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Working Memory Deficits and Social Problems in Children with ADHD

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Abstract Social problems are a prevalent feature of ADHD and reflect a major source of functional impairment for these children. The current study examined the impact of working memory deficits on parent- and teacher-reported social problems in a sample of children with ADHD and typically developing boys (N=39). Bootstrapped, bias-corrected mediation analyses revealed that the impact of working memory deficits on social problems is primarily indirect. That is, impaired social interactions in children with ADHD reflect, to a significant extent, the *behavioral outcome* of being unable to maintain a focus of attention on information within working memory while simultaneously dividing attention among multiple, on-going events and social cues occurring within the environment. Central executive deficits impacted social problems through both inattentive and impulsive-hyperactive symptoms, whereas the subsidiary phonological and visuospatial storage/rehearsal systems demonstrated a more limited yet distinct relationship with children's social problems.

Keywords ADHD · Working memory · Social problems · Central executive

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Clinically significant and impairing social problems are present in a majority of children with ADHD (52% to 82%; Huang-Pollock et al. 2009). The recognition of these problems as important features of the disorder is reflected in the current DSM-IV diagnostic criteria, which includes several symptoms related to impaired social conduct (e.g., difficulties in play activities, difficulties awaiting turn, not listening to others, frequent interrupting; APA 2000). Children with ADHD do not report experiencing social problems typically, but parent, teacher, and peer reports are highly consistent in attesting to their peer relational difficulties (van der Oord et al. 2005). For example, typically developing children rate children with ADHD and learning problems as less popular and less competent than their peers after only 1 min of observation (Bickett and Milich 1990), and children with ADHD are criticized and rejected by their peers within only 30 min of interaction (Boo and Prins 2007).

Peer nominations and teacher reports also reveal that children with ADHD like other children more than they are liked (Hoza et al. 2005), and are less popular, less cooperative, more disruptive, and have poorer overall social skills relative to their peers (Flicek 1992). In addition, parent and teacher reports reveal that these children are more likely to suffer from peer neglect and rejection, bully or be bullied (Bagwell et al. 2001), have fewer friends, appear more lonely, and engage in less varied activities relative to their typically developing peers (Heiman 2005). Observational studies are consistent with these reports, and reveal that children with ADHD not only make more demands, command statements, and negative responses during peer interactions, but also elicit more of these negative interactions from their peers (Cunningham and Siegel 1987) and parents (Winsler 1998).

Identifying potential underlying mechanisms and processes responsible for social problems in children with ADHD is imperative given the developmental continuity and pejorative long-term consequences associated with these difficulties. Problems forming and maintaining peer relationships begin in childhood for children with ADHD, and continue through adolescence (Bagwell et al. 2001) and into adulthood (Friedman et al. 2003). These problems are predictive of a host of negative outcomes, including delinquent behavior, substance abuse, and academic failure (Mikami and Hinshaw 2006).

Recent reviews are highly consistent in attributing social problems in children with ADHD to a performance deficit rather than a knowledge deficit (Boo and Prins 2007; Huang-Pollock et al. 2009). That is, they appear to possess age appropriate knowledge concerning the rules of social engagement, but fail to use this knowledge to guide their behavior when interacting with others. This inference is supported by findings from social skills training studies in which children with ADHD demonstrate appropriate social conduct when prompted, and by evidence of improved social interactions with other children and adults while receiving psychostimulant treatment without specific social skills training (Boo and Prins 2007). There is less agreement, however, regarding the underlying mechanisms and processes responsible for the failure of children with ADHD to engage in appropriate social behavior while interacting with others.

Early qualitative reviews attributed social problems in ADHD to the impairing nature of core symptoms such as impulsive and hyperactive behavior; specifically, the propensity of children with ADHD to be "intrusive, boisterous, annoying, and generally aversive to peers and others" (Landau and Moore 1991, p. 235). Empirical support for the relationship between core behavioral symptoms and social problems is derived from studies demonstrating significant correlations between social problems and ratings of inattention (r=0.61; Humphrey et al. 2007) and hyperactivity (r=0.53 to 0.61; Andrade et al. 2009). In addition, observational studies reveal that children with ADHD demonstrate less frequent visual orientation to others, take longer to respond, and provide more *non sequitur* responses during conversation relative to typically developing children (Stroes et al. 2003).

In contrast, several contemporary models predict that some or all of the core behavioral symptoms associated with ADHD may be secondary to underlying neurocognitive impairments such as deficient executive functioning (for a review, see Willcutt et al. 2005). For example, several studies have reported significant relationships between parent and teacher ratings of social problems and executive functioning tasks measuring planning, strategy generation, organization (Clark et al. 2002), effortful control (Dennis et al. 2007), and cognitive inhibitory control and verbal fluency (Nigg et al. 1999). Recent investigations, however, have found that executive functioning is unrelated to peer nominated social status (Diamantopoulou et al. 2007), and is not a significant mediator between ADHD symptoms and parent/teacher ratings of social problems (Huang-Pollock et al. 2009). In a similar vein, Biederman and colleagues (2004) found that children with ADHD with and without executive functioning deficits did not differ significantly in ratings of social impairment.

