Attention-deficit/hyperactivity disorder (ADHD)

Outline:

- History and Background Information
- DSM-5 Clinical Model of ADHD – basic assumptions
- Initial formulation of the functional WM model of ADHD
- Baddeley’s WM model as an experimental paradigm
- WM components implicated as core deficits in ADHD
- Hyperactivity and Inattention as secondary features of ADHD

“He who loves practice without theory is like the sailor who boards ship without a rudder and compass and never knows where he may cast”  Leonardo da Vinci (1452-1519)
493 BC

- Hippocrates described patients with "quickened responses to sensory experience, but also less tenaciousness because the soul moves on quickly to the next impression".
  - Condition attributed to an "overbalance of fire over water".
  - Remedy: "barley rather than wheat bread, fish rather than meat, water drinks, and many natural and diverse physical activities."

Circa 1600

- Shakespeare referred to a "malady of attention" in one of his characters in King Henry VIII.

Mid 1800s

- Heinrich Hoffman, a German physician, penned the poem "Fidgety Phil".
  - [Figety Phil](#)

1890

- William James, in his Principles of Psychology text (1890), described a normal variant of character which he called the "Explosive Will":
  - "... impulses seem to discharge so promptly onto movements that inhibitions get no time to arise. These are the ‘dare-devil’ and ‘mercurial temperaments, overflowing with animation, and fizzling with talk” (p.800)."
English physician George Still (1902) reported on a group of children in his clinical practice whom he defined as having a deficit in “volitional inhibition” or a “defect in moral control” over their behavior.

- Their behavior was described as aggressive, passionate, lawless, inattentive, impulsive, and overactive.
- An over-representation of male subjects (3:1).
- An aggregation of alcoholism, criminal conduct, and depression among the biological relatives.
- A familial predisposition to the disorder – hereditary.
Minimal Brain Damage/Dysfunction

Interest in children with similar characteristics arose in North America around the time of the encephalitis epidemic of 1917-1918.

- Children surviving these brain infections were noted to have many behavioral problems similar to ADHD.
- These cases and others known to have arisen from birth trauma, head injury, toxin exposure, and infections gave rise to the concept of a brain-injured child syndrome (Strausses & Lehtinen, 1947).
The brain-injured child syndrome eventually was applied to children manifesting these same behavior features but without evidence of brain damage or retardation.

This concept would later evolve into the concept ‘minimal brain damage’, and eventually ‘minimal brain dysfunction’ (MBD), owing to the dearth of evidence of brain injury in most cases (Dolphin & Cruickshank, 1951; Strauus & Kephardt, 1955).
During the 1950’s, greater attention was paid to the specific behaviors of hyperactivity and impulsivity resulting in the label “hyperkinetic impulse disorder.” The disorder was attributed to poor thalamic filtering of stimuli entering the brain (Laufer, Denhoff, & Solomons, 1957) and eventually termed the “hyperactive child syndrome” (Chess, 1960).

The influence of psychoanalytic thought at the time held sway when the DSM-II appeared and all childhood disorders were described as “reactions” – the hyperactive child syndrome became “hyperkinetic reaction of childhood” (DSM-II, 1968).
Hyperkinetic Reaction of Childhood

DSM-II (1968)

Characterized by overactivity, restlessness, distractibility and short attention span, especially in young children; the behavior usually diminishes in adolescence.

- Definition included problems of attention and distractibility along with those of hyperactivity/restlessness.
- The condition was assumed to be developmentally benign and not caused by brain damage - resulting in a departure from European thinking.
By the 1970s, research emphasizing the importance of problems with sustained attention and impulse control in addition to hyperactivity was emphasized (Douglas, 1972).

Douglas (1980; 1983) theorized that the disorder was comprised of four major deficits:

- The investment, organization, and maintenance of attention and effort.
- The ability to inhibit impulsive behavior.
- The ability to modulate arousal levels to meet situational demands.
- An unusually strong inclination to seek immediate reinforcement.
Douglas’s work coupled with numerous studies of attention, impulsiveness, and other cognitive sequelae resulted in the DSM-III (1980) moniker, Attention Deficit Disorder (ADD).

- Psychoanalytic perspective discarded.
- Cognitive-developmental nature emphasized.
- Symptom lists, cutoff scores recommended.
- Polythetic categorization scheme (3 major symptom groupings required for a diagnosis).
- Distinction between “with” and “without” hyperactivity.
Hyperactivity and impulsivity

Needed to:

- Differentiate the disorder from other conditions, and
- Predict developmental risks (Weiss & Hechtman, 1993).

Monothetic categorization scheme (14 symptoms - 1 list)

ADD without hyperactivity replaced with undifferentiated Attention Deficit Disorder based on insufficient research.
Attention-Deficit/Hyperactivity Disorder (DSM-IV, 1994)

Three (3) subtypes of ADHD (predominantly inattention; predominantly hyperactivity-impulsive; and combine type).

- **Hyperactivity-Impulsive Type** appears to be a developmental precursor to the combined type.
- **Hyperactive-Impulsive Type** was comprised primarily of preschool children (DSM-IV field trials).
- **Combined Type** and **Inattentive Type** were comprised primarily of school-age children.

The **Hyperactive-Impulsive** behavior pattern seems to emerge first in development during the preschool years, whereas symptoms of “inattention” associated with it appear to have their onset several years later (Loeber et al., 1992; Hart et al., 1995).
Attention-Deficit/Hyperactivity Disorder (DSM-IV, 1994)

Research began demonstrating that deficits were not limited to the attentional domain.

- Problems with motivation and insensitivity to response consequences were emphasized (poor performance under partial reward and extinction - Douglas, 1980s).
- Deficient “rule governed” behavior was hypothesized by Barkley (1981; 1989).
- Information processing paradigms failed to demonstrate that poor performance was due to attentional difficulties vs motivation and response inhibition (Sergeant, 1988).
- Factor analytic studies failed to differentiate hyperactivity and impulsivity domains (loaded together as 1 factor).
<table>
<thead>
<tr>
<th>Year</th>
<th>Description</th>
<th>Author(s)</th>
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<tbody>
<tr>
<td>493 BC</td>
<td>Overbalance of fire over water (Hippocrates)</td>
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<tr>
<td>1890</td>
<td>Explosive Will (James)</td>
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<td>1902</td>
<td>Volitional Inhibition, Deficit in Moral Control (Still)</td>
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<td>c. 1918</td>
<td>Brain Injured Child Syndrome (Strauss &amp; Lehtinen)</td>
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<td>1940s</td>
<td>Minimal Brain Damage (Dolphin &amp; Cruikshank)</td>
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<td>1968</td>
<td>Hyperkinetic Reaction of Childhood (DSM-II)</td>
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<td>1980</td>
<td>Attention Deficit Disorder (DSM-III)</td>
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## Evolution of the DSM

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Attention-Deficit/Hyperactivity Disorder (DSM-IV, 1994) continued

- Types of problems with “inattention” seen in the Inattentive Type appear to have their onset even later than those associated with hyperactive-impulsive behavior (Barkley, 1996).
- Implications:
  - Attentional impairment associated with the Predominantly Inattentive Type may be different from those seen in the other two types.
  - Inattentive Type symptoms: daydreaming, spacing out, in a fog, easily confused, staring frequently, lethargic, hypoactive, and passive. [DAMP: developmentally delayed attention, motor and perceptual abilities]
  - Inattentive Type also appears to have deficits in speed of information processing & focused or selective attention (Goodyear & Hynd, 1992; Lahey & Carlson, 1992).
  - Combined Type deficits are characterized as consisting of sustained attention (persistence) and distractibility difficulties.
Implications (Continued):

- Current clinical view of ADHD may be clustering two qualitatively different disorders into a single set of disorder.
- Children with ADHD Combined Type who move into the Inattentive Type (owing to developmental reduction in hyperactivity) as they get older are not actually changing types of ADHD; Their attentional problems should still be distinct (poor persistence, distractibility) from those seen in the Inattentive Type.
DSM-5 Criteria: 6 of 9 Inattention Symptoms

- fails to give close attention to details
- difficulty sustaining attention
- does not seem to listen
- does not follow through on instructions
- difficulty organizing tasks or activities
- avoids tasks requiring sustained mental effort
- loses things necessary for tasks
- easily distracted
- forgetful in daily activities
DSM-5 Criteria:
6 of 9 Hyperactive-Impulsive

- fidgets with hands or feet or squirms in seat
- leaves seat in classroom inappropriately
- runs about or climbs excessively
- has difficulty playing quietly
- is “on the go” or “driven by a motor”
- talks excessively
- blurts out answers before questions are completed
- has difficulty awaiting turn
- interrupts or intrudes on others
Other DSM-5 Criteria

- Developmentally Inappropriate Levels
- Duration of 6 Months
- Cross-setting Occurrence of Symptoms
- Impairment in Major Life Activities
- Onset of Symptoms/Impairment by 7
- Exclusions: Severe MR, Psychosis
- Subtyping into Inattentive, Hyperactive, or Combined Types
Unresolved Problems with DSM-5 Criteria

