Working Memory as a Core Deficit in ADHD: Preliminary Findings and Implications

Michael J. Kofler, Mark D. Rapport, Jennifer Bolden, and Thomas A. Altro

After conducting child outcome research for 25 years (MDR), it became clear that treatments for ADHD were maintenance therapies at best and that a better understanding of the disorder's core deficits was needed. This conclusion was supported by findings that methylphenidate–related changes in DSM–IV core variables (attention, impulsivity, hyperactivity) failed to predict expected changes in associated outcomes such as academic performance (Rapport, Chung, Shore, Denney, & Isaacs, 2000). The initial conceptualization of working memory as a core deficit followed two additional studies: (a) a structural equation model showing that children's memory was a better predictor of long–term scholastic outcomes than classroom behavior (Rapport, Scanlan, & Denney, 1999); and (b) a comprehensive review of laboratory–based studies finding that ADHD groups were reliably differentiated from typically developing groups by tasks that placed significant demands on children's working memory (Rapport et al., 2000). Other models of ADHD view working memory deficits as one of several executive functions undermined by deficient behavioral inhibition processes (Barkley, 1997), or as one of a constellation of executive function weaknesses that comprise a neurocognitive profile (Willcutt, Doyle, Nigg, Faraone, & Pennington, 2005).

For readers unfamiliar with the construct, working memory is a limited capacity system that provides temporary storage and processing of sensory information for use in guiding behavior (Baddeley, 2007). Invoking the computer as a metaphor, working memory might be considered the RAM of consciousness—it is responsible for our ability to temporarily hold, rehearse, and manipulate both verbal and visual information, as when comprehending this long sentence, following multi–step directions, engaging in a conversation, or solving simple or multi–step verbal or visual problems that must be held temporarily in consciousness. Collectively, these abilities underlie the capacity to perform complex tasks such as learning, comprehension, reasoning, and planning (Baddeley, 2007). Conversely, deficiencies in working memory are linked to a broad range of disadvantageous outcomes, including learning and language disabilities (De Jong, 1998), hyperactivity (Rapport et al., in press), academic performance deficits and scholastic underachievement (Gathercole, Pickering, Knight, & Stegmann, 2004; Rapport et al., 1999), classroom inattention (Gathercole & Alloway, 2008), and social interaction deficits (Alloway, Gathercole, & Adams, 2005).

We view working memory as a core, causal cognitive process responsible for ADHD (Figure 1). Behavioral inhibition deficits—if present in ADHD (Alderson, Rapport, & Kofler, 2007; Alderson, Rapport, Sarver, & Kofler, 2008; Lijffijt, Kenemans, Verbaten, & van Engeland, 2005)—are viewed as a byproduct of working memory deficits because inhibition is dependent on the registration of environmental stimuli (i.e., information must be activated in working memory before a decision to inhibit responding can be made; Rapport, Chung, Shore, & Isaacs, 2001). Deficits in working memory are presumed to account for several associated and secondary features of ADHD, including disorganization, inattentiveness, poor social skills, delay aversion, and hyperactivity/impulsivity. These deficiencies are further assumed to exert causal influences to varying degrees across a variety of other domains. Some of these, such as performance on tests of cognitive functioning, are directly affected by working memory processes. Others, such as academic achievement deficits, reflect the cumulative impact of working memory failure and secondary impairments on component academic skills combined with a variety of other influences (e.g., availability of tutoring, behavioral programming, or other compensatory resources).

The Children's Learning Clinic (CLC–IV) research group planned and designed a series of experimental protocols to investigate hypotheses and test specific predictions stemming from the functional working memory model of ADHD (for details, see Rapport et al., 2001, Rapport, Kofler, Alderson, & Raiker, 2008). These studies required considerable forethought, planning, and time investment due to several factors. The cognitive literature at the time included a wide range of working memory models; some were empirically based and lent themselves to scrutiny (e.g., Baddeley, 2007), whereas others were highly abstract, but largely un–testable (e.g., neural node network models). Moreover, there were no child–appropriate working memory tasks that would enable the systematic manipulation of parameters necessary to explore the myriad working memory processes and mechanisms suspected in ADHD. Finally, an estimated 45 hours *per child* was required to complete the comprehensive clinical evaluation, psychoeducational assessment, and 4–week Saturday testing protocols.

