parsing tasks into four categories: verbal storage, verbal CE, spatial storage, and spatial CE (Martinussen et al., 2005). Larger between-group effect sizes were associated with spatial storage (ES = 0.85) and spatial CE tasks (ES = 1.06), while moderate between-group effect sizes were associated with verbal storage (ES = 0.47) and verbal CE (ES = 0.43) tasks. This study also examined two potential moderating variables including whether reviewed studies covaried the presence of reading difficulties/language impairment (RD/LI) and IQ, and found that the presence of comorbid reading difficulties or language impairment were statistically significant moderators of between-group effect sizes across both the spatial storage and spatial CE tasks. That is, studies that covaried RD/LI yielded larger effect sizes when compared to studies that did not control for this variable. In addition, IQ did not moderate between-group effect sizes across the verbal storage and verbal CE tasks. Several methodological limitations to the review of Martinussen et al. (2005), however, suggest conclusions from these findings should be interpreted with caution. For example, the review included studies with samples of preschool-aged children and young adults. Inclusion of these age groups is expected to confound the findings and limit generalizability to school-aged children and young adolescents (Ang & Lee, 2008; Lemaire & Callies, 2009), particularly since the effect of age was not examined as a potential moderator. Moreover, failure to account for effect size variability across included studies suggests that examination of other potential moderators is warranted. Finally, the review's calculation of Cohen's *d* to estimate effect sizes erroneously provides equal weight to both small and large sample sizes.

The current study updates previous meta-analytic reviews (Martinussen et al., 2005; Willcutt et al., 2005) with 40 studies not included in the last meta-analytic review, for a total of 45 studies. Further, this is the first meta-analytic review to examine the potential moderating effects of a variety of subject (samples' sex ratio, age) and task (the number of trials per set size, the performance metric, response modality, and CE Demand) variables on working memory deficits in children with ADHD compared to typically developing children. Examination of moderating variables is essential due to their potential influence on within- and between-study effect size variability (Holmbeck, 1997). In addition, examination of potential moderators may explain heterogeneous findings within and between studies.

2. Method

Literature searches were performed using the MEDLINE, PsycARTICLES, and PsycINFO databases and completed in January 2012. The following keywords were utilized: attention deficit disorder, ADHD, hyper* and atten*, each of which was paired with working memory, visual span, spatial span, short-term memory, phonological, visuospatial, and digit span. An asterisk following a root word instructed search engines to look for any derivative of the word that is followed by the asterisk (e.g., hyper*: hyperactive, hyperactivity). Studies that were cited in the studies obtained from the initial search were examined (backward search), and a forward search was conducted using the Social Science Citation Index to locate relevant studies that cited the included studies of working memory in children with ADHD.

Articles were included if they utilized a task that required temporary mental storage of verbal or VS information. Additional inclusion criteria required that the article: (1) included a sample of children or early adolescents ages 8–16 years; (2) included a typically developing control group and a group identified as ADHD, ADD, ADDH, or hyperkinetic disorder; (3) included PH and/or VS scores (rather than one composite score that reflects an aggregate of PH and VS performance); (4) included between-subjects comparisons; (5) was a published article (e.g., not a dissertation); (6) included adequate data to calculate an effect size for between-group working memory performance differences (e.g., studies were excluded that reported event-related potentials recorded during working memory tasks); and (7) was a study written in English.

The age range of 8–16 years was selected based on developmental differences in cognitive strategies and processes observed in children and adolescents relative to adults (Ang & Lee, 2008; Lemaire & Callies, 2009). Studies of children below 8 years of age were specifically excluded due to previous findings that indicate high variability in developmental differences in memory at a very young age (Pillow, 2008), and heterogeneity in preschool/early elementary school children's reading ability, which may particularly influence PH task performance (Brunswick, Martin, & Rippon, 2012; Nation & Hulme, 2011). Previous studies have also highlighted the difficulty of providing valid ADHD diagnoses at young ages (Harvey, Youngwirth, Thakar, & Errazuriz, 2009; Lahey, Pelham, Loney, Lee, & Willcutt, 2005; Tandon, Si, & Luby, 2011).

A study was identified as having an ADHD group if the diagnosis of ADHD, ADD, ADDH, or hyperkinetic disorder was based upon a previous diagnosis, semi-structured interview, parent/teacher rating scales, or any combination of these diagnostic methods. PH and VS effect sizes were computed and examined separately due to neuropsychological (Baddeley, 2007), neuroanatomical (Smith, Jonides, & Koeppe, 1996), neuroimaging (Fassbender & Schweitzer, 2006), and factor analytic (Alloway, Gathercole, & Pickering, 2006) findings that provide evidence for two independent systems. Examination of separate VS and PH effect sizes also parallels the routine procedure of examining the PH and VS systems separately in clinical evaluations of working memory (e.g., the Children's Memory Scale and Wide Range Assessment of Memory and Learning, WRAML-2; Cohen, 1997; Sheslow & Adams, 2003). Finally, examination of PH and VS tasks together (i.e., aggregating across modalities) would omit PH or VS data, since only one data point could be selected from each study. That is, multiple effect sizes derived from the same sample risk threats to statistical independence and overweight findings from a single sample (Lipsey & Wilson, 2001). Multiple effect sizes were included from the same study, however, if they provided sufficient data to calculate independent PH and VS effect sizes (i.e., one score for each modality). Finally, unpublished studies were not included to allow for a more direct comparison between the current study and previous reviews that are based on published studies (e.g., Martinussen et al., 2005), and to reduce the potential for inclusion bias since it is unfeasible (and perhaps unlikely) to successfully gather every unpublished study to date (Norris & Ortega, 2000).

The initial broad search resulted in 243 studies; however, one hundred and ninety-eight studies did not meet criteria for inclusion and were therefore excluded from the meta-analysis. Specifically, 86 studies included participants outside of the a priori specified age range, 55 did not include a control group, 17 did not include an ADHD group, 11 only provided a combined VS and PH composite score, and 29 were not written in English. It is noted that only five of the 26 studies reviewed by Martinussen et al. (2005) were included based on the current inclusion criteria. Specifically, 18 studies[1] were excluded because the participants did not fall between ages 8 and 16 years. One study was omitted because it did not provide a single PH score (i.e., a Digit Span composite score was used that included both Digit Span-Forward and Digit Span-Backward, which have different levels of moderating variables; Schmitz et al., 2002). One study did not provide an ADHD group (Adams & Snowling, 2001), and one study's task examined learning and long-term memory (i.e., delay before recall was 20 min), rather than WM processes (Mataro, Garcia-Sanchez, Junque, Estevez-Gonzalez, & Pujol, 1997). Collectively, forty-five studies were included in the current study's final analyses. Six included studies were published before Martinussen's time parameters (i.e., earlier than 1997) and thirty-four included studies were published since Martinussen's literature search ended in 2003.

In an effort to include only one task from a study in a single modality, multiple tasks fitting criteria for the same condition were omitted based on a priori guidelines. Specifically, the first step gave preference to study conditions that provided the most complete data since incomplete data results in exclusion from later moderation analyses.[2] As a next step, conditions that placed greater demands on working memory (e.g., Letter–Number Sequencing; McGurk et al., 2004), particularly the CE, were given preference over conditions that reflected simple storage/rehearsal processes (e.g., Digit Span Forward; Wechsler, 2003). Collectively, this process resulted in 100% agreement between two independent coders. Finally, remaining studies that could not be selected by the above criteria were selected randomly when task demands were equivalent and none of the a priori selection guidelines provided resolution.