- Symptoms are not developmentally scaled
  - Need more appropriate items for adults
- Cutoffs are not developmentally referenced
  - May have to adjust thresholds if > 16 or < 4 yrs.
- Cutoffs not sex-referenced (lower for girls)
- Duration may be too short for preschoolers
  - Consider adjusting upward to 1 year
- Age of onset of 7 has no validity (childhood)
- Developmental deviance undefined (93%??)
- Implies need for parent-teacher agreement
  - Blend reports and use history of cross setting impairment
- No requirement for corroboration by others (adults)
ADHD - Inattentive Type

- Daydreaming/Spacey/Stares
- Slow Information Processing
- Hypoactive/Lethargic/Sluggish
- Easily Confused, Mentally “Foggy”
- Poor Focused/Selective Attention
- Erratic Retrieval - Long-Term Memory
- Socially Reticent/Uninvolved
ADHD Inattentive Type (2)

- Rarely Aggressive or ODD/CD
- Not Impulsive (By Definition)
- Less Likely to Have a Clinically Impressive Response to Stimulants (65% improve but only 20% show clinical response)
- Possibly Greater Family History of Anxiety Disorders and LD (?)
Inattentive Type is a New Disorder

- Focus on sluggish cognitive tempo
- Will not have same course and risks
- Probably requires different interventions
- Need to distinguish it from:
  - Sub-threshold Combined Type
  - Central Auditory Processing Disorder
  - Situational Stress Events or PTSD
  - Schizophrenic Spectrum Disorders
  - Learning Disabilities
  - Anxiety Disorders or Depression
  - Substance Use/Abuse Disorder
Beck et al. (2016) Sluggish Cognitive Tempo

- Sluggish
- Tired/lethargic
- Slow thinking/processing cognitive set
- Sleepy/drowsy
- Spacey
- In a fog
- Underactive/slow moving
- Daydreams
- Lost in thoughts
- Stares blankly
- Easily confused
- Apathetic / unmotivated
- Easily bored

[items with high factor loadings]
Prevalence (United States)

- Varies by gender, age, social class, & urban-rural (population density)
- 5-73% of children
- 4.7% of adult population (DSM-IV - All Types) (3.4% Combined/Hyper. Types)
- 3:1 males:females (community samples)
  - 5:1 to 9:1 (clinical samples)
Prevalence (Internationally)

- Canada (Montreal): 3.8-9.4% kids (DSM-III-R)
- Australia: 3.4% of kids (DSM-III-R)
- New Zealand: 6.7% kids, 2-3% teens (DSM-III-R)
- Germany: 4.2% children (ICD-9)
- India: 5-29% children (DSM-III)
- China: 6-9% children (DSM-III-R)
- Netherlands: 1.3% teens (DSM-III-R)
- Puerto Rico: 9.5% child & teens (DSM-III)
- Japan: 7.7% children (DSM-III-R ratings)
- Colombia: 2-13% (DSM-IV ratings)
- Brazil: 5.8% of 12-14 year olds (DSM-IV)
Persistence of Disorder
Evaluated via structured interviews (DSM-based)

Symptoms Decrease (graph)

Adolescence: (Based on parent reports)
- 50% persistence to adolescence (1970-80s)
- 70-80% in modern DSM studies (1990s onward)

Young Adulthood (age 20-26) (Barkley et al. in press)
- Depends on who you ask (self vs. parents)
- 3-8% Full disorder (self-report using DSM3R)
- 46% Full disorder (parent reports using DSM3R)
- 12% - Using 98th percentile (+ 2SDs; self-report)
- 66% - Using 98th percentile (parent report)
- Parent reports correlate more highly with various domains of major life activities than do self reports
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Etiologies - Heredity/Genetics

- **Family Aggregation of Disorder:**
  - 25-35% of siblings - 55-92% of identical twins
  - 15-20% of mothers - 25-30% of fathers
  - If parent is ADHD, 20-54% of offspring

- **Twin Studies of Heritability:**
  - Heritability = 57-97% (Mean 80%+; 95%+ if DSM)
  - Shared Environment = 0-6% (Not significant)
  - Unique Environment = 15-20%

- **Molecular Genetics (DRD4, DAT1, DBH?)**
Etiologies: Food Allergies & Miscellaneous Factors

- Sugar (Disproven)
- Hyper/hypoglycemia (No evidence)
- Food Allergies (Largely Disproven)
  - Possibly 5% of ADHD Preschoolers react adversely to high doses of food additives
- Side Effects of Anticonvulsants (10-35%)
  - mainly to phenobarbital and dilantin
- Thyroid abnormalities (unlikely)
  - Rare in children
  - Evidence is conflicting
Comorbid DSM-IV Disorders

As assessed by DSM-based structured interviews (e.g. Kiddie SADS, DISC-P)

- Oppositional Defiant Disorder (40-67%)
- Conduct Disorder (20-56%)
- Delinquent/Antisocial Activities (18-30%)
- Anxiety Disorders (10-40%; partly referral bias!)
  - Related more to poor emotion regulation than to fear
- Major Depression (0-45%; 27% by age 20)
- Bipolar Disorder (0-27%)
  - Not documented in any follow-up studies to date
Childhood Developmental Risks

Language Disorders (Expressive: 10-54%)
- Pragmatic deficits in 60% (Language tests)
- Central Auditory Processing Disorder (45-75%)
  - (Audiological examination and language processing tests)
- Developmental Coordination Disorder (50+%) 
  - (Motor development tests, e.g. Lincoln-Oseretsky)
- Reduced Physical Fitness, Strength, & Stamina (Standard physical fitness tests)
- Accident Proneness (parental reports)
  - 1.5 to 4x risk of injuries (non-head) (28 vs. 6% in Worcester 4-6 year olds) (greater in ODD subset)
  - 3x risk for accidental poisonings (23 vs. 7.7% of clinic referrals; 7.3 vs. 2.3% in community)
Seriousness and pervasiveness of impairments: Educational, Clinical, Interpersonal

- Poor School Performance (90%+)
  - More failing grades
  - Reduced productivity (greatest problem)
  - Lower GPA (1.7 vs 2.6)
  - Grade retentions (42% vs 13%)
  - Lower class rankings (69% vs 50%)
  - Higher rate of suspensions (60% vs 19%) and expulsions (14% vs 6%)

- Low Academic Achievement (10-15 pt. deficit)

- Low Average Intelligence (7-10 point deficit)

- Learning Disabilities (10 to 70%)
  - Reading (15-30%; 21% in Barkley, 1990)
  - Spelling (26% in Barkley, 1990)
  - Math (10-60%; 28% in Barkley, 1990)
  - Handwriting (common but % unspecified)

- Academic Outcomes
  - 23% to 32% fail to complete high school
  - 22% vs 77% enter college
  - 5% vs 35% complete college [Barkley et al. 2006 Milwaukee Young Adult Outcome Study]
Social-Emotional Impairments

Assessed via parent ratings, peer sociometrics, and videotaped interactions of ADHD children with others

- Increased parent-child conflict & stress
  - especially ODD/CD subgroup
- Peer Relationship Problems (50%+)
  - Less sharing, cooperation, turn-taking
  - More talking, commanding, intrusive, hostile
  - Most serious in ODD/CD subgroup
- Poor Emotional Control
  - More anger, frustration, hostility (ODD/CD)
  - Less self-regulation of emotional states
ADHD Cost of Illness (COI) in USA

COI = Educational accommodations
Mental health care
Parental work loss
Juvenile justice system involvement

COI = Mean = $14,576 annually per child (Pelham et al., 2007)
Range = $12,005 to $17,458

COI = $40.8 billion annually (based on assumed 5% prevalence rate and 2.8 million school age children in the United States (National Center for Education Statistics, 2010, enrollment data)
Persistence of Disorder
Evaluated via structured interviews (DSM-based)

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  - 66% - Using 98th percentile (parent report)
  - Parent reports correlate more highly with various domains of major life activities than do self reports
Psychiatric Disorders (age 20-26)

- ODD (12%+ by self-report) *(Not Significant)*
- Conduct Disorder (26%+ by self-report)*^*
- Depression (27%)^ (not found in other studies)
- Substance Use/Abuse Disorders (10-24%)^  
  - Greater Use of Alcohol, Tobacco, and Marijuana
  - Milwaukee Study: Not different from controls due to elevated drug use among controls

Personality Disorders:
- Antisocial (11-21%)*^  
  - Passive Aggr. (18%)*^  
  - Histrionic (12%)^  
  - Borderline (14%)*^  
- *=greater risk if elevated child conduct problems  
- ^=greater risk if CD at adulthood
Educational Outcomes (ages 20-25)

Assessed by self-report and high school transcripts:

- More grade retention (25-45%; MKE: 42 vs. 13)
- More are suspended (40-60%; MKE: 60 vs. 19)
- Greater expulsion rate (10-18%; MKE: 14 vs. 6)
- Higher drop out rate (30-40%; MKE 32 vs 0)
- Lower Class Ranking (MKE: 69% vs. 50%)
- Lower GPA (MKE: 1.7 vs. 2.6)
- Fewer enter college (MKE: 22 vs. 77%)
- Lower college graduate rate (5 vs. 35%)