Pre–calculated power analysis indicated that we would need a minimum of 20 children (10 ADHD and 10 typically developing children) to test the most basic hypotheses, which translated into 900 hours of direct participant contact for the initial studies. Thus, seven years elapsed between the initial conceptualization (Rapport et al., 2001) and the publication of our first working memory study (Rapport, Alderson et al., 2008).

We selected Alan Baddeley's (2007) working memory model as the basis for testing working memory hypotheses for several reasons. Extant empirical studies based on adult samples provided compelling empirical support for the model's basic tenets, and the model served as a useful conduit for exploring a wide array of working memory mechanisms and processes. Moreover, experimental protocols could be programmed readily using commercially available software. Baddeley's (2007) model describes three primary components of working memory: a domain–general central executive and two subsystems for the temporary storage and rehearsal of modality–specific information (Figure 2). The central executive is an attentional controller responsible for oversight and coordination of the subsidiary systems. Its primary functions are focusing attention, dividing attention among concurrent tasks, and providing an interface between long–term memory and working memory. The phonological subsystem is responsible for the temporary storage (25s) and rehearsal of verbal material, whereas the visuospatial subsystem provides this function for non–verbal visual and spatial stimuli. Extensive neuropsychological, neuroanatomical, neuroimaging, and factor analytic investigations support the distinct functioning of the two subsystems, their storage/rehearsal components, and the domain–general central executive (Baddeley, 2007).

Here we wish to summarize the results of our recent research into this working memory model of ADHD published earlier this year in the *Journal of Abnormal Child Psychology* (Rapport, Aldersen, Kofler et al., 2008) and discuss some of the implications of these findings.

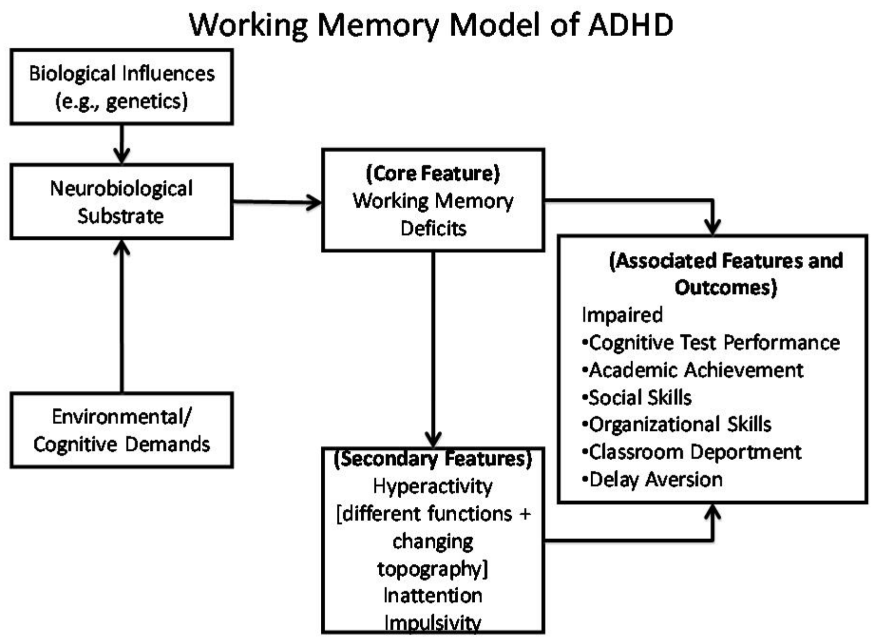

FIGURE 1. The Working Memory Model of ADHD.