Within the 45 studies, 54 experimental tasks/conditions were omitted to avoid inclusion of multiple effect sizes derived from the same sample. Nine tasks were excluded because they had less complete performance data compared to other tasks within the study (e.g., one study designed a novel WM task and did not report task parameters). Data from 24 simple-storage tasks were not included in favor of data from tasks that required mental manipulation of temporarily stored information. Nine tasks included a composite score (e.g., Digit Span that includes data from both forward and backward conditions) that was omitted. An additional 12 tasks did not differ with regard to predetermined inclusion criteria, so one task/condition was chosen randomly from each of the 12 studies. Finally, one study (Karatekin, 2004) provided nine experimental conditions with three set sizes and post-stimulus delays. Data from the condition with the second largest set size and delay (set size 7, 6- second response time) was included to best reflect the overall aggregate findings. Another study (Kobel et al., 2008) provided three WM loads (0-back, 2-back, 3-back), and data from the second load (2-back) was included in an effort to reflect the tasks' median working memory demand.

Collectively, 45 studies provided sufficient data to examine 34 and 30 independent samples' PH and VS working memory performance, respectively. Studies were coded independently by two advanced graduate students for performance and moderator variable data. Inter-rater agreement was initially 91.2%. After definitions were reviewed and clarified by the two raters, data was independently re-coded until inter-rater agreement reached 100%. A mixed-effects model was used in the primary estimation of all effect sizes. Hedges' g effect sizes were calculated with means and standard deviations for 32 PH studies and 28 VS studies. Sample size and Pearson r were used to calculate the effect size for one VS and one PH task (Alderson et al., 2010), and sample size and p value were used to

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[1] A list of excluded studies is available from the corresponding author.

[2] The weighted regression used to examine potential moderation effects deletes cases listwise so that any missing data from a single study results in exclusion from the analysis.

Table 1
Working memory studies of between-group comparisons of ADHD and typically developing children.

Citation	N	Percent female	Mean ages (SD)	Measure	Trial #	Response modality	Performance metric	CE demand	PH/VS	Effect size[a]	95% confidence interval
Gorenstein, Mammato, and Sandy (1989)	21 ADHD 26 TD	4.76 57.69	10.07 (1.23) 10.18 (1.13)	Sequential matching memory task: 2-back	35	Recognition	Trial	High	VS	0.667	0.09–1.25
Shue and Douglas (1992), Cond. 1	22 ADHD 18 TD	13.64 11.11	NR NR	Digits backward (WMS)	2	Recall	Trial	High	PH	−0.401	−1.02–0.22
Shue and Douglas (1992), Cond. 2	24 ADHD 24 ADHD	12.50 12.50	10.30 (1.57) 10.31 (1.54)	Self-ordered pointing task	3	Recognition	Stimuli	High	VS	0.835	0.25–1.42
Shapiro et al. (1993)	67 ADHD 38 TD	16.42 26.32	8.94 (1.32) 8.97 (1.16)	Face memory (MNTAP)	15	Recognition	Trial	High	VS	0.335	−0.06–0.73
Ross, Hommer, Breiger, Varley, and Radant (1994)	13 ADHD 10 TD	0 50.00	11.21 (1.33) 11.53 (1.03)	Memory guided saccade task	10	Recall	Stimuli	Low	VS	0.585	−0.23–1.40
Garcia-Sanchez, Estevez-Gonzalez, Suarez-Romero, and Junque (1997)	16 ADHD 35 TD	31.25 20.00	14.70 (0.50) 14.90 (0.70)	Benton visual retention test	10	Recall	Trial	Low	VS	0.865	0.26–1.47
Kaplan, Dewey, Crawford, and Fisher (1998), Cond. 1	53 ADHD 112 TD	13.21 26.79	12.37 (2.37) 11.27 (2.21)	Number/letter (WRAML)	1 to 5	Recall	Trial	Low	PH	0.547	0.22–0.88
Kaplan et al. (1998), Cond. 2	53 ADHD 112 TD	13.21 26.79	12.37 (2.37) 11.27 (2.21)	Picture memory (WRAML)	4	Recall	Stimuli	Low	VS	−0.283	−0.61–0.04
Norrelgen, Lacerda, and Forssberg (1999)	9 ADHD 19 TD	0 0	11.17 (NR) 11.52 (NR)	Memory test: 5 syllables	16	Recognition	Stimuli	Low	PH	0.768	−0.03–1.56
Cornoldi et al. (2001), Cond. 1	22 ADHD 22 TD	22.72 22.72	9.40 (1.10) 9.20 (1.10)	Categorization listening span test: final word recall	3 or 10	Recall	Stimuli	High	PH	0.907	0.30–1.52
Cornoldi et al. (2001), Cond. 2	34 ADHD 50 TD	26.47 28.00	9.26 (1.39) 9.18 (1.35)	VS WM selective span task	6	Recall	Stimuli	High	VS	0.565	0.12–1.01
Willcutt et al. (2001)	35 ADHD 84 TD	NR NR	10.80 (2.20) 10.70 (2.20)	Counting span	3	Recall	Trial	High	PH	0.179	−0.21–0.57
Rucklidge and Tannock (2002)	35 ADHD 37 TD	42.86 51.35	15.18 (1.36) 14.95 (1.10)	DS backward (WISC-III)	2	Recall	Trial	High	PH	0.253	−0.21–0.71
McInnes, Humphries, Hogg-Johnson, and Tannock (2003), Cond. 1	21 ADHD 19 TD	0 0	10.90 (1.20) 10.80 (0.80)	DS backward (CMS)	2	Recall	Trial	High	PH	1.540	0.84–2.24
McInnes et al. (2003), Cond. 2	21 ADHD 19 TD	0 0	10.90 (1.20) 10.80 (0.80)	Finger windows-backward (WRAML)	1	Recall	Trial	High	VS	1.820	1.09–2.55
Karatekin (2004), Cond. 1	24 ADHD 27 TD	4.00 14.81	11.41 (1.88) 11.08 (1.82)	Verbal WM task	16	Recognition	Trial	Low	PH	0.549	0.00–1.10
Karatekin (2004), Cond. 2	24 ADHD 27 TD	4.00 14.81	11.41 (1.88) 11.08 (1.82)	Spatial WM task	16	Recognition	Trial	Low	VS	0.352	−0.19–0.90
Westerberg, Hirvikoski, Forssberg, and Klingberg (2004)	27 ADHD 53 TD	0 0	11.40 (2.20) 11.40 (2.00)	Visuospatial WM task	2	Recall	Stimuli	Low	VS	1.262	0.76–1.76
Goldberg et al. (2005)	21 ADHD 32 TD	9.52 34.38	9.80 (1.30) 10.40 (1.50)	Spatial WM (CANTAB)	4	Recall	Stimuli	High	VS	0.547	−0.01–1.10
Jonsdottir, Bouma, Sergeant, and Scherder (2005), Cond. 1	15 ADHD 15 TD	26.67 40.00	10.67 (1.29) 10.33 (1.29)	Number recall (K-ABC)	2	Recall	Stimuli	Low	PH	0.191	−0.51–0.89
Jonsdottir et al. (2005), Cond. 2	15 ADHD 15 TD	26.67 40.00	10.67 (1.29) 10.33 (1.29)	Spatial memory (K-ABC)	2 to 4	Recall	Stimuli	Low	VS	0.360	−0.34–1.06
Passolunghi, Marzocchi, and Fiorillo (2005)	10 ADHD 10 TD	NR NR	9.80 (0.48) 9.85 (0.49)	DS backward (WAIS-R)	2	Recall	Trial	High	PH	1.019	0.12–1.92
Happé, Booth, Charlton, and Hughes (2006)	29 ADHD 31 TD	0 0	11.60 (1.70) 11.20 (2.00)	Spatial WM (CANTAB)	4	Recall	Stimuli	High	VS	1.030	0.50–1.56
Healey and Rucklidge (2006)	29 ADHD 30 TD	27.58 56.67	11.44 (0.85) 11.10 (0.89)	DS backward (WISC-III)	2	Recall	Trial	High	PH	0.556	0.04–1.07
Rosenthal, Riccio, Gsanger, and Jaratt (2006)	28 ADHD 27 TD	21.43 55.55	11.44 (2.11) 11.49 (2.21)	DS backward (WISC-III)	2	Recall	Trial	High	PH	0.693	0.16–1.23
Manassis, Tannock, Young, and Francis-John (2007), Cond. 1	21 ADHD 35 TD	19.00 37.00	9.60 (1.43) 9.71 (1.32)	CHIPASAT	305	Recall	Trial	High	PH	1.104	0.53–1.68
Manassis et al. (2007), Cond. 2	21 ADHD 35 TD	19.00 37.00	9.60 (1.43) 9.71 (1.32)	Finger windows-backward (WRAML)	1	Recall	Trial	High	VS	0.811	0.26–1.37
Pasini, Paloscia, Alessandrelli, Porfirio, and Curatolo (2007), Cond. 1	25 ADHD 44 TD	0 0	10.05 (2.33) 10.63 (2.06)	1-Back WM test: phonological	20	Recognition	Trial	High	PH	0.571	0.08–1.07
Pasini et al. (2007), Cond. 2	25 ADHD 44 TD	0 0	10.05 (2.33) 10.63 (2.06)	1-Back WM test: spatial	20	Recognition	Trial	High	VS	0.305	−0.18–0.79