MKE = Milwaukee Young Adult Outcome Study
Employment Problems

- More likely to be fired
  - (MKE: 55 vs. 23%; Mean 1.1 vs. 0.3 jobs)
- Change jobs more often (MKE: 2.7 vs. 1.3 over 2-8 years since leaving high school)
- More ADHD/ODD symptoms on the job
  - As rated by current supervisors (MKE)
- Lower work performance ratings
  - As reported by current supervisors (MKE)
- Lower social class (SES) (Hollingshead System)
- By 30s, 35% self-employed (NY Study)
Motor Vehicle Driving Risks

Assessed via self-report, driving records, lab testing, driving simulators, and BTW tests (Barkley studies)

- Poorer steering, more false braking, and slower reaction times to significant events
- Rated as using fewer safe driving habits
- More likely to drive before licensing
- More accidents (and more at faults) (2-3 vs. 0-2)
  - % with 2+ crashes: 40 vs. 6
  - % with 3+ crashes: 26 vs 9
- More citations (Speeding - mean 4-5 vs. 1-2)
- Worse accidents ($4200-5000 vs $1600-2200)
  - (% having a crash with injuries: 60 vs 17%)
- More Suspensions/Revocations (Mean 2.2 vs 0.7)
  - (% suspended: 22-24 vs. 4-5%)
Sexual-Reproductive Risks

Assessed via self-reports: (MKE study)

- Begin Sexual Activity Earlier (15 vs 16 yrs.)
- More Sexual Partners (18.6 vs. 6.5)
- Less Time with Each Partner
- Less Likely to Employ Contraception
- Greater Risk of Teen Pregnancy (38 vs. 4%)
- Ratio for Number of Births (42:1)
  - 54% Do Not Have Custody of Offspring
- Higher Risk for STDs (16 vs. 4%)
Etiologies - Heredity/Genetics

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- More ADHD/ODD symptoms on the job
  - As rated by current supervisors (MKE)
- Lower work performance ratings
  - As reported by current supervisors (MKE)
- Lower social class (SES) (Hollingshead System)
- By 30s, 35% self-employed (NY Study)
Motor Vehicle Driving Risks

Assessed via self-report, driving records, lab testing, driving simulators, and BTW tests (Barkley studies)

- Poorer steering, more false braking, and slower reaction times to significant events
- Rated as using fewer safe driving habits
- More likely to drive before licensing
- More accidents (and more at faults) (2-3 vs. 0-2)
  - % with 2+ crashes: 40 vs. 6
  - % with 3+ crashes: 26 vs 9
- More citations (Speeding - mean 4-5 vs. 1-2)
- Worse accidents ($4200-5000 vs $1600-2200)
  - (% having a crash with injuries: 60 vs 17%)
- More Suspensions/Revocations (Mean 2.2 vs 0.7)
  - (% suspended: 22-24 vs. 4-5%)
Sexual-Reproductive Risks
Assessed via self-reports: (MKE study)
- Begin Sexual Activity Earlier (15 vs 16 yrs.)
- More Sexual Partners (18.6 vs. 6.5)
- Less Time with Each Partner
- Less Likely to Employ Contraception
- Greater Risk of Teen Pregnancy (38 vs. 4%)
- Ratio for Number of Births (42:1)
  - 54% Do Not Have Custody of Offspring
- Higher Risk for STDs (16 vs. 4%)
Current Models of ADHD

- Behavioral inhibition deficits (Barkley)
- Cognitive-energetic model (Sergeant)
- Delay aversion (Sonuga-Barke)
- Dynamic developmental model (Sagvolden)
- State-regulation theory (van der Meere)
- Working memory deficits (Rapport)
Behavioral Inhibition Theory of ADHD

- A deficit in response inhibition
- That disrupts 4 executive functions
  - Sensing to the self (nonverbal working memory)
  - Self-speech (verbal working memory)
  - Self-management of emotion/motivation
  - Self-play – Mental planning-problem solving
- Impairing self-regulation across time to maximize delayed social consequences
- Making ADHD a form of time blindness or myopia to the future – an intention deficit
Behavioral Inhibition
Inhibit prepotent response
Stop an ongoing response
Interference control

Motor control/fluency/syntax
Inhibiting task irrelevant responses
Executing goal-directed response
Execution of novel/complex motor sequences
Goal-directed persistence
Sensitivity to response feedback
Task re-engagement following disruption
Control of behavior by internally represented information

Working Memory
Holding events in mind
Manipulating or acting on events
Initiation of complex behavior sequences
Retrospective function (hindsight)
Prospective function (forethought)
Anticipatory set
Sense of time
Cross-temporal organization of behavior

Self-regulation of affect/motivation/arousal
Emotional self-control
Objectivity/social perspective taking
Self-regulation of drive and motivation
Regulation of arousal in the service of goal-directed action

Internalization of speech
Description and reflection
Rule-governed behavior
Problem solving/self-questioning
Generation of rules and meta-rules
Moral reasoning

Reconstitution
Analysis and synthesis of behavior
Verbal fluency/behavioral fluency
Goal-directed behavioral creativity
Behavioral simulations
Syntax of behavior

(Barkley, 1997)
Behavioral Inhibition (Barkley, 2007)

- Inhibition of a prepotent response
- Stop an ongoing response
- Interference Control
Evolution of the Stop-Signal Task

- Logan (1981) developed his model following the work of Lappin and Eriksen (1964, 1966), who were doing similar studies on **ballistic responses**.


- Logan (1984) became interested in the extent to which **choice reaction times** are controlled or ballistic and ultimately developed his *Race Horse Model* of behavioral inhibition.
Continued Evolution of the Stop-Signal Task

Advantages over simple reaction time tasks, such as the go, no-go paradigm (Tekok-Kilic et al., 2001), include:

1. A greater demand on cognitive resources relevant to inhibitory processes (Logan, Cowan, & Davis, 1984)

2. The ability to examine speed-accuracy trade-off processes that reflect children’s strategic adjustment in primary task reaction time (Logan, 1981).

Early version of the Stop-Signal Task relied on fixed stop-signal delays, inhibition slopes, and logarithmic calculations of SSRT.
Horse Race Model of Behavioral Inhibition (Logan, Cowan, & Davis, 1984)

- Go and stop processes race to the finish line

- If go process wins, response is executed

- If stop process wins, response is inhibited
Stop-Signal Task Variables

- **Go-Signal** – stimuli (typically X or O) that signals one to respond.
- **Stop-Signal** – stimuli (typically an auditory tone) that signals one to withhold or stop a response.
- **Mean Reaction Time (MRT)** – choice reaction time to go-stimulus.
- **Stop-Signal Delay (SSD)** – stimulus onset asynchrony between the presentation of the go-stimulus and stop-stimulus.
- **Stop-Signal Reaction Time (SSRT)** – reaction time to the stop-stimulus, calculated as MRT-SSD.
Behavioral Inhibition and the Stop Signal Paradigm

SSRT = MRT – SSD

SSRT = Stop Signal Reaction Time
MRT = Mean Reaction Time
SSD = Stop Signal Delay
Mean Reaction Time (MRT)

Stop Signal

Go Tone

Tone

Time (in ms)

Stop Signal

Mean Reaction Time (MRT)

Response accuracy varies with tone presentation – easier to stop when stop signal is closer to go-signal
Alderson, Rapport, Sarver & Kofler (2008)

ADHD and Behavioral Inhibition: A Re-examination of the Stop-signal Task.

Journal of Abnormal Child Psychology.
Meta-Analysis of the Stop-Signal Task (Alderson, Rapport, & Kofler, 2007)

- Compared 23 studies of children with ADHD and typically developing children on the stop-signal task

- Results:
  - MRT: ADHD > NC (ES = 0.45)
  - MRT Variability: ADHD > NC (ES = 0.73)
  - SSRT: ADHD > NC (ES = 0.63)

- Results were highly consistent across meta-analytic reviews:
  - MRT: ESs = 0.49, 0.52, and 0.45
  - MRT Variability: 0.73, 0.72, and 0.72
  - SSRT: 0.64, 0.58, and 0.63
Meta-Analysis of the Stop-Signal Task (Alderson, Rapport, & Kofler, 2007)

- SSD: ADHD = NC (ES = -0.02 unstandardized)
- SSD is direct reflection of inhibitory success.
- SSD was indirectly estimated
Biological Influences, e.g., genetics

NEUROBIOLOGICAL SUBSTRATE

Behavioral Interventions

ENVIRONMENTAL/COGNITIVE DEMANDS

CORE FEATURES:
- Inattention
- Hyperactivity
- Impulsivity

SECONDARY FEATURES:
- Academic Underachievement
- Social Skill Deficits
- Poor Organizational Skills
- Classroom Deportment
- Cognitive Abilities

DSM-5 CLINICAL MODEL OF ADHD

Pharmacological Treatment
Initial Conceptualization of the Functional Working Memory Model of ADHD
The enigma – why do large magnitude changes in core symptoms not translate into sustainable or generalizable changes in treated children?