OUR METHODS

The present study examined working memory functioning in children with ADHD relative to typically developing children. We initially examined whether systematically increasing memory load (set size) differentially affects either of the two subsystems. Each subsystem was examined subsequently using latent variable analysis to ascertain the extent to which central executive processes and/or specific components (input, storage/rehearsal processes) account for working memory deficits in children with ADHD. Because no one task or measure is likely to provide an uncontaminated estimate of central executive functioning due to its multiple functions, cognitive scientists have recently embraced latent variable analysis to address this conundrum. This approach uses regression or structural equation techniques to isolate unique and shared variance among working memory tasks that represent storage/rehearsal and central executive processes, respectively. The process has the added benefit of reducing or eliminating variance related to non–working memory processes and measurement error (Swanson & Kim, 2007).

Our Participants

Two groups of boys aged 8 to 12 (*M* = 9.04, *SD* = 1.36; *n*= 23) participated in the study: children with ADHD–Combined Type (n = 12), and typically developing (*n* = 11) children without a psychological disorder. All parents and children gave informed consent/assent, and IRB approval was obtained prior to data collection. Diagnosis was based on best practice and included detailed developmental histories, parent and child semi–structured interviews, and parent and teacher rating scales (for additional details, see Rapport, Alderson et al., 2008).

Visuospatial and Phonological Working Memory Tasks

Our tasks are shown in Figure 3 and detailed in Rapport, Alderson et al. (2008).

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Briefly, 4 set sizes (3, 4, 5, & 6 stimuli per trial) of both tasks were administered in counterbalanced order, with 24 trials at each set size. Both tasks require children to mentally store, rehearse, and manipulate the serial order of verbal (phonological task) or spatial (visuospatial task) stimuli. The columns on the visuospatial task were offset from a standard 3x3 grid to minimize the likelihood of phonological coding of the stimuli (e.g., by equating the squares to numbers on a telephone pad). The primary dependent variable was stimuli correct per trial. Separate central executive, phonological storage/rehearsal, and visuospatial storage/rehearsal component variables were derived using latent variable analysis.

Phonological and Visuospatial Encoding

The Reading Speed task provided an index of children's ability to rapidly encode, process, and articulate visually presented words. Children read a 203–word second grade reading passage. Completion time (ms) was recorded by computer, and words per second were used in the current study. Scores from the Symbol Search B subtest of the WISC–III or WISC–IV provide an index of how rapidly children process, encode, and distinguish unfamiliar visual symbols. Visuospatial encoding was defined as raw score divided by task duration (i.e., symbols per second).

WHAT WE FOUND

Children with ADHD did not differ from typically developing (TD) children on age or intelligence, but read slower and had lower socio–economic status (SES) scores than TD children. Symbol Search group differences were non–significant. Reading Speed, Symbol Search, IQ, age, and SES were not significant covariates of any of the analyses.

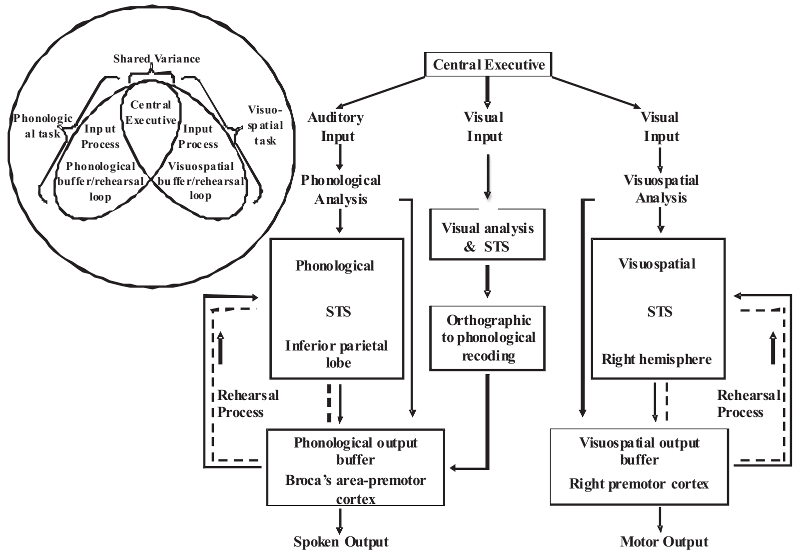

FIGURE 2. Adapted and expanded version of Baddeley's (2007) working memory model and associated anatomical loci. The insert shows the component processes related to the phonological and visuospatial tasks. STS = short-term store. Reprinted from Rapport et al. (2008). *Journal of Abnormal Child Psychology, 36*, 825-837, with the kind permission of Springer Science and Business Media.