Table 1 (*continued*)

Citation	N	Percent female	Mean ages (SD)	Measure	Trial #	Response modality	Performance metric	CE demand	PH/VS	Effect size[a]	95% confidence interval
Soderlund, Sikstrom, and Smart (2007)	14 ADHD 21 TD	0 0	11.20 (1.20) 11.20 (1.10)	Verbal task	12	Recall	Trial	Low	PH	0.136	−0.53–0.80
Yang et al. (2007), Cond. 1	40 ADHD 40 TD	20.00 15.00	8.46 (1.63) 8.63 (1.37)	DS backward (C-WISC)	2	Recall	Trial	High	PH	0.723	0.27–1.17
Yang et al. (2007), Cond. 2	40 ADHD 40 TD	20.00 15.00	8.46 (1.63) 8.63 (1.37)	Corsi block tapping test	2 to 3	Recall	Trial	Low	VS	1.035	0.57–1.50
Drechsler, Rizzo, and Steinhausen (2008)	23 ADHD 24 TD	8.70 4.17	12.20 (0.80) 11.90 (0.60)	2-Back	75	Recognition	Trial	High	PH	0.179	−0.38–0.74
Kobel et al. (2008)	14 ADHD 12 TD	0 0	10.43 (1.34) 10.92 (1.62)	2-Back	40	Recognition	Trial	High	PH	1.047	0.25–1.85
Rapport et al. (2008), Cond. 1	12 ADHD 11 TD	0 0	8.75 (1.29) 9.36 (1.43)	Phonological task (number–letter)	24	Recall	Stimuli	High	PH	2.718	1.61–3.83
Rapport et al. (2008), Cond. 2	12 ADHD 11 TD	0 0	8.75 (1.29) 9.36 (1.43)	Visuospatial task (dot in the box)	24	Recall	Stimuli	High	VS	2.928	1.77–4.08
Skowronek, Leichtman, and Pillemer (2008), Cond. 1	12 ADHD 17 TD	0 0	12.20 (1.48) 11.50 (1.59)	DS backward (WISC-III)	2	Recall	Trial	High	PH	0.949	0.19–1.71
Skowronek et al. (2008), Cond. 2	12 ADHD 17 TD	0 0	12.20 (1.48) 11.50 (1.59)	Simon task	1	Recall	Trial	Low	VS	0.980	0.22–1.74
Tiffin-Richards, Hasselhorn, Woerner, Rothenberger, and Banaschewski (2008)	20 ADHD 19 TD	10.00 31.58	11.60 (1.30) 11.70 (1.30)	DS backward (HAWIK-R)	2	Recall	Trial	High	PH	0.852	0.21–1.50
Coutinho, Mattos, and Malloy-Diniz (2009)	186 ADHD 80 TD	15.10 23.75	11.50 (2.32) 12.38 (2.41)	DS backward (WISC-III)	2	Recall	Trial	High	PH	0.417	0.15–0.68
De Jong, Van de Voorde, Roeyers, Raymaekers, Allen, et al. (2009)	16 ADHD 26 TD	12.50 38.46	8.80 (1.30) 9.30 (0.90)	Corsi block tapping test	2 to 3	Recall	Trial	Low	VS	1.321	0.65–1.99
De Jong, Van de Voorde, Roeyers, Raymaekers, Oosterlaan, et al. (2009b)	24 ADHD 26 TD	16.67 38.46	9.00 (1.31) 9.31 (0.92)	Corsi block tapping test	2 to 3	Recall	Stimuli	Low	VS	5.347	4.17–6.53
Fassbender et al. (2009)	12 ADHD 13 TD	8.33 38.46	10.94 (4.22) 10.60 (1.80)	Visual serial addition task	30	Recognition	Trial	High	PH	0.538	−0.24–1.31
Gau, Chiu, Shang, Cheng, and Soong (2009), Cond. 1	53 ADHD 53 TD	24.50 24.50	12.70 (1.40) 12.70 (1.20)	DS backward (WISC-III)	2	Recall	Trial	High	PH	0.245	−0.13–0.62
Gau et al. (2009), Cond. 2	53 ADHD 53 TD	24.50 24.50	12.70 (1.40) 12.70 (1.20)	Spatial span (CANTAB)	2 to 3	Recall	Trial	Low	VS	0.101	−0.28–0.48
Gomarus et al. (2009)	15 ADHD 15 TD	26.67 26.67	9.82 (1.09) 10.15 (1.41)	Visual memory search task	320	Recognition	Trial	High	PH	1.114	0.36–1.87
Loe, Feldman, Yasui, and Luna (2009)	26 ADHD 33 TD	38.46 48.48	10.20 (1.60) 10.40 (1.70)	Memory guided saccade task	32	Recall	Stimuli	Low	VS	0.727	0.20–1.25
Mahone, Mostofsky, Lasker, Zee, and Denckla (2009)	60 ADHD 60 TD	40.00 48.33	10.30 (1.30) 10.30 (1.30)	Memory guided saccade task	≥72	Recall	Stimuli	Low	VS	0.096	−0.26–0.45
Alderson et al. (2010), Cond. 1	14 ADHD 13 TD	0 0	9.27 (1.09) 10.29 (1.53)	Phonological task (number-letter)	24	Recall	Stimuli	High	PH	2.778	1.42–4.13
Alderson et al. (2010), Cond. 2	14 ADHD 13 TD	0 0	9.27 (1.09) 10.29 (1.53)	Visuospatial task (dot in the box)	24	Recall	Stimuli	High	VS	2.886	1.49–4.28
Alloway, Elliott, and Place (2010), Cond. 1	13 ADHD 13 TD	23.08 46.15	9.10 (0.75) 9.30 (0.58)	Counting recall (AWMA)	6	Recall	Trial	High	PH	1.413	0.58–2.25
Alloway et al. (2010), Cond. 2	13 ADHD 13 TD	23.08 46.15	9.10 (0.75) 9.30 (0.58)	Spatial span (AWMA)	6	Recall	Trial	High	VS	1.205	0.39–2.02
Huang-Pollock and Karalunas (2010)	27 ADHD 39 TD	31.25 64.58	10.42 (1.47) 10.48 (1.08)	Alphabet arithmetic	288	Recall	Trial	High	PH	0.825	0.32–1.33
Kofler et al. (2010), Cond. 1	15 ADHD 14 TD	0 0	9.22 (1.06) 10.29 (1.46)	Phonological task (number–letter)	24	Recall	Trial	High	PH	2.139	1.24–3.04
Kofler et al. (2010), Cond. 2	15 ADHD 14 TD	0 0	9.22 (1.06) 10.29 (1.46)	Visuospatial task (dot in the box)	24	Recall	Trial	High	VS	2.047	1.16–2.93
Marx et al. (2010)	20 ADHD 20 TD	0 0	9.75 (1.84) 9.76 (1.59)	2-Back	60	Recognition	Trial	High	PH	0.436	−0.18–1.05
Nyman et al. (2010), Cond. 1	30 ADHD 30 TD	16.70 13.30	8.67 (0.80) 8.63 (0.72)	DS backward (WISC-III)	2	Recall	Trial	High	PH	0.731	0.21–1.25
Nyman et al. (2010), Cond. 2	30 ADHD 30 TD	16.70 13.30	8.67 (0.80) 8.63 (0.72)	Corsi block tapping test	2 to 3	Recall	Trial	Low	VS	0.073	−0.43–0.57
O'Brien et al. (2010), Cond. 1	56 ADHD 90 TD	46.43 46.67	10.20 (1.30) 10.20 (1.30)	DS backward (WISC-IV)	2	Recall	Trial	High	PH	0.324	−0.01–0.66
O'Brien et al. (2010), Cond. 2	56 ADHD 90 TD	46.43 46.67	10.20 (1.30) 10.20 (1.30)	Spatial WM (CANTAB)	4	Recall	Stimuli	High	VS	0.407	0.07–0.74
Zinke et al. (2010)	22 ADHD 39 TD	18.18 35.90	9.80 (0.89) 9.73 (0.74)	1-Back: pictures	24	Recognition	Trial	High	VS	0.142	−0.37–0.66