- Pharmacodynamic studies reveal DA and NA activation of cortical-subcortical pathways involving the frontal/prefrontal, temporal lobe, and basal ganglia – areas that play a critical role in executive functions (EFs)

- Optimal activation of structures underlying EFs and accompanying arousal is necessary but insufficient to facilitate the development of executive function processes supported by these structures and wide range of behaviors dependent upon these processes
ADHD N = 76
NC N = 25
*J AM. ACAD. CHILD ADOLESC. PSYCHIATRY*
BASELINE MODEL

ATTENTION

0.34

IMPULSIVITY

0.41

HYPERACTIVITY

0.518, p<.05

0.02, n.s.

0.01 n.s.

ACADEMIC PERFORMANCE

R² = 0.27

*CFI = 1.00

b TREATMENT MODEL

ATTENTION

0.37, p<.05

0.37

IMPULSIVITY

- 0.18, n.s.

0.71

HYPERACTIVITY

0.05, n.s.

ACADEMIC PERFORMANCE

R² = 0.20

*CFI = 0.99

N = 76 @
B, PI, 5, 10, 15, 20 mg MPH

Direct Observations

Teacher ratings

% academic assignments completed correctly

*CFI=comparative fit index


TOSCA = Test of Scholastic Abilities

- Mother
- Self
- Police
- TOSCA-a
- TOSCA-b

Later Delinquency
- 15 years

Later School Achievement
- 13 years

Early Conduct Problems
- 8 years

Early Attention Deficit
- 8 years

Early IQ
- 8 years

Mother Self Police TOSCA-a TOSCA-b

.84 .68 .53 ns .95 .95

.68 .78 .55 -.38 .75

.54 .59 .55 -.38 .75

.53 ns -.27 .66

.68 -.27 .66

.59 -.38 .75

-.41

.94 .93

COMPARATIVE FIT INDEX = .94
ROBUST FIT INDEX = .93

n = 325
SA=SAT
Overview of Executive Functions (EFs)

Executive Function (EF): an umbrella term used to describe a broad range of ‘top-down’ cognitive processes and abilities that enable flexible, goal-directed behavior; and represents the dominant paradigm during the past decade following Dr. Barkley’s (1997) seminal theoretical paper in 1997.

Ensuing debate focused on two alternative models:
1. EF viewed as a unitary construct with interrelated sub-processes.
2. EF viewed as a componential model of dissociable EF processes

Accumulating evidence supports an integration of the two approaches (i.e., interrelated sub-processes governed by a domain general executive or attentional controller (e.g., Miyake et al., 2000) emphasizing 3 primary executive functions:

- **Updating**: the continuous monitoring and quick addition or deletion of contents within one’s working memory
- **Inhibition**: the capacity to supersede responses that are prepotent in a given situation
- **Shifting**: the cognitive flexibility to switch between different tasks or mental states
Miyake et al. (2000): 3-factor model of executive function based on SEM

Lehto et al. (2003): replicated factor structure in 8-13 year old children

Huizinga et al. (2006): WM & set shifting are developmentally contiguous between 7 & 21 years of age

FIG. 2. The estimated three-factor model. Single-headed arrows have standardized factor loadings next to them. The loadings, all significant at the .05 level, are equivalent to standardized regression coefficients (beta weights) estimated with maximum likelihood estimation. The numbers at the ends of the smaller arrows are error terms. Squaring these terms gives an estimate of the variance for each task that is not accounted for by the latent construct. The curved, double-headed arrows have correlation coefficients next to them and indicate significant correlations between the latent variables.
Miyake et al., 2008: Genetic Contribution associated with EFs

Figure 7. Nested factors executive function model with Wechsler Adult Intelligence Scale full-scale IQ (WAIS–IQ). Numbers above the ACEs for the latent variables and WAIS–IQ are the percentages of those variables accounted for by genetic and environmental influences. Numbers occluding the double-headed arrows are correlation coefficients. Correlations for components with zero or near-zero variance were not estimated. Numbers occluding arrows are standardized factor loadings. Numbers under the lower ACEs are estimates for task-specific variances. Boldface type and solid lines indicate $p < .05$. Anti = antisaccade; stop = stop signal; keep = keep track; letter = letter memory; S2ba = spatial 2-back; num = number–letter; col = color–shape; cat = category switch.
WORKING MEMORY MODEL OF ADHD

Rapport et al., 2001

Biological Influences, e.g., genetics

NEUROBIOLOGICAL SUBSTRATE

CORE FEATURES:
INATTENTION
HYPERACTIVITY
IMPULSIVITY

ENVIRONMENTAL/COGNITIVE DEMANDS

SECONDARY FEATURES
Biological Influences (e.g., genetics) → Neurobiological Substrate → Working Memory Deficits

Environmental/Cognitive Demands → Working Memory Deficits

Genotype

Endophenotype(s)

Medication (e.g., MPH) → Working Memory Deficits

Cognitive Training → Working Memory Deficits

Accommodations (e.g., 504 Plans) → Working Memory Deficits

Core Behavioral Symptoms
- Inattention
- Hyperactivity
- Impulsivity

Phenotype

Behavioral Treatment (e.g., BPT, SST)

Functional Impairments
- Family functioning
- Peer relationships
- Academic functioning

Intraindividual Variability
- Behavioral Disinhibition
- Lower IQ Test Performance
- Oppositional Behavior
What is Working Memory?

- Working memory is a limited capacity system that enables individuals to store briefly and process information (Baddeley, 2007).

Alan Baddeley’s (2007) WM Model

Domain General

Shared Variance

Phonological task

Central Executive

Visuospatial task

Input Process

Phonological buffer/rehearsal loop

Visuospatial buffer/rehearsal loop

Output

Rehearsal Process

Phonological buffer
Broca’s area-premotor cortex

Spoken Output

Visual Input

Visual analysis & STS

Orthographic to phonological recoding

Visuospatial output buffer
Right premotor cortex

Motor Output

Central Executive

Auditory Input

Phonological Analysis

Phonological STS

Inferior parietal lobe

Rehearsal Process

Phonological output buffer

Visuospatial

STS

Right hemisphere

Visuospatial

STS

Right premotor cortex

Motor Output

Domain General
Central Executive Processes: Past Conceptualization

- Continuous Updating
- Manipulation/Dual Processing
- Interference Control
- Serial Reordering

Interface With LTM

[Baddeley, 2007]
Development of Working Memory in Children: Peak Developmental Periods

Phonological (Verbal) STM
Visuospatial STM
Central Executive (CE)

AGE: 6 7 8 9 10 11 12 13 14 15

Tillman et al. (2011). Developmental Neuropsychology, 36, 181-198
Auditory Input

Phonological Analysis

Central Executive

Visual Input

Visual analysis & STS

Orthographic to phonological recoding

Phonological output buffer
Broca’s area-premotor cortex

Inferior parietal lobe

Speech Motor Cortex

Spoken Output

Attentional Focus for processing + Interaction with LTM
Forward and Backward Span Tasks

- Operation span: 0.63
- Reading span: 0.77
- Counting span: 0.80
- Backward span: 0.74
- Forward span, dissimilar: 0.60
- Forward span, similar: 0.70

Working Memory

- Fluid IQ: 0.49

Short-Term Memory

- 0.63

Forward and backward span tasks load on the same dimension & are both measures of short-term storage (Engle, Tuholski, Laughlin, & Conway, 1999).
Working Memory, Short-Term Memory, and General Fluid Intelligence: A Latent-Variable Approach

ENGLE, TUHOLSKI, LAUGHLIN, AND CONWAY

Figure 2. (a) Path model for two-factor model (A₁). All paths are significant at the .05 level. (b) Path model for two-factor model with additional tasks (B₂). Paths significant at the .05 level are indicated by solid lines. OSPAN = operation span; RSPAN = reading span; CSPAN = counting span; BSPAN = backward span; FSPAN = forward span, dissimilar; FSPANS = forward span, similar; KTRACK = keeping track; IFRSM = Immediate Free Recall Secondary Memory; CONTOP = continuous opposites; WM = working memory; STM = short-term memory.
Figure 4. Path model for Model D. Significant paths are indicated by an asterisk. OSPAN = operation span; RSPAN = reading span; CSPAN = counting span; BSPAN = backward span; FSPAN D = forward span, dissimilar; FSPAN S = forward span, similar; WM = working memory; STM = short-term memory; gF = fluid intelligence.
The potential importance of working memory as a underlying core deficit in children with ADHD
Higher –order cognitive tasks, skills, and abilities dependent on working memory components