The discrepancy between studies reporting significant and non-significant relationships between executive function deficits and social problems in children with ADHD may reflect subtle differences among the studies, including sample demographics, diagnostic procedures, and the selection of measures used to estimate executive functioning deficits. This latter variable is a promising candidate for explaining between-study differences. Specifically, investigations reporting a significant relationship used individual executive function tasks as predictors (e.g., Clark et al. 2002), whereas those reporting a non-significant relationship calculated a composite executive functioning index to estimate the construct (e.g., Diamantopoulou et al. 2007). This discrepancy highlights the potential importance of isolating specific executive functioning processes such as working memory when investigating potential mechanisms underlying social performance deficits in children with ADHD.

Working memory is a limited capacity system for temporarily storing and processing internally held information for use in guiding behavior (Baddeley 2007). It consists of three primary components: two subsidiary systems responsible for the temporary storage and rehearsal of phonological (verbal) and visuospatial information, and a domain-general central executive.[1] The central executive is distinct from the more general *executive functioning* construct described in the literature, and refers to two empirically validated processes: focusing attention within working memory, and dividing attention among concurrent tasks (Baddeley 2007). The central executive also oversees and coordinates the phonological and visuospatial storage/processing components, and influences their interaction with long-term memory.

The relationship between social problems and working memory deficits in children with ADHD has not been investigated directly, despite consistent evidence that working memory is impaired in ADHD (Martinussen et al. 2005), and is linked functionally to both inattentive and

[1] A third storage component—viz., the episodic buffer—has been proposed recently to explain the integration of information from multiple cognitive systems, but is currently considered a "conceptual tool" (Baddeley 2007 page 149) rather than a formal component of the model.

hyperactive behavior (Kofler et al. 2010; Rapport et al. 2009). Other studies, however, have reported a significant relationship between working memory deficits and social problems in preschool children (Alloway et al. 2005) and children with 22q11 gene deletion disorder (Kiley-Brabeck and Sobin 2006). Recent experimental evidence (Phillips et al. 2007) also supports the involvement of working memory in social interactions, and indicates that increasing concurrent working memory demands significantly disrupts an individual's dynamic social decoding ability (i.e., the ability to rapidly interpret nonverbal social and emotional cues in others).

The functional working memory model of ADHD (Rapport et al. 2008b) makes three specific predictions regarding the impact of working memory deficits on social problems (Fig. 1) that can be tested empirically. First, working memory deficits in children with ADHD may impair their ability to store and recall information related to social functioning and process social cues effectively (Phillips et al. 2007). In this case, central executive and/or phonological/visuospatial subsystem performance deficits are expected to have a direct effect on social problems (Fig. 1 path c). Alternatively, working memory deficits may impact social problems indirectly (Fig. 1 path a*b). This hypothesis is based on previous findings indicating that working memory deficits are related functionally to inattentive and hyperactive behaviors (Kofler et al. 2010; Rapport et al. 2009), which in turn, are correlated highly with social problems (Andrade et al. 2009; Humphrey et al. 2007). The hypothesized indirect effect would thus indicate that one or more of the hallmark ADHD symptoms (inattention, impulsivity-hyperactivity) that occur because of working memory failure (e.g., interrupting others due to an inability to store intended speech temporarily while interacting with others) contribute significantly to the social problems experienced by children with ADHD. Finally, social problems experienced by children with ADHD may reflect both direct and indirect effects of working memory. In contrast, finding that inattention and/or impulsivity-hyperactivity show strong continuity with social problems independent of working memory influences (Fig. 1: significant path b, non-significant paths a & c) would lend support to prevailing views that the mechanism by which children with ADHD experience social problems is due primarily to the disruptive nature of core symptoms as opposed to the emergence of these symptoms secondary to working memory deficits.

The current study is the first to test empirically whether working memory deficits predict social problems in children with ADHD and typically developing children. Mediation analyses were used to estimate the direct and indirect impact of central executive, phonological storage/rehearsal, and visuospatial storage/rehearsal working memory functioning on cross-informant reports of ADHD symptoms and social problems.

Method

Participants

The sample comprised 39 boys aged 8 to 12 years (M= 9.70, SD=1.33), recruited by or referred to the Children's Learning Clinic-IV (CLC-IV) through community resources (e.g., pediatricians, community mental health clinics, school system personnel, self-referral). The CLC-IV is a research-practitioner training clinic known to the surrounding community for conducting developmental and clinical child research and providing pro bono comprehensive diagnostic and psychoeducational services. Its client base consists of

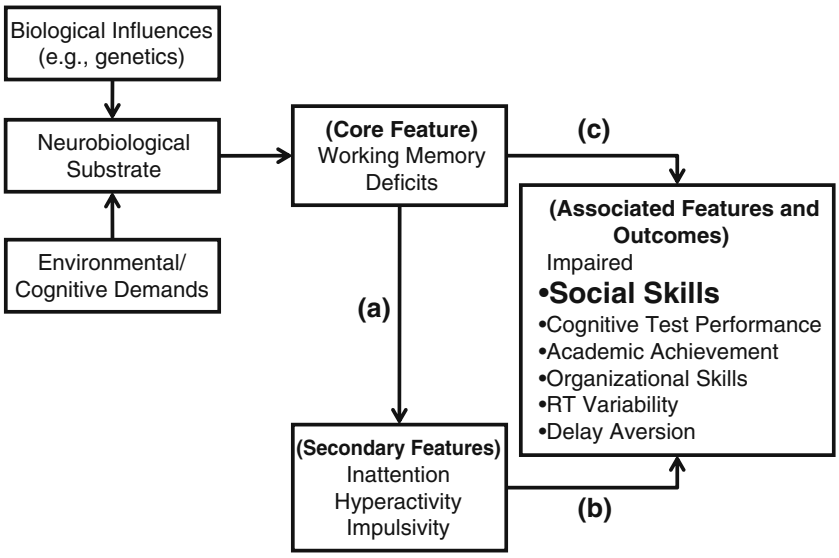

Fig. 1 The working memory model of ADHD. Working memory deficits are hypothesized to impact social deportment directly (path c) and/or indirectly through their impact on the primary behavioral symptoms of the disorder (path a*b)

children with suspected learning, behavioral or emotional problems, as well as typically developing children (those without a suspected psychological disorder) whose parents agreed to have them participate in developmental/clinical research studies. A psychoeducational report was provided to the parents of all participants. All parents and children gave their informed consent/assent to participate in the study, and the university's Institutional Review Board approved the study prior to the onset of data collection.