(*continued on next page*)

Table 1 (*continued*)

Citation	N	Percent female	Mean ages (SD)	Measure	Trial #	Response modality	Performance metric	CE demand	PH/VS	Effect size[a]	95% confidence interval
Alloway (2011), Cond. 1	50 ADHD 50 TD	14.00 40.00	9.75 (1.00) 9.91 (1.00)	Listening recall (AWMA)	6	Recall	Trial	High	PH	0.834	0.43–1.24
Alloway (2011), Cond. 2	50 ADHD 50 TD	14.00 40.00	9.75 (1.00) 9.91 (1.00)	Spatial span (AWMA)	6	Recall	Trial	High	VS	0.794	0.39–1.20
Fassbender et al. (2011)	13 ADHD 13 TD	15.38 38.46	10.7 (4.13) 10.6 (1.80)	Visual serial addition task	30	Recognition	Trial	High	PH	0.535	−0.22–1.29

Note. All studies were between-group comparisons of ADHD and typically developing children. Number of females reported as percentage. ADHD = Attention-Deficit/Hyperactivity Disorder; AWMA = Automated Working Memory Assessment; C-WISC = Wechsler Intelligence Scale for Children—Revised—Chinese Edition; CANTAB = Cambridge Neuropsychological Test Automated Battery; CE = central executive; CHIPASAT = Children's Paced Auditory Serial Addition Task; CMS = Children's Memory Scale; DS = Digit Span; HAWIK-R = Wechsler Intelligence Scale for Children—Revised—German Edition; K-ABC = Kaufman Assessment Battery for Children; MNTAP = Minnesota Tests of Affective Processing; NR = not reported; PH = phonological; TD = typically developing; VS = visuospatial; WAIS = Wechsler Adult Intelligence Scale; WISC = Wechsler Intelligence Scale for Children; WM = working memory; WMS = Wechsler Memory Scale; WRAML = Wide Range Assessment Of Memory And Learning.

[a] Positive effect sizes reflect poorer performance (lower accuracy or greater errors) by the ADHD group.

calculate the effect size for one VS (Shapiro, Hughes, August, & Bloomquist, 1993) and one PH task (Gomarus, Wijers, Minderaa, & Althaus, 2009). Table 1 provides a complete list of studies and included moderating variables and Hedges' g effect size estimates.

2.1. Potential moderators

2.1.1. Percent female

The ADHD phenotype frequently presents differently in females and males, such that females are more likely to exhibit attention difficulties in the absence of hyperactivity–impulsivity symptoms, which are typically present in boys with the disorder (Abikoff et al., 2002; Biederman & Faraone, 2004; Graetz, Sawyer, & Baghurst, 2005). In addition, previous research suggests that executive function (e.g., working memory) deficits in females are less severe relative to deficits present in boys (Seidman, Biederman, Faraone, & Weber, 1997), and unlike their male counterparts, females with ADHD exhibit less decreased neural activity in the prefrontal regions associated with working memory (Valera et al., 2010). These findings suggest that studies with samples consisting of a high percentage of females with ADHD are expected to find smaller magnitude between-group differences relative to studies that utilized predominantly male samples. Consequently, the percent of female participants in the ADHD group was examined as a moderator to determine if small magnitude or non-significant statistical findings in previous experimental and meta-analytic studies can be explained by gender differences in ADHD. The percentage of females in the ADHD group included in each study was analyzed as a continuous moderating variable.

2.1.2. Age

Previous studies suggest that working memory tends to emerge early in life, continues to develop until about 13–15 years (Brocki & Bohlin, 2004; Brocki & Bohlin, 2006; Korkman, Kemp, & Kirk, 2001), and improves with age among both children with ADHD and typically developing children (Klingberg, Forssberg, & Westerberg, 2002; Van der Molen, Van Luit, Van der Molen, Klugkist, & Jongmans, 2010). Further, children with ADHD exhibit working memory functioning similar to younger children (Brocki & Bohlin, 2006). Consequently, studies that included samples of older children were expected to find smaller effects, as older children with ADHD would have more time to developmentally “catch up” to their non-affected peers. The overall sample's mean age was analyzed as a continuous moderating variable.