<table>
<thead>
<tr>
<th>Central Executive</th>
<th>Phonological Storage/Rehearsal</th>
<th>Visuospatial Storage/Rehearsal</th>
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</thead>
<tbody>
<tr>
<td>• General fluid intelligence</td>
<td>• Verbal reasoning</td>
<td>• Visual reasoning</td>
</tr>
<tr>
<td>• Verbal and visual reasoning</td>
<td>• Vocabulary learning</td>
<td>• Speech production</td>
</tr>
<tr>
<td>• Vocabulary learning</td>
<td>• Word recognition</td>
<td></td>
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<tr>
<td>• Literacy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Arithmetic</td>
<td>• Verbal achievement</td>
<td></td>
</tr>
<tr>
<td>• Reading comprehension</td>
<td>• Math achievement</td>
<td></td>
</tr>
<tr>
<td>• Listening comprehension</td>
<td>• Math achievement</td>
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<tr>
<td>• Ability to follow directions</td>
<td>• Phonological/ syntactic abilities</td>
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</tr>
<tr>
<td>• Note taking</td>
<td></td>
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<tr>
<td>• Writing</td>
<td>• Attentive behavior</td>
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<tr>
<td>• Bridge playing</td>
<td></td>
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<tr>
<td>• Chess playing</td>
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<tr>
<td>• Learning to program computers</td>
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<tr>
<td>• Verbal achievement</td>
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<tr>
<td>• Math achievement</td>
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<td>• Lexical-semantic abilities</td>
<td>• Orthographic abilities</td>
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<td>• Orthographic abilities</td>
<td>• Complex learning</td>
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<td>• Complex learning</td>
<td>• Motor activity</td>
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<td>• Motor activity</td>
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<tr>
<td>• Attentive behavior</td>
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</tr>
</tbody>
</table>
IQ 5 Years

R^2 = .58

IQ 5 Years

R^2 = .22 - .81

Reading

Math

Spelling

Age 11 Academic Achievement

Alloway and Gathercole, 2008 (Nature)
# Working memory impairments in children with ADHD

<table>
<thead>
<tr>
<th>WM Systems</th>
<th>WM Components</th>
<th>Meta-analyses</th>
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</thead>
<tbody>
<tr>
<td>VS Working Memory</td>
<td>PH Working Memory</td>
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<tr>
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<td>VS Storage/Rehearsal</td>
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<td>CE</td>
<td>0.43-1.06</td>
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<table>
<thead>
<tr>
<th>Authors</th>
<th>Mean</th>
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<td>Martinussen &amp; Tannock, (2006)</td>
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<td>Marzocchi et al. (2008)</td>
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</tbody>
</table>

**Trends:**
(a) Deficits in both systems/all three subcomponents
(b) Deficits in CE > VS > PH
Working Memory Deficits in ADHD:
The functional relationship between central executive processes, hyperactivity, and inattention

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Dustin E. Sarver, Ph.D.
U of Mississippi Medical School
Joe S. Raiker, Ph.D.
Florida International University
Alan Baddeley’s (2007) WM Model

**Domain General:**
- Internal Focus of Attention
- Divided Attention
- Interaction with LTM

**Initial Focus:**
- Examining CE & subsidiary system processes

**Central Executive**
- Input Process
- Phonological task
- Phonological output buffer/rehearsal loop
- Visuospatial task
- Visuospatial output buffer/rehearsal loop

**Auditory Input**
- Phonological Analysis
- Phonological STS
- Inferior parietal lobe

**Visual Input**
- Visual analysis & STS
- Orthographic to phonological recoding

**Visuospatial Input**
- STS
- Right hemisphere

**Phonological STS**
- Inferior parietal lobe
- Broca’s area-premotor cortex

**Visuospatial STS**
- Right premotor cortex

**Spoken Output**
- Motor Output
Participants and Inclusion Criteria

- **Diagnostic Procedures**
  - Extensive child histories (pre, pari, post-natal; early developmental; medical; educational; psychiatric; parent/family)
  - K-SADS Semi-Structured Clinical Interview, Lifetime Version [parent and child interviewed separately]

- **Parent Rating Scales [ADHD factor in clinical range; DSM criteria]**
  - Child Symptom Inventory – 4 Parent Form (DSM-IV criteria)
  - Child Behavior Checklist – Parent Form (ADHD factor in clinical range)

- **Teacher Rating Scales [ADHD factor in clinical range; DSM criteria]**
  - Child Symptom Inventory – 4 Teacher Report Form (DSM-IV criteria)
  - Child Behavior Checklist – Teacher Report Form (TRF)
Participants and Inclusion Criteria

- **Other Child Measures and Inclusion/Exclusion Criteria**
  - WISC-IV Full Scale Intellectual Evaluation
  - Kaufmann Test of Educational Achievement – 2nd Edition
  - Children’s Depression Inventory (CDI)
  - Revised Children’s Manifest Anxiety Scale (RCMAS)
  - For ADHD: onset prior to 7 years of age; moderate to severe impairment across multiple settings; not better accounted for by other Dx or illness.
  - Comorbidity allowed for ODD
A Child Assessment requires the following:

- Detailed developmental history (includes pre/pari/postnatal, medical, social, education, family psychiatric & medical histories)
  - K-SADS semi-structured interview with parent and child
  - WISC-IV (full IQ battery) with child
  - KTEA (full achievement battery) with child
  - CBCL, CSI-P (Child Symptom Inventory), Barkley HSQ
  - TRF and CSI-T
  - Additional Clinical Scales (CDI, Manifest Anxiety Scale, Behavioral/physical Complaints Scale)

- 4, 3-hour assessment sessions, once per week x 4 consecutive weeks (Saturdays) x 6 adults
  - Protocol scoring and data input
  - Noldus Observer observations (per child)
  - Case conceptualization and written report
  - Parent debriefing

30 participants require approximately 3750 hours
[excluding the r/o participants who fail to meet dx criteria]
Power Analysis

• An average effect size (ES) of 0.70 was calculated based on the average magnitude of ADHD PH and VS deficits reported by Martinussen et al. (2005).

• GPower software version 3.0.5 (Faul, Erdfelder, Lang, & Buchner, 2007) was used to determine needed sample size using this ES, with power set to .80 as recommended by Cohen (1992).

• For an ES of 0.70, $\alpha = .05$, power $(1 – \beta) = .80$, 2 groups, and 4 repetitions (i.e., set sizes), 20 total subjects are needed for a repeated measures ANOVA to detect differences and reliably reject $H_0$. 23 total children participated in the study.
<table>
<thead>
<tr>
<th>Variable</th>
<th>ADHD (n = 12)</th>
<th>Typically Developing (n = 11)</th>
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<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
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<tr>
<td>Age</td>
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<td>Attention Problems</td>
<td>78.50</td>
<td>10.53</td>
<td>55.64</td>
<td>7.06</td>
<td>36.68***</td>
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<td>Attention Problems</td>
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<td>8.83</td>
<td>48.73</td>
<td>16.92</td>
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<td>ADHD, Combined</td>
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<td>4.98</td>
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<td>ADHD, Combined</td>
<td>9.83</td>
<td>5.32</td>
<td>2.73</td>
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<td>13.06**</td>
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</tbody>
</table>

Note: ADHD = attention-deficit/hyperactivity disorder; CBCL = Child Behavior Checklist; CSI = Child Symptom Inventory; FSIQ = Full Scale Intelligence Quotient; SES = Socioeconomic Status; TRF = Teacher Report Form.

* p ≤ .05, ** p ≤ .01, *** p ≤ .001
Phonological (PH) Working Memory Task

**Storage component**: child must hold 3 to 6 stimuli in memory

**Processing component**: child must manipulate the order of stimuli from low to high, and mentally move the letter to the last place during recall
Phonological (PH) WM Task

Children are instructed to recall the numbers in order from smallest to largest, and say the letter last.

Phonological Task

Verbal Response: 2, 5, 6, M
Correct Response Sequence

3, 4, 5, 6 stimuli sequences
Visuospatial (VS) WM Task

Children are instructed to indicate the serial position of black dots in the order presented by pressing the corresponding squares on a computer keyboard, and indicate the position of the red dot last.

Visuospatial Task

- Black Dot 1
- Black Dot 2
- Red Dot
- Black Dot 3
- Correct Response Sequence

3, 4, 5, 6 stimuli sequences
Phonological and Visuospatial WM Deficits in boys with ADHD

PH, VS, and CE Performance Composite Scores

PH Storage/Rehearsal Performance Composite Score
PH ES = .55 [1.89 w/CE]

VS Storage/Rehearsal Performance Composite Score
VS ES = .89 [2.31 w/CE]

CE Performance Composite Score
CE ES = 2.76
Years in Age

[Gathercole & Alloway, 2008]
Shaw et al. 2007
ADHD & Cortical Development
Alan Baddeley’s (2007) WM Model

Domain General

Central Executive

Auditory Input

Phonological Analysis

Phonological

STS

Inferior parietal lobe

Rehearsal Process

Phonological output buffer
Broca’s area-premotor cortex

Spoken Output

Visual Input

Visual analysis & STS

Orthographic to phonological recoding

Visuospatial Analysis

Visuospatial

STS

Right hemisphere

Rehearsal Process

Visuospatial output buffer
Right premotor cortex

Motor Output

Shared Variance

Phonological task

Input Process

Phonological buffer/rehearsal loop

Central Executive

Phonological task

Input Process

Phonological buffer/rehearsal loop

Visuospatial task

Input Process

Visuospatial buffer/rehearsal loop

PH Store

Subvocal Rehearsal

Rehearsal Process

Orthographic to phonological recoding

Visual Input

Central Executive

Visual Input

Central Executive
To what extent do WM related phonological (PH) deficits reflect short-term storage as opposed to articulatory (covert) rehearsal deficiencies?