Two groups of children participated in the study: children with ADHD, and typically developing children without a psychological disorder. The ADHD and typically developing groups were combined to increase variability based on converging evidence that ADHD core symptoms (Frazier et al. 2007; Levy et al. 1997) and working memory abilities (Alloway et al. 2006) are distributed normally in children and reflect dimensional constructs. In the current sample, combining the two groups resulted in normal distributions for all variables (all skewness and kurtosis $p>0.05$).

Group Assignment

All children and their parents participated in a detailed, semi-structured clinical interview using the Kiddie Schedule for Affective Disorders and Schizophrenia for School-Aged Children (K-SADS). The K-SADS assesses onset, course, duration, severity, and impairment of current and past episodes of psychopathology in children and adolescents based on DSM-IV criteria. Its psychometric properties are well established, including interrater agreement of 0.93 to 1.00, test-retest reliability of 0.63 to 1.00, and concurrent (criterion) validity between the K-SADS and psychometrically established parent rating scales (Kaufman et al. 1997).

Twenty-three children met the following criteria and were included in the ADHD-Combined Type group: (1) an independent diagnosis by the CLC-IV's directing clinical psychologist using DSM-IV criteria for ADHD-Combined Type based on K-SADS interview with parent and child which assesses symptom presence and severity across home and school settings; (2) parent ratings of at least 2 *SD*s above the mean on the Attention-Deficit/Hyperactivity Problems DSM-Oriented scale of the Child Behavior Checklist (CBCL; Achenbach and Rescorla 2001), or exceeding the criterion score for the parent version of the ADHD-Combined subtype subscale of the Child Symptom Inventory-4: Parent Checklist (CSI-P; Gadow et al. 2004); and (3) teacher ratings of at least 2 *SD*s above the mean on the Attention-Deficit/Hyperactivity Problems DSM-Oriented scale of the Teacher Report Form (TRF; Achenbach and Rescorla 2001), or exceeding the criterion score for the teacher version of the ADHD-Combined subtype subscale of the Child Symptom Inventory-4: Teacher Checklist (CSI-T; Gadow et al. 2004). The CBCL, TRF, and CSI are among the most widely used behavior rating scales for assessing psychopathology in children. Their psychometric properties are well established (Rapport et al. 2008b). All children in the ADHD group met criteria for ADHD-Combined Type, and eight were comorbid for Oppositional Defiant Disorder (ODD). None of the children were comorbid for additional DSM-IV childhood disorders.

Sixteen children met the following criteria and were included in the typically developing group: (1) no evidence of any clinical disorder based on parent and child K-SADS interview; (2) normal developmental history by maternal report; (3) ratings within 1.5 *SD*s of the mean on all CBCL and TRF scales; and (4) parent and teacher ratings within the non-clinical range on all CSI subscales. Typically developing children were recruited through contact with neighborhood and community schools, family friends of referred children, and other community resources.

Children who presented with (a) gross neurological, sensory, or motor impairment, (b) history of a seizure disorder, (c) psychosis, or (d) Full Scale IQ score less than 85 were excluded from the study. None of the children were receiving medication during the study; eight of the children with ADHD had received previous trials of psychostimulant medication. Demographic and rating scale data for the two groups are provided in Table 1.

Measures

Working Memory

The phonological (PH) and visuospatial (VS) working memory tasks used in the current study are described in detail by Rapport and colleagues (2008a). Each child was administered four phonological and four visuospatial tasks (i.e., PH and VS set sizes 3, 4, 5, and 6) across the four testing sessions. The eight working memory set size conditions each contained 24 unique trials of the same stimulus set size, and were counterbalanced across the four testing sessions to control for order effects and proactive interference across set size conditions (Conway et al. 2005). Previous studies of ADHD and typically developing children indicate large magnitude between-group differences (Rapport et al. 2008a), and performance on these tasks predicts ADHD-related impairments in objectively measured activity level (Rapport et al. 2009) and attentive behavior (Kofler et al. 2010). Evidence for reliability and validity of the eight working memory tasks includes high internal consistency ($\alpha=0.82$ to 0.97), and demonstration of the expected magnitude of relationships (Swanson and Kim 2007) with an established measure of short-term memory (WISC-III or -IV Digit Span raw scores: $r=0.50$ to 0.66).