2.1.3. Trials per set size

Studies that utilize relatively few trials are expected to be less reliable since multiple trials can be averaged in an effort to reduce error (Bland & Altman, 1996) and the use of fewer trials is associated with lower internal consistency (Welsh, Revilla, Strongin, & Kepler, 2000). Furthermore, previous research suggests that demands on working memory may have a cumulative effect, such that working memory resources are depleted after multiple trials (Anguera et al., 2012), and an adequate number of trials must be included to provide a valid measure of learning (Stepanov, Abramson, Wolf, & Convit, 2010). That is, studies with relatively few trials are expected to put fewer demands on working memory resources relative to studies with many trials (Burton & Daneman, 2007). Consequently, studies that rely on relatively few trials per set size may not effectively capture between-group working memory differences and are expected to find smaller between-group effect sizes relative to studies that included a greater number of trials per set size (Rapport et al., 2008). A dichotomous moderating variable, *Trials Per Set Size*, was created by categorizing studies that included fewer than ten trials per set size as “low” (coded as 0), and studies that included greater than or equal to ten trials per set size as “high” (coded as 1). Using a dichotomous variable allowed for the inclusion of studies with variable set sizes. In addition, 10 was chosen as the cut point since previous research has demonstrated that learning and memory begins to degrade after 7–10 trials (Stepanov et al., 2010).

2.1.4. Performance metric

Working memory performance accuracy is typically defined as either total correct trials or total correct stimuli, with the number of total correct trials currently being the most frequent approach to measuring working memory performance. Examination of total correct trials as a dependent measure, however, may not provide the most valid measure of participants' working memory abilities because discontinuing a task after a predetermined number of incorrect trials (e.g., after two incorrect trials on digit-span tasks) may discard potential correct answers on subsequent trials, and consequently underestimate one's working memory ability (Conway, Cowan, & Bunting, 2001). That is, external factors such as momentary distraction or lack of motivation during a smaller set size may result in errors that lead to a discontinued test and an underestimate of the participants' maximum storage capacity. Examination of the performance metric as a moderator may explicate whether small or statistically nonsignificant effect sizes reported in previous studies may be explained by the use of total trials correct as a dependent measure. Consequently, the moderating variable *Performance Metric* was created by coding studies as trials correct (0) or stimuli correct (1).

2.1.5. Response modality

Recall and recognition tasks rely on separate cognitive processes (Kahana, Rizzuto, & Schneider, 2005) and are correlated with discrete neurological structures located in the anterior cingulate, thalamus, globus pallidus, and cerebellum (Cabeza et al., 1997). Recall tasks are expected to place greater working memory demands on children because they require more effortful, self-initiated processes, compared to the simpler task of choosing a stimulus among a group of options (recognition task; Baddeley, Chincotta, Stafford, & Turk, 2002; Craik & McDowd, 1987). Consequently, studies that utilize recognition tasks are expected to find statistically non-significant or small effect sizes relative to studies that utilize recall tasks, due to less demand placed on the working memory system. *Response Modality* was examined as a moderating variable to determine if small or statistically nonsignificant effect sizes may be explained by the use of recognition rather than recall tasks. Studies were categorized into those that included recognition tasks (0) and those that included recall tasks (1) as their measure of working memory.

2.1.6. CE demand

Extant studies traditionally reify tasks that require temporary storage, maintenance, and manipulation of PH or VS information (i.e., place high demand on the CE) as measures of working memory (Luciana, Conklin, Hooper, & Yarger, 2005; Passolunghi & Mammarella, 2010). Examples of these tasks include Digit Span-Backward Letter–Number Sequencing from the Wechsler scales (Wechsler, 2003) and Finger Windows-Backward from the WRAML-2 (Sheslow & Adams, 2003). These tasks are frequently categorized as placing a higher demand on the CE since they require the participant to remember stimuli and later recall the stimuli in a different pattern than the original presentation. Previous experimental (Lambek et al., 2010; Rucklidge & Tannock, 2002; Toplak, Rucklidge, Hetherington, John, & Tannock, 2003; Willcutt et al., 2001) and meta-analytic (Martinussen et al., 2005; Willcutt et al., 2005) reviews have adopted this rationale to examine the difference between tasks that provide a measure of storage (e.g., Digit Span-Forward with low CE Demand) and those that require manipulation (e.g., Digit Span-Backward with high CE Demand). The potential moderator variable *CE Demand* was created by dichotomously coding studies as 0 (low CE Demand) or 1 (high CE Demand). Specifically, high-CE demand studies were defined as those that required temporary storage and manipulation of information (e.g., backward span tasks); and/or required shifts of focused attention to concurrently process/evaluate new stimuli while maintaining other information in temporary storage (e.g., dual tasks, sentence span tasks); and/or required comparison of a presented stimulus to temporarily stored information while concurrently updating stored information (e.g., *n*-back tasks). Low-CE demand studies were defined as those that only required the temporary storage and rehearsal of PH or VS information.

3. Results

3.1. Effect sizes

Effect size estimates were computed using Comprehensive Meta-Analysis Version 2 (CMA; Borenstein, Hedges, Higgins, & Rothstein, 2005) software. Positive effect sizes indicate higher mean scores for the control group relative to the ADHD group, while negative effect sizes indicate lower mean scores for the control group relative to the ADHD group. Hedges' g effect sizes were used in the current meta-analysis since the metric weights each effect size by its standard error: a procedure that corrects the problem of equal weight given to effect sizes of small and large samples (Lipsey & Wilson, 2001). Effect sizes are classified as small ($ES \leq 0.30$), medium ($0.30 < ES < 0.67$), or large ($ES \geq 0.67$), whereas an ES of zero indicates no difference between means (Lipsey & Wilson, 2001). While most studies reported accuracy (number of trials or stimuli correct) as their dependent variable, several studies reported errors (number of trials or stimuli incorrect). The direction of the effect size of the latter studies was reversed to provide uniform effect size data (e.g., an effect size of −0.46 was changed to 0.46). Finally, effect sizes were screened for outliers (i.e., values ≥ 3 SD above or below the mean) that may bias analyses.

A significant large effect size of 0.74 (95% confidence interval = 0.53 to 0.95) was calculated from 29 VS studies, which indicated that children with ADHD performed worse on VS tasks relative to typically developing children. A Q-test was performed to examine the studies' effect size distribution. A significant Q rejects the assumption of homogeneity and supports the examination of potential moderator effects (Lipsey & Wilson, 2001). The Q-test ($Q(28) = 124.70$, $p < .001$) indicated that there was significant heterogeneity among the calculated effect sizes, with effect sizes ranging from −.28 to 2.93. One study (De Jong, Van de Voorde, Roeyers, Raymaekers, Allen, et al., 2009) was excluded from the overall effect size calculation and further moderation analyses due to its exceptionally large magnitude effect size (5.35), which was larger than three standard deviations from the mean of the included effect sizes. Fail-Safe N analyses were subsequently performed to determine the likelihood that missing/unpublished studies may reduce the confidence interval of the effect size to include zero (i.e., result in no significant differences in ADHD and control groups; Lipsey & Wilson, 2001). The Fail-Safe N analysis revealed that approximately 1312 additional studies would need to be included to yield an effect size with a confidence interval that included zero. A funnel plot created from included studies was slightly asymmetrical with more studies found to the right of the point of no effect (Hedges' $g = 0$), and suggests there is mild evidence of publication bias within the sample of studies.