Phonological Working Memory

Baddeley, 2007
Contribution of Phonological Processing to other abilities

Auditory Input

Phonological Analysis

Phonological

STS

Inferior parietal lobe

Phonological output buffer
Broca’s area-premotor cortex

Rehearsal Process

Spoken Output

Language Processing (Adams & Gathercole, 1995)

Math Achievement (Gathercole, Alloway, Willis, & Adams, 2006)

Reading Decoding and Reading Comprehension (Swanson & Howell, 2001)

Understanding Classroom Instructions (Gathercole & Alloway, 2008)

Left, temporo-parietal cortex (Jonides et al., 1998)

Left, prefrontal region (Broca’s area) Awh et al., 1996; Smith & Jonides, 1999)
**Phonological Memory Task**

**Presentation Phase**
- 2-Words
- 4-Words
- 6-Words

**Storage/Rehearsal Phase**
- 3-seconds delay
- 12-seconds delay
- 21-seconds delay

**Recall Phase**
- List length set based on each child’s span

**Phonological Analysis**
- Auditory Input
- Central Executive

**Phonological Memory Task**
- STS
- Inferior parietal lobe
- Phonological output buffer
- Broca’s area-premotor cortex
- Spoken Output

21 distinct trials at each list length
Each child is performing at their established memory span

- ADHDs lose ~ 30% of words learned or .5 SD per 9-s recall
- TDs lose ~ 10% of words learned

Short-term storage capacity ES = 1.15 to 1.98
Articulatory rehearsal ES = .47 to 1.02
Are components of working memory functionally related to hyperactivity?

Biological Influences (e.g., genetics) → Neurobiological Substrate → Working Memory Deficits → (Core Feature) Working Memory Model of ADHD

Environmental/Cognitive Demands → (Secondary Features) Hyperactivity, Inattentiveness, Impulsivity

(Secondary Features) Hyperactivity, Inattentiveness, Impulsivity → (Associated Features and Outcomes)
- Impaired
- Cognitive Test Performance
- Academic Achievement
- Social Skills
- Organizational Skills
- Classroom Deportment
- Delay Aversion
Mean Weekday Hourly Activity Scores

Porrino et al. (1983)
Arch Gen Psychiatry, 40, 681-687

Controls  \( n = 12 \)
Hyperactives  \( n = 12 \)
\( * p < .05 \)
“Little evidence was found, however, to support the hypothesis that hyperactivity is simply an artifact of the structure and attentional demands of a given setting.” p.681

“... a substantial ubiquitous increase in simple motor behavior is a clear characteristic of this group.” p. 685

“In a variety of situations with differing degrees of structure and attentional demand, hyperactives showed consistently higher levels of motor movement than did their normal controls.” p. 686

Mean Hourly Activity Scores During the Week

Overall Weekly Mean

Lunch/Recess

Reading

Mathematics

Physical Education

Controls

Hyperactives

* $p < .01$

Porrino et al., 1983
DEPENDENT MEASURES AND TECHNIQUES

ACTIGRAPHS

- Ambulatory Monitoring, Inc. MicroMini Motionlogger®

- **SETTING:** Low PIM Mode [intensity of movement] [Proportional Integrating Measure]

- **SAMPLING RATE = 16 samples per second collapsed into 1-minute epochs**

- **Placement:** both ankles; non-dominant wrist
Control Conditions

Children were instructed to use the Microsoft® Paint program for five consecutive minutes both prior to (C1) and after (C2) completing the VS and PH tasks during four consecutive Saturday assessment sessions.

The Paint program served as pre and post conditions to control for potential within-day fluctuations in attention and fatigue effects, and because it requires no storage or CE processing.
Experimental Design

- Phonological WM (21 consecutive trials) at 4 set sizes (3, 4, 5, 6) [programmed using SuperLab 2.0]

- Visuospatial WM (21 consecutive trials) at 4 set sizes (3, 4, 5, 6) [programmed using SuperLab 2.0]

- All tasks administered in counterbalanced order across 4-week Saturday assessment sessions.
Power Analysis

- An average effect size (ES) of 0.72 was calculated from two studies providing actigraph means and SDs for children with ADHD and typically developing (TD) children during laboratory tasks (Dane, Schachar, & Tannock, 2000; Halperin et al., 1992).

- GPower software version 3.0.5 (Faul, Erdfelder, Lang, & Buchner, 2007) was used to determine needed sample size using this ES, with power set to .80 as recommended by Cohen (1992).

- For an ES of 0.72, $\alpha = .05$, power $(1 – \beta) = .80$, 2 groups, and 6 repetitions (C1, set sizes 3-6, C2 as described below), 18 total subjects are needed for a repeated measures ANOVA to detect differences and reliably reject $H_0$.  

- 23 total children participated in the study
Primary Hypothesis

- If activity level is functionally related to PH/VS subsidiary system processes, we would expect movement to vary systematically as greater demands are imposed on the storage/rehearsal systems.

- If activity level is functionally related to Central Executive processes, we would expect movement to increase from control (minimal CE or storage demands) to WM demand conditions, but not vary between set size conditions because no additional demands are placed on the CE when only the number of stimuli increase (i.e., no additional processing demands are imposed).
Activity Level Assessed During the PH and Control Conditions

Total extremity activity level (right foot, left foot, and non-dominant hand) expressed in PIM (Proportional Integrated Measure) units for children with ADHD (triangles) and typically developing children (circles) under control (C1, C2) and four phonological set size (PH 3, 4, 5, 6) working memory task conditions. Vertical bars represent standard error.

Computation of Hedges’ g indicated that the average magnitude difference between children with ADHD and TD children was 1.49 standard deviation units (range: 0.93 to 2.10).
Activity Level Assessed During the VS and Control Conditions

Hedges’ $g$ effect size indicated that the average magnitude difference in activity level between children with ADHD and TD children during visuospatial WM tasks was 1.83 standard deviation units (range=1.47 to 2.67).

Total extremity activity level (right foot, left foot, and non-dominant hand) expressed in PIM (Proportional Integrated Measure) units for children with ADHD (triangles) and typically developing children (circles) under control (C1, C2) and four visuospatial set size (VS 3, 4, 5, 6) working memory task conditions. Vertical bars represent standard error.
STEP 1:
PH, VS, and CE Performance Composite Scores

PH Storage/Rehearsal Performance Composite Score

CE Performance Composite Score

VS Storage/Rehearsal Performance Composite Score
**STEP 2:**

Activity Level Directly Related to PH and VS Storage/Rehearsal Functioning

Results indicated that PH functioning was **NOT** a significant contributor to objectively measured activity level (average $R^2 = .10$; values ranged from .06 to .21 and were all non-significant with one exception).

Results indicated that VS functioning was **NOT** a significant contributor to objectively measured activity level (average $R^2 = .07$; values ranged from less than .001 to .14 and were all non-significant).
Results indicated that CE functioning was a significant contributor of objectively measured activity level (average $R^2 = .32$; values ranged from .17 to .61; all $p \leq .04$).

An independent samples t-test on the derived CE-activity level variable indicated a significant between-group difference, $t(21)=7.54$, $p<0.0005$, with children with ADHD evincing higher rates of activity directly associated with CE functioning relative to TD children.

Hedges’ g effect size indicated that the average magnitude difference between children with ADHD and TD children was 3.03 standard deviation units (SE=0.60).
Activity Level Assessed During the PH and Control Conditions

Total extremity activity level (right foot, left foot, and non-dominant hand) expressed in PIM (Proportional Integrated Measure) units for children with ADHD (triangles) and typically developing children (circles) under control (C1, C2) and four phonological set size (PH 3, 4, 5, 6) working memory task conditions. Vertical bars represent standard error.
The 2 (group: ADHD, TD) by 2 (condition: C1, C2) Mixed-model ANOVA was non-significant for group, condition, and the group by condition interaction (all $p \geq .52$), indicating that children with ADHD were not ubiquitously more motorically active than typically developing children during the clinical assessment after accounting for task-related WM demands.

Hedges’ $g$ effect size indicated that the average magnitude difference between children with ADHD and TD children was 0.20 standard deviation units ($SE=0.29$), with a confidence interval that included 0.0.
Video examples of children while performing the phonological and visuospatial task
Control Condition
Findings Summary

- All children are significantly more active when engage in tasks requiring working memory.

- Children with ADHD are significantly more active than TDs when engaged in tasks requiring WM.

- Children with ADHD are not significantly more active than typically developing children after controlling for the influence of WM [not ubiquitously hyperactive]

- Central Executive functioning (not storage/rehearsal) is functionally related to children’s activity level.

- Differences in children’s activity level during WM task may reflect underlying differences in arousal.
Working Memory Model of ADHD

Biological Influences (e.g., genetics)

Neurobiological Substrate

Environmental/Cognitive Demands

(Core Feature) Working Memory Deficits

(Associated Features and Outcomes)
- Impaired
  - Cognitive Test Performance
  - Academic Achievement
  - Social Skills
  - Organizational Skills
  - Classroom Deportment
  - Delay Aversion

(Secondary Features)
- Inattentiveness
- Hyperactivity
- Impulsivity

(Secondary Features)
Dependent Measures and Techniques

Noldus Observer

- Mutually exclusive Behavioral Codes
  - Oriented to task
    - Head is directed within 45° vertically/horizontally of the center of the monitor.