Table 1 Sample and demographic variables

Variable	ADHD		Typically developing		
	$\overline{X}$	SD	$\overline{X}$	SD	F
Age	9.22	1.06	10.38	1.42	8.43*
FSIQ	103.65	13.18	109.56	12.69	1.96
SES	47.34	12.14	52.16	10.61	1.62
CBCL Social Problems	59.61	14.66	55.31	7.79	1.14
TRF Social Problems	61.70	10.12	52.00	4.04	12.38***
CSI-Parent ADHD, Combined	78.65	10.55	50.25	13.21	55.57***
CSI-Teacher ADHD, Combined	65.35	10.18	49.38	8.69	26.10***

ADHD attention-deficit/hyperactivity disorder, *CBCL* Child Behavior Checklist, *CSI* Child Symptom Inventory severity *T*-scores, *FSIQ* Full Scale Intelligence Quotient, *SES* socioeconomic status, *TRF* Teacher Report Form

* $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$

Phonological (PH) Working Memory Task The phonological working memory task is similar to the Letter-Number Sequencing subtest on the WISC-IV, and assesses phonological working memory based on Baddeley's (2007) model. Children were presented a series of jumbled numbers and a capital letter on a computer monitor, and 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 through headphones in a separate room and independently recorded oral responses (interrater reliability=95.8% agreement).

Visuospatial (VS) Working Memory Task Children were shown nine squares arranged in three offset vertical columns on a computer monitor. 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 presented within the squares was black; the exception was a red dot that never appeared as the first or last stimulus in the sequence. Children were instructed to indicate the serial position of black dots in the order presented by pressing the corresponding squares on a computer keyboard, and to indicate the serial position of the red dot last.

Independent Variables Performance data was calculated according to recommendations by Conway and colleagues (2005). Stimuli correct per trial for each set size reflected the average number of stimuli that children reordered and recalled in the correct phonological or visuospatial serial location, and was used for latent variable analyses to statistically isolate working memory performance attributable to central executive and subsystem storage/rehearsal functioning. Briefly, the central executive was estimated by regressing the lower-level subsystem processes onto each other based on the replicated finding that the PH and VS systems are functionally and anatomically independent, with the exception of a shared (domain-general) central executive controller (Baddeley 2007). This procedure is described in detail in Rapport et al. (2008a), and resulted in estimates of each of the three working memory components at each set size (set sizes 3–6). The predictor scores at each set size were averaged afterwards to provide an estimate of the central executive, whereas residual variance reflects PH and VS functioning, respectively, independent of central executive influences.[2]

Social Problems

Parent and teacher ratings of children's social problems served as the primary outcome variable in the current study. The CBCL and TRF require respondents to rate each of 119 behaviors on a 3-point Likert scale (0 = *not true*, 1 = *somewhat/sometimes true*, 2 = *very or often true*). CBCL and TRF Social Problems clinical syndrome scale raw scores were obtained by summing responses across the 11 items on the parent and teacher Social Problems subscales (22 total items). Scores were added across informants given the moderate correlation between parent and teacher ratings of Social Problems (r=0.31; Achenbach and Rescorla 2001) to provide a wider sampling of behavior across settings while conserving power, increasing variability, and controlling for mono-informant bias (combined scale α=0.86). Test-retest reliability of the Social Problems scale is reported at 0.90 (parent) and 0.95 (teacher; Achenbach and Rescorla 2001).

The CBCL/TRF Social Problems subscales contain items related to several areas of social functioning, including peer rejection (e.g., not liked, teased, not getting along with others), social interaction style (e.g., dependent, prefers younger children), the impact of peer rejection (appears lonely), and behaviors that are correlated with peer rejection (e.g., clumsiness, speech problems). As an initial

[2] Precedence for using shared variance to statistically derive central executive and/or storage/rehearsal variables is found in Kane et al. (2004) and Swanson and Kim (2007).

study, we selected global measures of social problems because (a) ADHD children demonstrate difficulties in all of these areas (Boo and Prins 2007), and (b) concurrent validity of these scales has been demonstrated relative to global as well as specific indices of social difficulties. For example, CBCL/TRF Social Problems scores demonstrate the expected pattern of relationships with measures of social skills (r=0.72; Bohlin and Janols 2004), social withdrawal (r=0.53 to 0.57; Achenbach and Rescorla 2001), and measures of DSM-IV disorders whose core features include social deficits, such as Autism and Asperger's Syndrome (r=0.48 to 0.51; Sprafkin et al. 2002). Previous studies also have shown that children with and without ADHD differ significantly on CBCL/TRF Social Problems items (e.g., Bagwell et al. 2001).

ADHD Symptoms

Parent and teacher ratings of children's ADHD symptoms were measured by the CSI Inattentive and Hyperactivity/Impulsivity symptom subscales (Gadow et al. 2004). The CSI was selected to decrease the potential impact of mono-instrument bias for models predicting social problems from ADHD symptoms (i.e., illusory correlations occurring when subscales on the same rating scale are compared). The CSI assesses symptoms of childhood psychopathology based on DSM-IV criteria. The psychometric properties of the parent and teacher versions are well established, including high internal consistency (α=0.94 to 0.96) and 2-4 week test-retest reliability (r=0.79 to 0.85). Each item is rated for severity on a 4-point Likert scale (0 = *never* to 3 = *very often*). Items are identical across the parent and teacher versions of the CSI Inattentive (9 items) and Hyperactivity/Impulsivity (9 items) symptom subscales. ADHD symptom scores for the current study reflect total severity raw scores for both subscales combined across the parent and teacher ratings as recommended (Rapport et al. 2008b).

Measured Intelligence

All children were administered either the Wechsler Intelligence Scale for Children third or fourth edition to obtain an overall estimate of intellectual functioning based on each child's estimated Full Scale IQ (FSIQ; Wechsler 2003). The changeover to the fourth edition was due to its release during the conduct of the study and to provide parents with the most up-to-date intellectual evaluation possible.