Tier I: Set Size

The first level of analysis examined the effect of increasing set size on phonological (Figure 4a) and visuospatial (Figure 4b) working memory performance across groups. Separate mixed–model ANOVAs for the phonological and visuospatial tasks were both significant for group, set size, and the group by set size interaction. Post hoc pairwise comparisons revealed that children with ADHD performed significantly worse across all set sizes compared to TD children; however, the performance patterns for the two groups was appreciably different as depicted in Figure 4.

Tier II: Components of Working Memory

Separate central executive, phonological storage/rehearsal, and visuospatial storage/rehearsal performance variables were derived using best practice latent variable analysis to estimate ADHD–related impairment in the individual components of working memory. Independent samples *t*–tests on the derived variables revealed significant ADHD–related deficits in phonological storage/rehearsal (Hedges' *g* effect size (ES) = 0.55; 95% CI = 0.51 – 0.59), visuospatial storage/rehearsal (ES = 0.89; 95% CI = 0.80 – 0.98), and central executive processes (ES = 2.76; 95% CI = 2.64 – 2.88).

IMPLICATIONS OF OUR FINDINGS

The current study examined overall, domain–general (central executive), and subsidiary (phonological and visuospatial storage/rehearsal) working memory processes in children with ADHD–Combined Type relative to typically developing children. ADHD–related working memory deficits were apparent across all three

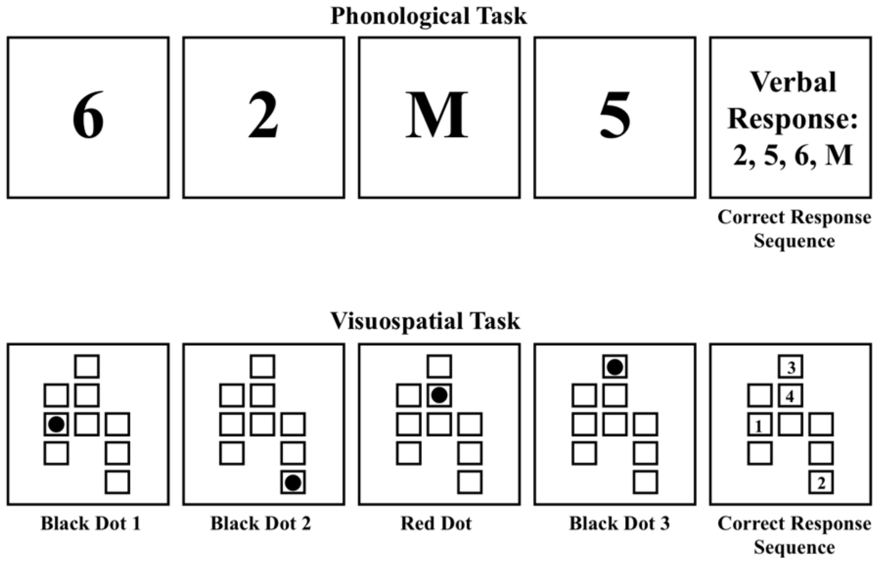

FIGURE 3. Visual schematics of the phonological (top) and visuospatial (bottom) tasks. . Reprinted from Rapport et al. (2008). *Journal of Abnormal Child Psychology, 36*, 825-837, with the kind permission of Springer Science and Business Media.

working memory components—with the largest magnitude deficits apparent in the central executive—even after controlling for reading speed, nonverbal visual encoding, age, IQ, and SES. These deficiencies were apparent under even the lowest stimulus set size conditions, and they became more pronounced under higher memory load conditions.