- Observers
  - Two coders per tape
  - Observers pre-trained to exceed 80% agreement
  - Interrater reliability = .94; Kappa = .88
Power analysis

- GPow 3.0.5 (Faul et al., 2007)
- Power = .80 (Cohen, 1992)
- ES = 1.4 (Kofler et al., 2008)
- 2 groups (ADHD, TDC)
- 6 repetitions (C1, set sizes 3-6, C2)
- Needed N = 12
  - Current study N = 29
# Sample and demographic variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>ADHD</th>
<th>Typically Developing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\bar{X}$</td>
<td>SD</td>
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<td>Age</td>
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<td>FSIQ</td>
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<td>SES</td>
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<td>11.50</td>
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<td>CBCL</td>
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<td>AD/HD Problems</td>
<td>72.47</td>
<td>5.79</td>
</tr>
<tr>
<td>TRF</td>
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<td></td>
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<td>AD/HD Problems</td>
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<td>8.62</td>
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<tr>
<td>CSI-Parent</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ADHD, Combined</td>
<td>76.33</td>
<td>10.72</td>
</tr>
<tr>
<td>CSI-Teacher</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ADHD, Combined</td>
<td>64.00</td>
<td>10.95</td>
</tr>
</tbody>
</table>

Note: ADHD = attention-deficit/hyperactivity disorder; CBCL = Child Behavior Checklist; CSI = Child Symptom Inventory; FSIQ = Full Scale Intelligence Quotient; SES = socioeconomic status; TRF = Teacher Report Form.

* $p \leq .05$, ** $p \leq .01$, *** $p \leq .001$
IQ as a covariate of WM

- **Share significant variance** ($r = .47$ to $ .90$)
  - Ackerman et al., 2005; Colom et al., 2005; Engle et al., 1999

- **WM = 1 of 4 factors on IQ test**
  - WMI-FSIQ: $r = .76$ (Wechsler, 2003)
    - $r = .40$ to $ .56$ with PSI, PRI, & VCI

- **Latent variable analysis**
  - Regression: CE, phonological S/R, and visuospatial S/R variance removed from FSIQ ($R^2 = .31$, $p = .02$)

- **Residual FSIQ (IQ unrelated to WM)**
  - ADHD = TDC ($p = .92$)
Hypotheses: Inattentiveness may be associated with any of the following deficiencies:

I. Deficient CE processes [internal focus of attention]

II. Exceeding child’s storage capacity [STS]

III. Deficiencies in both the CE and PH/VS storage capacity

IV. Ubiquitous inattentiveness unrelated to WM processes
Experimental Design

- Phonological WM (21 consecutive trials) at 4 set sizes (3, 4, 5, 6) [programmed using SuperLab 2.0]

- Visuospatial WM (21 consecutive trials) at 4 set sizes (3, 4, 5, 6) [programmed using SuperLab 2.0]

- All tasks administered in counterbalanced order across 4-week Saturday assessment sessions.

- Control conditions (C-1, C-2): Children used the Paint Program the initial and last condition for each session.
Tier I: Attentive behavior and phonological memory load

- Group, set size, and group x set size: all $p < .0005$
- Post hocs:
  - TDC > ADHD across all conditions (all $p \leq .009$)
  - ADHD: Pre = Post > 3 = 4 > 5 = 6
  - TDC: Pre = Post > 3 = 4 = 5 > 6
  - Pre = Post ($p \geq .18$)
  - Hedges’ $g = 1.55$ (SE = 0.42)

[Graph depicting percent oriented and incorrect stimuli per trial for different conditions and groups, with key points and trends noted.]

- 76% [24% off-task]
### Table 2. Mean Off-task Rates, Standard Difference Scores, and Effect Sizes in Children with ADHD and Typically Developing Children

<table>
<thead>
<tr>
<th>Study</th>
<th>ADHD % Off-task M (SD)</th>
<th>Control % Off-task M (SD)</th>
<th>Std. Diff. Scores (%)</th>
<th>Hedges’ g Effect Sizes (Std. Error)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Werry &amp; Quay (1969)</td>
<td>46.3 (12.8)</td>
<td>23 (15.4)</td>
<td>50.3</td>
<td>2.09 (0.53)</td>
</tr>
<tr>
<td>Forness &amp; Esveldt (1975)</td>
<td>47.0 (16.5)</td>
<td>34 (12.4)</td>
<td>27.7</td>
<td>0.88 (0.30)</td>
</tr>
<tr>
<td>Shecket &amp; Shecket (1976)</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>0.00*</td>
</tr>
<tr>
<td>Abikoff et al. (1977)</td>
<td>13.1 (10.0)</td>
<td>2.1 (2.6)</td>
<td>84.2</td>
<td>1.50 (0.21)</td>
</tr>
<tr>
<td>Campbell et al. (1978)</td>
<td>16.73 (15.15)</td>
<td>12.41 (10.88)</td>
<td>25.8</td>
<td>0.32 (0.35)</td>
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<tr>
<td>Jacob et al. (1978)</td>
<td>15.8 (NR)</td>
<td>10.5 (NR)</td>
<td>33.3</td>
<td>1.41 (0.53)*</td>
</tr>
<tr>
<td>Klein &amp; Young (1979)</td>
<td>39.8 (9.0)</td>
<td>26.6 (5.0)</td>
<td>33.1</td>
<td>1.78 (0.40)</td>
</tr>
<tr>
<td>Abikoff et al. (1980)</td>
<td>15.1 (23.4)</td>
<td>4.1 (7.8)</td>
<td>72.8</td>
<td>0.62 (0.19)</td>
</tr>
<tr>
<td>Zentall (1980)</td>
<td>15.0 (NR)</td>
<td>7.1 (NR)</td>
<td>52.2</td>
<td>0.45 (0.25)</td>
</tr>
<tr>
<td>Abikoff &amp; Gittel (1984)</td>
<td>17.4 (12.3)</td>
<td>3.5 (6.6)</td>
<td>79.7</td>
<td>1.39 (0.29)</td>
</tr>
<tr>
<td>Abikoff &amp; Gittel (1985)</td>
<td>15.7 (10.4)</td>
<td>2.5 (4.6)</td>
<td>84.1</td>
<td>1.71 (0.31)</td>
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<tr>
<td>Atkins et al. (1985)</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>0.59 (0.30)*</td>
</tr>
<tr>
<td>Book &amp; Sleen (1987)</td>
<td>5.11 (4.82)</td>
<td>0.78 (1.47)</td>
<td>84.7</td>
<td>1.21 (0.17)</td>
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<tr>
<td>Cunningham &amp; Siegel (1987)</td>
<td>33.0 (NR)</td>
<td>26.4 (NR)</td>
<td>19.9</td>
<td>0.51 (0.26)*</td>
</tr>
<tr>
<td>Roberts (1990)</td>
<td>39.5 (18.8)</td>
<td>12.9 (20.9)</td>
<td>67.3</td>
<td>1.31 (0.39)</td>
</tr>
<tr>
<td>DuPaul &amp; Rapport (1993)</td>
<td>44.26 (16.56)</td>
<td>19.72 (11.56)</td>
<td>55.4</td>
<td>1.66 (0.31)</td>
</tr>
<tr>
<td>Lett &amp; Kamphaus (1997)</td>
<td>18.3 (16.5)</td>
<td>12.7 (12.7)</td>
<td>30.6</td>
<td>0.36 (0.29)</td>
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<td>Nolan &amp; Gadow (1997)</td>
<td>30.5 (15.9)</td>
<td>13.3 (8.3)</td>
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<td>1.34 (0.27)</td>
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<tr>
<td>DuPaul et al. (1998)</td>
<td>33.0 (19.2)</td>
<td>9.5 (11.9)</td>
<td>71.2</td>
<td>1.31 (0.45)</td>
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<td>Skansgard &amp; Burns (1998)</td>
<td>23.8 (10.3)</td>
<td>4.8 (6.1)</td>
<td>79.8</td>
<td>2.23 (0.60)</td>
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<td>Solano et al. (2001)</td>
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<td>NR</td>
<td>0.58 (0.19)*</td>
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<td>Abikoff et al. (2002)</td>
<td>10.6 (24.0)</td>
<td>3.3 (13.2)</td>
<td>68.8</td>
<td>0.38 (0.06)</td>
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<td>Lauth &amp; Mackowiaki (2004)</td>
<td>83.0 (12.0)</td>
<td>70.0 (13.0)</td>
<td>15.7</td>
<td>1.03 (0.20)</td>
</tr>
</tbody>
</table>

Column M (SD) = 28.15 (18.28) 14.96 (16.47) 54.65 (23.71) 0.71 (0.04)*

**Best case estimation:**

**ES = 1.40**
Tier I: Attentive behavior and visuospatial memory load

- Group, set size, and group x set size: all $p < .0005$
- Post hocs:
  - TDC > ADHD across all conditions (all $p \leq .009$)
  - ADHD: Pre = Post > 3 > 4 = 5 = 6
  - TDC: Pre = Post = 3 = 4 = 5 > 6
  - Pre = Post ($p \geq .18$)
  - Hedges’ $g = 1.45$ (SE = 0.42)
WM Components and Attentive Behavior
[2 (group) x 3 (conditions) mixed-model ANOVA]

CE:  CE < CE = CE
(S/R Not Overwhelmed) (S/R Overwhelmed)
Hedges' g ES Magnitude of Working Memory Deficits in ADHD

- PH WM (Rapport et al., 2008)
- PH WM After Accounting for Inattentive Behavior
- VS WM (Rapport et al., 2008)
- VS WM After Accounting for Inattentive Behavior

- PH WM: 1.9
- PH WM After Accounting: 1.1
- VS WM: 2.3
- VS WM After Accounting: 1.5
Magnitude of Attention Deficits in ADHD

- Attention During PH Tasks
- Attention During PH Tasks After Accounting for WM Deficits
- Attention During VS WM Tasks
- Attention During VS Tasks After Accounting for WM Deficits

Hedges' g ES

<table>
<thead>
<tr>
<th></th>
<th>PH Attention</th>
<th>VS Attention</th>
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<tr>
<td></td>
<td>1.6</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>
Summary

- Initial inattentiveness in ADHD reflects underlying deficits in CE processes – most likely the internal focus of attention

- Exceeding WM storage capacity results in similar rates of inattentiveness in children with ADHD and typically developing children

- WM deficits remain after accounting for between-group differences in inattentiveness.