Procedures

All children participated in four consecutive Saturday assessment sessions at the CLC-IV. The phonological and visuospatial tasks were administered as part of a larger battery of laboratory-based tasks that required the child's presence for approximately 2.5 h per session. Children completed all tasks while seated alone in an assessment room. All children received brief (2-3 min) breaks following every task, and preset longer (10–15 min) breaks after every two to three tasks to minimize fatigue.

Mediation Analyses

All analyses were completed utilizing a bias-corrected bootstrapping procedure following the steps recommended by Shrout and Bolger (2002). Bootstrapping was used to estimate and determine the statistical significance of all total, direct, and indirect effects, and is appropriate for samples as low as 20 (Shrout and Bolger 2002). An indirect effect refers to the impact of an independent variable on a dependent variable through a mediating variable. Effect ratios (indirect effect divided by total effect) were calculated to estimate the proportion of each significant total effect that was attributable to the indirect effect, and were used instead of the traditional *full* versus *partial mediation* monikers as recommended by Shrout and Bolger (2002). All variables were standardized to facilitate between- and within-model comparisons. AMOS version 18.0.2 was used for all analyses, and 1,000 samples were derived from the original sample (n=39) by a process of resampling with replacement (Shrout and Bolger 2002). Only observed variables were included in the mediation models; therefore, all models are just-identified with perfect fit and no fit statistics are reported.

A three-tiered data analytic approach was employed to examine the study's primary hypotheses. Intercorrelations between working memory component scores (CE, PH storage/rehearsal, VS storage/rehearsal), Social Problems, and ADHD symptom domains were computed in Tier I of the analyses as a first step to determine whether mediation analyses were justified. Tier II used bootstrapped mediation analyses as described above to test whether working memory's impact on social problems is direct, indirect through its impact on ADHD symptoms (inattentive and/or hyperactive/impulsive behavior), both direct and indirect, or better accounted for by the expression of ADHD core symptoms without the influence of working memory. A final set of analyses (Tier III) were performed to contrast directly the magnitude of significant indirect effects obtained in the Tier II models.

Results

Power Analysis

Sample size required for mediation models is dependent upon several factors including (a) the magnitude of the

relationship between the independent variable and the potential mediator (α); (b) the magnitude of the relationship between the potential mediator and the dependent variable controlling for the independent variable (β); and (c) which statistical test of mediation is employed (Fritz and MacKinnon 2007). A large magnitude effect size was predicted based on established large magnitude relationships (effect sizes≥1.9) between working memory tasks and ADHD symptoms (Kofler et al. 2010; Rapport et al. 2009) and between ADHD symptoms and social problems (r=0.53 to 0.61; Andrade et al. 2009; Humphrey et al. 2007). Mediation analysis using the bias-corrected bootstrapping procedure requires 34 total participants to achieve 0.80 power (Fritz and MacKinnon 2007). Thirty-nine children participated in the current study.

Preliminary Analyses

All variables (CE, PH storage/rehearsal, VS storage/rehearsal, Social Problems, and ADHD symptoms) were screened for univariate/multivariate outliers and tested against $p<0.001$. No outliers were identified. Mean group substitution was used to estimate teacher-rated Social Problems and ADHD Symptoms for one TD child because he was home-schooled.[3]

Sample ethnicity was mixed with 24 Caucasian (62%), 8 Hispanic (20%), 2 African American (5%), and 5 multiracial children (13%). All parent and teacher ADHD rating scale scores were significantly higher for the ADHD group relative to the TD group as expected (see Table 1). Children with ADHD and TD children differed on age (p=0.006) but not SES (p=0.17) or FSIQ (p=0.21). In general, children with ADHD were slightly younger than typically developing children (Table 1). Age and FSIQ were not significant covariates of any of the mediation analyses (all $p\geq0.28$). We therefore report simple model results with no covariates.

Tier I Intercorrelations

All variables were interrelated significantly with four exceptions (Table 2). The PH and VS performance variables were not correlated significantly with cross-informant ratings of Social Problems (both $p\geq0.14$). They were retained and tested in the Tier II mediation analyses, however, because an indirect relationship between two variables can exist even when a direct relationship is not apparent (Shrout and Bolger 2002). In contrast, VS performance was not related significantly to Hyperactivity/Impulsivity symptoms (p=0.19), and PH performance was not related significantly to Inattentive Symptoms (p=0.08). Therefore, models investigating potential indirect effects of VS through Hyperactivity/Impulsivity symptoms and PH through Inattentive symptoms were not tested because indirect effects require a significant relationship between the independent variable and the potential mediator.

Tier II Mediation Analyses

Separate mediation models were tested for each of the three working memory components (CE, PH storage/rehearsal, VS storage/rehearsal) to examine total, direct, and indirect effects of working memory components on cross-informant ratings of social problems. These analyses were repeated, substituting Inattentive then Hyperactivity/Impulsivity symptom clusters for the ADHD Combined symptoms to examine whether significant indirect effects were attributable to working memory's impact on specific behavioral symptom clusters. Effect ratios were not calculated for models with nonsignificant total effects. Standardized β-weights, *SE*, and 95% confidence intervals are shown in Tables 3, 4, and 5.