A significant large between-group (ADHD, TD) effect size of 0.69 (95% confidence interval = 0.53 to 0.84) was calculated from 34 PH studies and indicated children with ADHD performed worse on PH tasks compared to their typically developing peers. A Q-test ($Q(33) = 88.18$, $p < .001$) indicated that there was significant heterogeneity among the calculated effect sizes, with effect sizes ranging from −0.40 to 2.78. A Fail-Safe N analysis revealed that approximately 1649 additional studies would be needed to yield an effect size with a confidence interval that included zero (i.e., no significant between-group differences of performance on PH tasks). A funnel plot of included effect sizes was slightly asymmetrical with more studies found to the right of the point of no effect (Hedges' $g = 0$), and suggests there is mild evidence of publication bias within the sample of studies.

3.2. Moderator variables

Following the guidelines provided by Lipsey and Wilson (2001),[3] a mixed-effects weighted regression was completed with SPSS for Windows 18.0. The regression analyses were conducted in SPSS in lieu of CMA to allow for examination of the unique contribution of each potential moderator (i.e., CMA Version 2 only allows for examination of single moderators). A mixed-effects model was chosen due to the assumption that the proposed moderating variables likely did not account for all between-study effect size variability. That is, a mixed-effects model assumes that each included study is similar, but not identical, and effect size heterogeneity may result from fixed effects (i.e., moderators), random effects (e.g., covariates not measured but associated with the use of diverse working memory tasks), and error (Overton, 1998). The weighted regression provided a measure of overall fit (Q_R), as well as an error/residual term (Q_E). Specifically, a significant Q_R indicates that the model accounts for significant variability among effect sizes, while a significant Q_E indicates that the residual variance is greater than what is expected from random study-level sampling error (Lipsey & Wilson, 2001). Both statistics are distributed as chi-square. Furthermore, the weighted regression provides incorrect standard errors and p values since the method for assigning degrees of freedom are different for meta-analyses (Borenstein, Hedges, Higgins, & Rothstein, 2009). Consequently, beta-weights from each regression

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[3] Syntax to complete a mixed-model meta-regression is available from Lipsey and Wilson (2001).

were corrected and compared to a z-table to determine if the moderator was statistically significant (Guy, Edens, Anthony, & Douglas, 2005; Lipsey & Wilson, 2001). As a final step, all moderators were correlated to check for multicollinearity. All correlations between moderators were not significant (all $p > .05$), with the exception of a correlation between Response Modality and Trials per Set Size in PH studies ($r(32) = -.68$, $p < .05$). These moderators were retained in the analyses, however, due to previous findings from Monte Carlo simulations that indicate weighted-multiple regressions in meta-analyses are relatively immune to the influence of multicollinearity among moderating variables (Steel & Kammeyer-Mueller, 2002).

3.2.1. Visuospatial working memory (VS)

The potential moderating variables Percent Female, Age, Trials Per Set Size, Performance Metric, Response Modality, and CE Demand were included in the regression equation. The results of the weighted-multiple regression indicated that the model explained a significant proportion of effect size variability ($R^2 = 0.55$) in the VS effect size distribution, $Q_R = 27.11$, $df = 6$, $p < .001$. Four of the moderating variables significantly predicted effect size variability across the studies: Percent Female, $z = -3.72$, $p < .001$; Response Modality, $z = 3.63$, $p < .001$; Trials Per Set Size, $z = 2.26$, $p = .024$; and CE Demand, $z = 2.29$ $p = .022$. Studies that included a fewer number of females, recall tasks, a larger number of trials, and tasks that placed high demands on the CE were associated with larger between-group differences. A nonsignificant sum-of-squares residual, $Q_E = 22.32$, $df = 22$, $p = .441$, indicated that unexplained variability was not greater than would be expected from sampling error alone, and suggests the overall model is a good fit (Field & Gillett, 2010; Lipsey & Wilson, 2001). Table 2 provides a summary of the data for the regression analysis.

3.2.2. Phonological working memory (PH)

The potential moderating variables Percent Female, Age, Trials Per Set Size, Performance Metric, Response Modality, and CE Demand were included in the regression equation. The results of the weighted-multiple regression indicated that the model explained a significant proportion of effect size variability ($R^2 = 0.49$) across the PH effect size distribution, $Q_R = 24.99$, $df = 6$, $p < .001$. Four of the moderating variables significantly predicted effect size variability across studies: Percent Female, $z = -1.99$, $p = .046$; Response Modality, $z = 2.71$, $p = .007$; Trials Per Set Size, $z = 2.27$, $p = .023$; and CE Demand, $z = 2.09$, $p = .037$. Studies that included a fewer number of females, recall tasks, a larger number of trials, and tasks that placed high demands on the CE were associated with larger between-group differences. A nonsignificant sum-of-squares residual, $Q_E = 25.76$, $df = 24$, $p = .366$, indicated that unexplained variability was not greater than would be expected from sampling error alone, suggesting the overall model is a good fit (Field & Gillett, 2010; Lipsey & Wilson, 2001). Table 2 provides a summary of the data for the regression analysis.

Table 2
Weighted regression model and moderating variables for PH and VS.

	PH			VS		
	Q	df	p	Q	df	p
Regression	24.99	6	$.001^{***}$	27.11	6	$.001^{***}$
Residual	25.76	24	.366	22.32	22	.441
R^2	0.49			0.55		
Moderator variables	β^{a}	z	p	β^{a}	z	p
Constant	.71			.95		
Percent female	−.328	−1.99	$.046^{*}$	−.558	−3.72	$.001^{***}$
Age	−.233	−1.52	.127	−.191	−1.20	.229
Trials per set size	.477	2.27	$.023^{*}$	.390	2.26	$.024^{*}$
Response modality	.581	2.71	$.007^{**}$	.689	3.63	$.001^{***}$
Performance metric	.245	1.62	.105	−.055	−.361	.719
CE demand	.320	2.09	$.037^{*}$	.377	2.29	$.022^{*}$

Note. β = standardized beta weight; CE = central executive; df = degrees of freedom; PH = phonological; Q = chi-square value; R^2 = variance accounted for by the model; VS = visuospatial; z = z-value.

[a] Represents the standard deviation change in the dependent variable per each standard deviation change in the independent variable.

[*] $p < .05$.

[**] $p < .01$.

[***] $p < .001$.