Typically developing children showed initial gains in both subsystems as set size increased from 3 to 4 stimuli, and either recalled additional stimuli (phonological) or maintained their level of recall performance (visuospatial) under the higher (5, 6) stimulus set size conditions. In contrast, the phonological and visuospatial recall performance of children with ADHD peaked under the set size 4 condition, and it declined under higher set size conditions. The ADHD group's visuospatial subsystem recall never exceeded 1.6 stimuli on average, and it significantly deteriorated under high set size conditions. Collectively, these results suggest an underlying impairment in the storage/rehearsal functioning in both subsystems, as well as possible differences in the use of meta–memory strategies to maintain gains under higher set size conditions. Systematically increasing the number of stimuli to be recalled will eventually overwhelm even an intact working memory system, and conscious strategies must be employed to optimize recall under these circumstances.

Parsing the central executive's shared contribution from the phonological and visuospatial subsystems revealed several interesting findings. The magnitude of group differences associated with the two subsidiary systems indicated a more dysfunctional visuospatial relative to phonological subsystem in children with ADHD. The difference in central executive functioning between the two groups was remarkable (ES = 2.76) and highlights the critical role played by the central executive in directing and focusing attention, while providing the necessary oversight and coordination for the two subsidiary systems in addition to serving as a conduit between working memory and long–term memory. One or more of these abilities are clearly impaired in children with ADHD. The finding that both systems remained impaired after removing the central executive's contribution provided additional confirmation of phonological and visuospatial storage/rehearsal processing deficiencies in ADHD.

The current results have both applied and heuristic implications for the field, assuming the findings generalize to the larger population of affected children. Impaired central executive processing and phonological/visuospatial storage/rehearsal deficits likely disrupt basic learning processes, as well as the incremental acquisition of skill and knowledge obtained in educational settings that are highly dependent on working memory (Alloway et al., 2005). The association between working memory functioning and academic

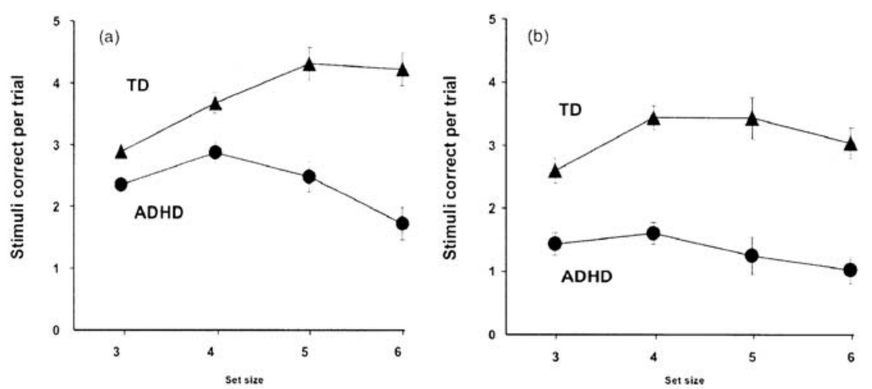

FIGURE 4. Number of (a) phonological and (b) visuospatial stimuli correct as a function of set size and group: TD (triangles) and ADHD children (circles). Vertical bars represent standard error. Reprinted from Rapport et al. (2008). *Journal of Abnormal Child Psychology, 36*, 825-837, with the kind permission of Springer Science and Business Media.

achievement is well established (e.g., Gathercole et al., 2004), and may reflect ADHD–related underarousal (Mann, Lubar, Zimmerman, Miller, & Muenchen, 1992) and developmental delays in cortical maturation of prefrontal cerebral regions related to working memory, attention, and motor planning (Shaw et al., 2007). The resultant culmination of disrupted learning processes likely contributes to the longitudinal findings of poor school performance, significant scholastic underachievement, and low high school graduation rates characteristic of ADHD (Barkley, Fischer, Smallish, & Fletcher, 2006). Additional research is needed to examine which elements of working memory are associated with specific academic skill deficits and other symptoms of ADHD in anticipation of designing proactive interventions to enhance working memory performance.

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