Central Executive (CE) Examination of the total effect indicated that CE performance exerted a significant effect on cross-informant Social Problems ratings (β=-0.36). In addition, CE exerted a direct effect on ADHD Combined Symptoms (β=-0.64), with lower CE performance associated with an increased severity of Social Problems and ADHD Symptoms. ADHD symptoms also predicted Social Problems (β=0.48). Interpretation of the full bootstrapped mediation model indicated that CE exerted a significant indirect effect (β=-0.31) on Social Problems through its impact on ADHD Symptoms. The direct effect of CE on Social Problems was not significant after accounting for the indirect effect (p=0.70). Examination of the effect ratio (ER) revealed that the indirect effect accounted for 86% of the total effect of CE on Social Problems (ER=0.86). This pattern of results was highly consistent across the ADHD Combined, Inattentive (ER=0.78), and Hyperactivity/Impulsivity (ER=0.61) symptom models.

Phonological Storage/Rehearsal (PH) The total effect of PH performance on Social Problems was not significant (p=0.43). In contrast, PH exerted a significant direct effect on cross-informant ADHD Symptoms (β=-0.36), with lower PH performance associated with an increased severity of ADHD Symptoms. In addition, ADHD symptoms predicted Social Problems (β=0.53). Interpretation of the full bootstrapped mediation model indicated that PH performance exerted a significant indirect effect (β=-0.19) on Social Problems through its effect on ADHD symptoms. This pattern of results was consistent across the ADHD Combined and Hyperactivity/Impulsivity symptom models.

[3] Results of all analyses were unchanged with this child removed.

Table 2 Zero-order correlations

		1	2	3	4	5	6
1.	Central executive						
2.	VS storage/rehearsal	0.57***					
3.	PH storage/rehearsal	0.53***	-0.37*				
4.	ADHD combined symptoms	-0.64***	-0.33*	-0.36*			
5.	Inattentive symptoms	-0.62***	-0.42**	-0.28, *ns*	0.93***		
6.	Hyperactivity/impulsivity symptoms	-0.58***	-0.22, *ns*	-0.39*	0.94***	0.75***	
7.	Social problems	-0.36*	-0.24, *ns*	-0.15, *ns*	0.52**	0.51**	0.46**

PH phonological, VS visuospatial; *$p<0.05$, **$p\leq0.01$, ***$p\leq0.001$

Inattentive symptoms were not tested as a potential mediator due to their nonsignificant relationship with PH performance (see Tier I).

Visuospatial Storage/Rehearsal (VS) The total effect of VS performance on Social Problems was not significant ($p=0.14$). In contrast, VS exerted a significant direct effect on cross-informant ADHD Symptoms (β=-0.33), with lower VS performance associated with an increased severity of ADHD Symptoms. In addition, ADHD symptoms predicted Social Problems (β=0.49). Interpretation of the full bootstrapped mediation model indicated that VS exerted a significant indirect effect (β=-0.16) on Social Problems. This pattern of results was consistent across the ADHD Combined and Inattentive symptom models. Hyperactivity/Impulsivity symptoms were not tested as a potential mediator due to their nonsignificant relationship with VS performance (see Tier I).

Tier III Model Comparison

A final set of analyses were conducted to compare the significant indirect effects of working memory components on Social Problems found in the Tier II models. Specifically, the magnitude of these effects was compared across models. Beta-weights and standard errors were used to calculate the *gap* between the lower bound for one variable's confidence interval and the upper bound for the other variable. This difference is compared to the pooled *SE* across variables, with gaps equal to or larger than the pooled *SE* indicating significant differences between models (Cumming and Finch 2005, rule 7). Two sets of comparisons were undertaken to contrast the magnitude of the indirect effects for: (a) the three working memory components (CE, PH, and VS) on separate and combined ADHD symptom clusters; and (b) separate and combined symptom clusters for each working memory component (e.g., does the CE exert a larger indirect effect on

Table 3 Mediation analyses: Impact of WM and ADHD-Combined Symptoms on Social Problems

		Working Memory Component								
Path		Central Executive			Phonological Storage/Rehearsal			Visuospatial Storage/Rehearsal		
	Total Effect	β	*SE*	*p*	β	*SE*	*p*	β	*SE*	*p*
c	WM→Social Problems	-0.36	0.16	*	-0.15	0.19	0.43	-0.24	0.16	0.14
	Direct Effects									
a	WM→ADHD Symptoms	-0.64	0.12	**	-0.36	0.15	*	-0.33	0.16	*
b	ADHD Symptoms→Social Problems	0.48	0.19	*	0.53	0.15	**	0.49	0.15	**
c'	WM→Social Problems	-0.06	0.20	0.70	0.04	0.19	0.90	-0.08	0.15	0.60
	Indirect Effects (through mediator)									
ab	WM→Social Problems									
	Bootstrap Estimate	-0.31	0.12	*	-0.19	0.11	**	-0.16	0.09	*
	95% CI of Bootstrap	-0.55 to -0.05		*	-0.45 to -0.03		**	-0.34 to -0.02		*
	Model Summary	R^2	p		R^2	p		R^2	p	
		0.27	**		0.27	**		0.27	**	

Bias-corrected bootstrapping was used for all analyses. Path labels reflect standard nomenclature (cf. Fritz and MacKinnon 2007) and are depicted in Fig. 1; c and c' reflect the total and direct effect of WM on social problems before and after accounting for ADHD symptoms, respectively; WM = working memory; *$p\leq0.05$, **$p\leq0.01$

Table 4 Mediation analyses: Impact of WM and Inattentive Symptoms on Social Problems