3.3. Best case estimate

Best case estimation involves solving the regression equations derived from the two previous moderation analyses (i.e., PH and VS), with levels of each moderator that are considered best practice according to empirical research (Lipsey & Wilson, 2001). The weighted regression model allows estimation of between-group differences based on the influence of best practice levels of each moderating variable. Practically, the best case estimation procedure provides an estimate of the effect size that is expected if best practice procedures are utilized. Best case methodological variables include fewer females (0), younger children (8), larger number of trials (1), recall tasks (1), stimuli correct as the dependent measure (1), and high CE Demand (1). Values for the continuous variables female (0%) and age (8 years) were chosen to reflect the lowest percentage of females and age represented in the sample of included studies, respectively. Possible values for all dichotomous variables ranged between 0 and 1. To solve the equations, each PH moderator value was first multiplied by its respective unstandardized regression coefficient. The resulting products were subsequently summed and added to the PH regression equation's constant to provide an estimate of the best case PH effect size. The same procedure was repeated to estimate the best case VS effect size. Collectively, solving the regression equations for VS and PH studies with values to provide a best case estimate suggested that effect sizes of 2.15 and 2.01, respectively, are expected when studies include no females, younger children (8 years old, per the current study's inclusion criteria), a greater number of trials per set size, recall tasks, stimuli correct as the dependent variable, and place relatively higher demand on the CE.

An overlap statistic (OL%; Zakzanis, 2001) was calculated to examine the amount of expected overlap in working memory performance between the ADHD group and typically developing group, if the best case methodology is used. Given the best case estimate, the VS working memory performance of children with ADHD is only expected to overlap the performance of typically developing children by approximately 15.7% to 18.9%. In addition, there is approximately a 98% chance that the VS performance of children with ADHD will be below the mean score of children in the typically developing group. The overlap of PH working memory performance between children with ADHD and typically developing children is expected to be approximately 18.9%, and there is an estimated 98% chance that children with ADHD would exhibit PH working memory performance that is below the average score of children in the typically developing group. Table 3 provides results from the best case estimation and overlap statistic.

4. Discussion

Overall, studies that examined PH and VS working memory tasks yielded significantly large effects (PH = 0.69 and VS = 0.74), which indicate that children with ADHD generally demonstrate poorer performance on PH and VS working memory tasks relative to typically developing children. The magnitude of the current findings is similar to Willcutt et al.'s (2005) previous meta-analytic review that reported ESs of 0.59 and 0.75 for PH and VS working memory, respectively. In contrast, our findings were larger than the PH effect size estimates (0.43–0.47) reported by Martinussen et al. (2005), but smaller relative to their VS effect sizes of 0.85–1.06.

Table 3
Best case estimation and predicted overlap of ADHD and TD groups' WM performance.

Variable included	Effect size	% Nonoverlap	% Overlap	Overlap statistic[a]	% ADHD<TD[b]
CE demand					
PH Studies	2.01	81.1	18.9	0.92	98
VS Studies	2.15	81.1–84.3	15.7–18.9	0.92–0.96	98

Note. ADHD = attention-deficit/hyperactivity disorder; CE = central executive; PH = phonological; TD = typically developing; VS = visuospatial; WM = working memory.

[a] Probability of a randomly selected participant in the ADHD group performing lower than a randomly selected participant in the TD group.

[b] Percentage of the ADHD group that would fall below average in the TD group.

The discrepancy between the current findings and those of Martinussen et al. (2005) may reflect study-wide differences in task reification. That is, Martinussen and colleagues identified and grouped tasks as either storage or CE based on the amount of mental manipulation of information required for task completion (e.g., forward span tasks were categorized as storage while backward span tasks were categorized as CE). In contrast, the current study separated tasks according to modality (VS or PH) and then examined the effect of CE processes on between-group performance differences with the use of a moderator variable (CE Demand). This approach was believed to be a methodological improvement as it allowed for examination of the CE's moderation of between-study effect size heterogeneity, after covarying other task and sampling moderators. Inclusion of simple storage tasks (e.g., forward span tasks) in the overall ES estimates in the current study, however, likely reduced the VS effect size magnitude (Rapport et al., 2008). Finally, the relative similarity between the PH and VS effect sizes (ES difference of .05 with overlapping 95% CIs) in the current study is in contrast with previous meta-analytic (Martinussen et al., 2005; Willcutt et al., 2005) findings that have consistently revealed larger between-group differences in the VS domain. Consideration of the effect sizes predicted by the current best case estimation procedures, however, also suggests that larger magnitude effects are expected during VS, relative to PH tasks, and are consistent with the previous findings of Martinussen et al. (2005). Consideration of potential moderating effects may further explicate this discrepancy.

Consistent with a priori hypotheses, studies that required children to recall rather than recognize target stimuli, presented a larger number of trials per set size, and put greater demands on the CE component of working memory, were associated with larger effect size estimates. In addition, studies with samples consisting of fewer females were associated with larger between-group differences in PH and VS working memory performance. Examination of each moderator's standardized regression coefficient reveals that Response Modality (recall vs. recognition) was the strongest predictor of effect size heterogeneity, regardless of modality. The remaining moderators' regression coefficients were relatively consistent when compared across modalities, with the exception of Percent Female. Although the moderator was statistically significant in both PH and VS regression models, the effect of sex ratio was a weaker predictor of PH effect size heterogeneity. Consideration of typical working memory development, however, may explicate this finding. Specifically, extant literature suggests that most children experience a developmental shift around ages 6 or 7 years from predominantly relying on the VS system to predominantly relying on the PH system, and the association between CE and PH storage/rehearsal processes remains limited until at least 10 years of age (Gathercole, Pickering, Ambridge, & Wearing, 2004). The average age of participants included in the current meta-analysis was 9.47 years, suggesting that the inclusion of younger participants may have led to poorer PH working memory performance, regardless of sex. That is, the overall young age of the included samples may have suppressed potential sex differences as both young males and females are expected to exhibit relatively poor PH performance, and sex differences are not expected to emerge until later ages (Gathercole et al., 2004).

Although CE Demand was a statistically significant moderator of effect size variability across both VS and PH tasks, the relatively small magnitude of its contribution to each regression model was surprising. Previous studies that have utilized a latent variable approach to examine the independent contributions of CE and storage/rehearsal processes to the ADHD phenotype have consistently demonstrated compelling evidence that ADHD-related hyperactivity (Rapport et al., 2009), inhibition deficits (Alderson et al., 2010), attention deficits (Kofler, Rapport, Bolden, Sarver, & Raiker, 2010), and social skills deficits (Kofler et al., 2011) are predominantly attributable to CE processes. Consequently, CE Demand was expected to be one of the strongest predictors of ES variability, relative to other examined moderators. Consideration of the CE Demand coding criteria utilized in the current study, and particularly the inclusion of backward span tasks in the "high" CE demand category, may explicate this discrepancy. Previous experimental (Rosen & Engle, 1997), factor analytic (Cantor, Engle, & Hamilton, 1991), and structural equation model (Engle, Tuholski, Laughlin, & Conway, 1999b) studies have demonstrated that simple reversal of stimuli (e.g., Digit Span Backward) does not place sufficient demand on the CE (i.e., the "working" component of WM) to correctly reify a task as being a measure of working memory, relative to dual tasks that require frequent attentional shifts between concurrent processing of new information and rehearsal/maintenance of information temporarily held in the buffer/storage component. In contrast to the findings of Engle et al. (1999b), the current study coded backward span tasks with other tasks known to put high demands on the CE due to (1) the far greater proportion of published findings that identify backward span tasks as measures of WM (Oberauer, Süβ, Schulze, Wilhelm, & Wittmann, 2000), and (2) a need to develop a clearly defined and replicable coding scheme. That is, the findings from Engle et al. (1999b) could not sufficiently inform the development of precise moderator coding criteria, given the broad diversity of WM tasks included in the current review. Collectively, these findings suggest that coding backward span tasks with other high CE demand studies may have artificially deflated the moderator's magnitude. In addition, these findings emphasize the need for future research that improves task reification by examining the specific WM processes that are measured by the heterogeneous pool of available WM tasks.