		Working Memory Component								
Path		Central Executive			Phonological Storage/ Rehearsal			Visuospatial Storage/Rehearsal		
	Total Effect	β	*SE*	*p*	β	*SE*	*p*	β	*SE*	*p*
c	WM→Social Problems	-0.36	0.14	*		N/A		-0.24	0.16	0.12
	Direct Effects									
a	WM→ADHD Symptoms	-0.62	0.08	**				-0.42	0.15	*
b	ADHD Symptoms→Social Problems	0.45	0.16	*				0.49	0.13	**
c'	WM→Social Problems	-0.08	0.18	0.63				-0.04	0.16	0.73
	Indirect Effects (through mediator)									
ab	WM→Social Problems									
	Bootstrap Estimate	-0.28	0.10	**				-0.20	0.09	**
	95% CI of Bootstrap	-0.50 to -0.09		**				-0.44 to -0.07		**
	Model Summary	R^2		p				R^2		p
		0.26		**				0.26		**

Note: Path labels reflect standard nomenclature (cf. Fritz and MacKinnon 2007) and are depicted in Fig. 1; c and c' reflect the direct effect of WM on social problems before and after accounting for ADHD symptoms, respectively; N/A = Model not tested due to nonsignificant PH-Inattentive relationship found in Tier I; WM = working memory; $*p \leq 0.05$, $**p \leq 0.01$

Social Problems through its impact on Inattentive or Hyperactivity/Impulsivity symptoms?).

WM Component Comparisons CE exerted a larger magnitude indirect effect on Social Problems through ADHD-Combined symptoms relative to the indirect effects of PH and VS (CE>PH=VS; both proportion gap>1.0). In contrast, the indirect effect of CE was of similar magnitude to the indirect effects of PH and VS for the Hyperactive/Impulsive and Inattentive symptom models, respectively (both proportion gap<1.0). Collectively, these results indicate that the CE exerts a larger overall indirect influence

Table 5 Mediation analyses: Impact of WM and Hyperactivity/Impulsivity Symptoms on Social Problems

		Working Memory Component								
Path		Central Executive			Phonological Storage/Rehearsal			Visuospatial Storage/ Rehearsal		
	Total Effect	β	*SE*	*p*	β	*SE*	*p*	β	*SE*	*p*
c	WM→Social Problems	-0.36	0.14	*	-0.15	0.19	0.43		N/A	
	Direct Effects									
a	WM→ADHD Symptoms	-0.58	0.11	**	-0.39	0.14	*			
b	ADHD Symptoms→Social Problems	0.38	0.19	0.07	0.48	0.17	**			
c'	WM→Social Problems	-0.14	0.20	0.39	0.03	0.20	0.92			
	Indirect Effects (through mediator)									
ab	WM→Social Problems									
	Bootstrap Estimate	-0.22	0.13	*	-0.19	0.10	**			
	95% CI of Bootstrap	-0.49 to -0.002		*	-0.48 to -0.04		**			
	Model Summary	R^2		p	R^2		p			
		0.23		**	0.22		**			

Path labels reflect standard nomenclature (cf. Fritz and MacKinnon 2007) and are depicted in Fig. 1; c and c' reflect the direct effect of WM on social problems before and after accounting for ADHD symptoms, respectively; N/A = Model not tested due to nonsignificant VS-Hyp/Imp relationship found in Tier I; WM = working memory; $*p \leq 0.05$, $**p \leq 0.01$, $***p \leq 0.001$

on Social Problems relative to both PH and VS, and that this increased magnitude is conveyed through CE's impact on overall ADHD symptoms, rather than specifically through the inattentive or hyperactive/impulsive clusters.

ADHD Symptom Cluster Comparisons CE exerted similar magnitude indirect effects on Social Problems for the Combined, Inattentive, and Hyperactivity/Impulsivity symptom clusters (all models: proportion gaps<1.0). PH exerted similar magnitude indirect effects on Social Problems for the Combined and Hyperactivity/Impulsivity symptom clusters, whereas VS exerted similar magnitude indirect effects for the Combined and Inattentive symptom clusters (all contrasts: proportion gap<1.0). Indirect effects for PH and VS on Social Problems were not significant for Inattentive and Hyperactivity/Impulsivity symptom clusters, respectively (Tier I).

Discussion

The current study is the first to examine the direct and indirect impact of specific working memory component processes on social problem severity in children with ADHD and typically developing children. Latent variable analysis and a bias-corrected bootstrapping procedure were used to examine model-implied interrelationships among the three primary components of working memory (central executive, phonological storage/rehearsal, and visuospatial storage/rehearsal) and cross-informant reports of ADHD symptoms and social problems. Results revealed a complex interactional pattern among the three working memory components and children's social problems. Of the three components, only the domain-general central executive was found to have a direct effect on social problems. This finding was consistent with previous studies documenting a significant relationship between working memory and social deportment in other populations of children (Alloway et al. 2005). This relationship, however, was attenuated fully by accounting for the robust indirect effect of the central executive on social problems through its impact on ADHD symptoms (both as unique clusters and as a combined cluster). The phonological and visuospatial storage/rehearsal subsidiary working memory components, in contrast, showed a more limited yet distinct relationship with children's social problems. The phonological storage/rehearsal component's relationship to children's social problems occurred solely through its influence on hyperactive/impulsive behavior, whereas the visuospatial component's contribution occurred exclusively through its influence on inattentive behaviors.

The overall finding that central executive working memory processes contribute to children's inattentive and hyperactive/impulsive behavior—and in doing so, negatively impact their social interactions—is consistent with past research demonstrating a robust relationship between central executive deficits, inattentiveness (Kofler et al. 2010), and excessive gross motor activity (Rapport et al. 2009). In those studies, central executive deficits were related functionally to direct observations of decreased visual attention and higher rates of actigraph-measured motor activity in children with ADHD relative to typically developing children. Thus, the process by which central executive deficits impact social interactions in children with ADHD appears to reflect the *behavioral outcome* of being unable to maintain a focus of attention on information within working memory while simultaneously dividing attention among multiple, on-going events and social cues occurring within the environment. That is, the inability to hold and process information effectively creates a world in which they must act quickly and without forethought to compensate for the rapid rate at which mental representations fade. This hypothesis is consistent with observations and anecdotal reports of children with ADHD interacting with others; they typically speak and act hastily before an intended verbalization or action fades from memory, rather than listening to and observing what others are saying and doing.

The distinct indirect effects associated with the two subsystems also merit consideration. The phonological storage/rehearsal component's unique contribution to children's hyperactive/impulsive behavior problems, which in turn adversely influence their social interactions, could be due to any of three related processes associated with this component: an overly rapid decay of information held in the store, deficient rehearsal processes, and/or a greater vulnerability to interference effects (i.e., irrelevant thoughts replacing what is stored currently in working memory). Deficits in any of the three processes would make it extraordinarily difficult to engage in the give-and-take, listen-and-wait behaviors required for adept social interactions (Rapport et al. 2008b). This explanation is also consistent with the observation that a majority of *DSM-IV* hyperactivity/impulsivity items refer to intrusive verbal behavior and the inability to maintain thoughts and forestall action (e.g., blurts out answers, interrupts conversations, trouble waiting one's turn, talks excessively, trouble playing leisure activities quietly).

The finding that visuospatial storage/rehearsal and central executive processes demonstrated similar magnitude indirect effects on social problems through their impact on inattentive symptoms was consistent with previous studies indicating that deficits in both working memory components negatively impact children's inattentive behavior (Kofler et al. 2010). These findings suggest that an additional reason that children with ADHD experience social problems is that their visuospatial storage/rehearsal and central executive deficits result in impaired sustained

attention (Kofler et al. 2010) and less frequent visual orientation to others during social interactions (Stroes et al. 2003). These behavioral outcomes, in turn, are interpreted negatively by others and are associated with peer criticism and rejection (Andrade et al. 2009).

The direct and indirect effects of working memory explained a substantial percentage of the variance in parent- and teacher-reported social problems (R^2 range= 0.22 to 0.27), considering that we were predicting global ratings of children's social behavior using brief laboratory tasks. Nevertheless, significant unexplained variance remained across models, indicating that other processes and mechanisms are implicated in the social problems experienced by children with ADHD. Inhibitory deficits are unlikely to represent a strong candidate based on the recent results of a longitudinal study of preschool children, wherein early ADHD-related inhibitory differences predicted only 1–8% of variance in social skills problems 5 years later (Gewirtz et al. 2009). As noted earlier, however, inhibitory processes related to working memory may prove to be one of several factors contributing to social problems in ADHD if irrelevant thoughts gain access to working memory, forcing relevant thoughts out of consciousness. Additional factors such as insufficient social cognitive abilities (Marton et al. 2009) and reputation among peers (Bickett and Milich 1990) have been shown to contribute to the social problems experienced by children with ADHD; however, the extent to which these difficulties are secondary to ADHD-related working memory deficits remains unknown.

The unique contribution of the current study was the investigation of the interrelationships among working memory processes, ADHD behavioral symptoms, and social problem severity in children with ADHD and typically developing children. Several caveats require consideration when interpreting the present findings despite these and other methodological refinements (e.g., working memory component and bootstrapped mediation analyses). Independent experimental replications with larger samples that include females, older children, and other ADHD subtypes are needed to assess the generalizability of highly controlled laboratory experiments with stringent inclusion criteria. Our sample size was sufficient, however, based on the a priori power analysis. Finally, our reliance on global ratings of children's social problems may have introduced sources of error (e.g., negative halo effects, rater expectation bias), but also may result in improved ecological validity relative to analog measures designed to assess social interactions. Nevertheless, reliance on global indices may have limited our ability to determine the direct impact of working memory components on specific aspects of social behavior and competence. As an initial study we felt that it was prudent to establish a global link among the constructs before designing intensive protocols that would allow a more nuanced investigation of these complex interrelationships. Future studies that use longitudinal methodology or concurrently manipulate working memory demands while observing children's social deportment across settings are needed to further elucidate the complex interactions among working memory deficits, ADHD symptoms, and social problems.

Collectively, current and past findings indicate that social problems are a major source of functional impairment for children with ADHD (Boo and Prins 2007), and that working memory impairments significantly predict these pervasive difficulties. These findings extend previous research by suggesting that working memory deficit-related inattentive and impulsive behaviors (Kofler et al. 2010) interfere with age-appropriate social interactions. The results also may help explain why social skills training provides limited incremental benefit beyond psychostimulant medication for children with ADHD (Boo and Prins 2007). Cognitive-behavioral treatments aimed at improving the social interactions of children with ADHD may need to include procedures aimed at improving children's ability to briefly store and process the verbally- and visually-mediated information that characterize children's social interactions.

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