Age and Performance Metric were the only moderators that did not predict between-study effect size heterogeneity. Despite including studies with samples of children as old as 16 years, the majority of reviewed studies included samples with an average age between 8–10 years. Consequently, restriction of range may have resulted in the statistically non-significant effect of age. The statistically nonsignificant moderation effect of Performance Metric was particularly surprising given previous research that suggests the examination of stimuli correct as a dependent variable, relative to trials correct, is a more sensitive measure (Conway et al., 2001). The current analyses, however, only inform about potential interaction effects and suggest that children with ADHD are not disproportionately affected by differences in tasks' performance metric. It is expected that the main effect of Performance Metric would be statistically significant if it was examined independently.

Overall, the current study's findings suggest that several methodological variables (i.e., greater trial numbers, recall tasks, fewer number of females, greater CE demands) are associated with large between-group working memory differences, while other variables (i.e., fewer trial numbers, recognition tasks, greater number of females, fewer CE demands) may suppress between-group effects. The influence of participant and task moderating variables is exemplified with findings from the best case estimates that solved each regression equation based on theoretically and methodologically best-practice procedures (Lipsey & Wilson, 2001). That is, working memory studies are predicted to yield exceptionally large PH (2.01) and VS (2.15) effect sizes when best case procedures are utilized, suggesting that approximately 98% of children with ADHD are expected to perform below the PH and VS means of typically developing children. These findings contrast conclusions from previous meta-analytic (Martinussen et al., 2005; Willcutt et al., 2005) and experimental (Lambek et al., 2010; Rucklidge & Tannock, 2002; Toplak et al., 2003; Willcutt et al., 2001) studies that suggest WM is not a neurocognitive deficit central to ADHD because between-group differences in WM performance are not uniformly found in all children with the disorder. It is noted, however, that the best case procedure only provides a hypothetical estimate and additional research that uses suggested parameters are needed before strong conclusions can be made.

Only two studies included in the current review were identified as utilizing task and sampling procedures consistent with best case methodology (Alderson et al., 2010; Rapport et al., 2008). Rapport and colleagues' PH task, for example, presents a jumbled sequence of numbers and a letter, and requires children to recall and say the numbers in numerical order and the letter last. This task is presented across 4 blocks of 24 trials, with each block differing in set size demands (i.e., number of stimuli to recall; 3, 4, 5, and 6) to assess potential between-group differences in storage capacity. Although similar to the Letter–Number Sequencing (LNS) task from the Wechsler scales (Wechsler, 2003), this task is expected to place greater demands on WM due to the greater number of trials per set size (i.e., LNS only presents 3 trials per set size). Rapport and colleagues' analogous VS task presents a series of jumbled black dots and one red dot in an offset 3 × 3 matrix. Children are required to recall and point to the serial location of the black dots followed by the red dot. Again, this task capitalizes on the increased demands of 24 consecutive trials per set size, recall rather than recognition processes, and increased CE demands relative to backwards span tasks. It is noted that Rapport et al.'s average, large-magnitude effect sizes of 2.72 and 2.93 suggest our best case estimation procedure may provide a moderate underestimation, and emphasizes the need for additional replication studies that utilize these sampling and task parameters.

Finally, the current findings have profound clinical implications with regards to both assessment and treatment of ADHD. For example, convergence of heuristic (Martinussen et al., 2005) and applied (Mayes & Calhoun, 2006) research may imply that clinicians should look for evidence of poor working memory performance on standardized intelligence tests to bolster their differential diagnosis of ADHD. In contrast, the current meta-analytic findings suggest that WM measures frequently included in cognitive assessments, such as the WISC-IV (Wechsler, 2003), may not adequately detect deficits in affected children, since standardized WM measures typically present few trials per set size and place low demands on the CE (i.e., Digit Span Forward and Digit Span Backward both load on the WISC-IV working memory factor; Wechsler, 2003). It is also not clear whether the same moderating variables that influence the detection of ADHD-related WM deficits would also affect treatment outcomes. Evidence from emerging clinical interventions developed to improve working memory, such as the Cogmed Working Memory Training (Klingberg et al., 2005), has provided encouraging results with improved WM performance and attention in children following completion of the program (Beck, Hanson, Puffenberger, Benninger, & Benninger, 2010; Klingberg et al., 2005). Examination of WM tasks included in the training, however, suggests the PH components are predominantly recognition tasks (Klingberg et al., 2002). PH tasks that instead target recall processes may result in larger treatment gains, given Response Modality was associated with the largest magnitude moderation effect in both PH and VS regressions.

The current study updated the previous meta-analytic reviews of Martinussen et al. (2005) and Willcutt et al. (2005) with 40 studies not included in the previous reviews, and was the first meta-analysis to examine previously unexamined moderators of working memory deficits in children with ADHD compared to typically developing children. A few potential limitations, however, warrant consideration. For example, several studies did not specify which subtype/s of ADHD (e.g., inattentive, hyperactive/impulsive, combined) were included. It is possible that including heterogeneous samples consisting of multiple ADHD subtypes may have confounded between-group effect size estimates. This concern is tempered, however, by findings from previous literature that suggest children in the inattentive, hyperactive/impulsive, and combined subtypes perform similarly on working memory tasks (Mayes, Calhoun, Chase, Mink, & Stagg, 2009). In addition, the funnel plots (PH and VS) reported in the current study suggested mild asymmetry in the distributions, which may indicate the presence of publication bias. Interpretation of asymmetrical funnel plots warrants caution; however, as asymmetry often reflects study heterogeneity due to methodological differences, rather than publication bias (Tang & Liu, 2000). Finally, although the current study limited its focus to ADHD, working memory impairments have been observed in other psychiatric diagnoses such as major depressive disorder (Rose & Ebmeier, 2005; Walsh et al., 2007) and generalized anxiety disorder (Hayes, Hirsch, & Mathews, 2008). Future studies are needed to determine if the presentation and/or magnitude of ADHD-related working memory deficits are unique to the disorder or characteristic of psychopathology more generally. Further research is also needed to explicate whether the current study's findings would yield the same results with preschool-age children or late adolescents/adults. It is expected that studies of very young children would report greater overall effect sizes, as children with ADHD would have had less time to developmentally catch up to their peers (Brocki & Bohlin, 2006; Mariani & Barkley, 1997). Conversely, studies of adults with ADHD are expected to exhibit relatively smaller magnitude effects, given the lifelong trajectory of ADHD that appears to attenuate in late adolescence and adulthood (Biederman, Mick, & Faraone, 2000; Faraone, Biederman, & Mick, 2006). This is likely particularly true for the VS system which is typically relied upon less as age increases (Woods, Lovejoy, & Ball, 2002). The effects of other moderators, such as Response Modality and Trials Per Set Size, are expected to remain relatively stable in both young children and adults.

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