- Between-group inattentiveness differences are no longer significant after accounting for WM differences
Deficient WM systems/subsidiary systems & processes
Biological Influences (e.g., genetics)

Neurobiological Substrate

Environmental/Cognitive Demands

D1 receptor

(Core Feature)
Working Memory Deficits

(Secondary Features)
Inattentiveness
Hyperactivity
Impulsivity**

(Associated Features and Outcomes)
• Cognitive Test Performance
• Improved Learning
• Academic Achievement
• Social Skills**
• Organizational Skills
• Classroom Deportment
• Behavioral Inhibition

Alderson et al. (2010)

Insert PP slides of Impulsivity and Social Skill Deficits
Consolidation – the process by which short-term memories become long-term memories

Hippocampus: central to the consolidation of declarative memories based on the seminal studies by Scoville and Miller (1957; J Neurochem) following the bilateral medial temporal lobotomies that removed the ‘H.M.’s” hippocampi, the parahippocampal cortex, and parts of his amygdala.

- H.M. lost the ability to form new declarative memories

- Consolidation requires 3 interrelated processes:
  1. Stimulation of glutamate receptors [note: which can be blocked by infusing glutamate receptor antagonists into the hippocampus]
  2. Protein synthesis
  3. Gene transcription – process of transferring DNA sequence information into RNA information [note: protein synthesis & gene transcription are not needed for STM]

- LTM process can be tested at a 3-hour interval to ensure consolidation [Lombroso & Ogren, 2008; J Am Acad Child Adolescent Psychiatry, 47]
Fig. 3 Selected outcome variables for MTA children, graphed by 36-month ADHD symptom latent class and LNCG. CIS = Columbia Impairment Rating Scale; LNCG = local normative comparison group; ODD = oppositional defiant disorder; SNAP = Swanson, Nolan, Pelham Rating Scale.
N = 325 children
SA=SAT performance
CD = TRF conduct disorder problems

Childhood Academic Impairments

Evaluated using teacher reports, academic achievement tests (e.g., WRAT, Woodcock), and IQ tests (WISC, Woodcock, Peabody)

• Poor School Performance (90%+)
  – (reduced productivity is greatest problem)

• Low Academic Achievement (10-15 pt. deficit)

• Low Average Intelligence (7-10 point deficit)

• Learning Disabilities (24-70%)
  – Reading (15-30%; 21% in Barkley, 1990)
  – Spelling (26% in Barkley, 1990)
  – Math (10-60%; 28% in Barkley, 1990)
  – Handwriting (common but % unspecified)
Characteristics of Reliable Tests, Tasks, and Paradigms Used to Differentiate Children with ADHD from Normal Controls [n= 439 task comparisons in 142 studies]


<table>
<thead>
<tr>
<th>Task</th>
<th>Recognition</th>
<th>Recall</th>
<th>Working Memory Parameter</th>
<th>Working Memory Subvocal Speech</th>
<th>Working Memory Buffer</th>
<th>Response Stimulus Present</th>
<th>Self- (S)/ Other- (O) Paced</th>
<th>Effect Size</th>
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<tbody>
<tr>
<td><strong>Reliable Tasks:</strong></td>
<td></td>
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<td>CPT</td>
<td>yes</td>
<td>no</td>
<td>s or msec</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>O</td>
<td>0.85</td>
</tr>
<tr>
<td>Go/No-Go</td>
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<td>no</td>
<td>msec</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>O</td>
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<tr>
<td>Stop Signal</td>
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<td>no</td>
<td>msec</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>O</td>
<td>1.03</td>
</tr>
<tr>
<td>Vis Mem (recall)</td>
<td>no</td>
<td>yes</td>
<td>s</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>S/O</td>
<td>0.78</td>
</tr>
<tr>
<td><strong>Unreliable Tasks:</strong></td>
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</tr>
<tr>
<td>Boston Naming</td>
<td>no</td>
<td>yes</td>
<td>s-min</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>S</td>
<td>0.65</td>
</tr>
<tr>
<td>Finger tapping</td>
<td>no</td>
<td>no</td>
<td>s-min</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>S</td>
<td>0.27</td>
</tr>
<tr>
<td>Language</td>
<td>no</td>
<td>yes</td>
<td>min</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>S</td>
<td>0.47</td>
</tr>
<tr>
<td>Pegboard</td>
<td>yes</td>
<td>no</td>
<td>s-min</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>S</td>
<td>0.37</td>
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<td>Rey AVLT</td>
<td>no</td>
<td>yes</td>
<td>s-min</td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>S</td>
<td>n/a</td>
</tr>
<tr>
<td>Tower of London</td>
<td>no</td>
<td>yes</td>
<td>s-min</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>S</td>
<td>n/a</td>
</tr>
<tr>
<td>Trail making</td>
<td>yes</td>
<td>no</td>
<td>min</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>S</td>
<td>0.55</td>
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<tr>
<td>Visual motor</td>
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<td>no</td>
<td>min</td>
<td>no</td>
<td>no</td>
<td>yes</td>
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<td>WRAML</td>
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<td>s-min</td>
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<td>no</td>
<td>S</td>
<td>0.35</td>
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</tbody>
</table>

Note: AVLT = Auditory Verbal Learning Test; CPT = Continuous Performance Test; WRAML = Wide Range Assessment for Memory and Learning; n/a = unable to calculate effect size owing to insufficient statistical information.
Educational Outcomes

Assessed by school data, self-report, & high school transcripts:

- Lower Class Ranking (MKE: 69% vs. 50%)
- Lower GPA (MKE: 1.7 vs. 2.6)
- Poorer school performance—reduced productivity (+90%)
- Low academic achievement (10-15 point deficit)
- Higher rate of LD: reading, spelling, math, writing (24%-70%)
- More grade retention (25-45%; MKE: 42 vs. 13)
- More are suspended (40-60%; MKE: 60 vs. 19)
- Greater expulsion rate (10-18%; MKE: 14 vs. 6)
- Higher drop out rate (23-40%; MKE 32 vs 0)
- Fewer enter college (MKE: 22% vs. 77%)
- Lower college graduate rate (5% vs. 35%)

MKE = Milwaukee Young Adult Outcome Study
What is Working Memory?

- Working memory is a limited capacity system that enables individuals to store briefly and process information (Baddeley, 2007).
Phonological Working Memory

Phonological output buffer
Broca’s area-premotor cortex

Central Executive

Auditory Input

Phonological Analysis

Visual Input

Visual analysis & STS

Orthographic to phonological recoding

Phonological STS
Inferior parietal lobe

Rehearsal Process

Spoken Output

Baddeley, 2007

http://docsbrainblocks.com/images/dyslexia_1.jpg
Requires short-term storage but no processing – limited demand on the CE
What components of the WM Phonological Store are deficient?

Child must hold 2, 4, or 6 single syllable words under 3 distinct recall conditions:

<table>
<thead>
<tr>
<th>Recall conditions: 3-seconds</th>
<th>12-seconds</th>
<th>21-seconds</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 words</td>
<td>2 words</td>
<td>2 words</td>
</tr>
<tr>
<td>4 words</td>
<td>4 words</td>
<td>4 words</td>
</tr>
<tr>
<td>6 words</td>
<td>6 words</td>
<td>6 words</td>
</tr>
</tbody>
</table>

[Word lists and recall conditions completely counterbalanced over 4 sessions 1-week apart]
What components of the WM Phonological Store are deficient?

Analyses:

- Examine word list effect for ADHD & TD children under 3-sec [minimal delay condition – WM store can hold information for 2-3-s without invoking the rehearsal mechanism] – results indicate whether storage capacity is limited in children with ADHD.

- Select the longest word list a child can successfully recall at 50% or greater to establish individual word span (Conway et al., 2005).

- Examine potential rehearsal mechanism deficiencies by comparing each child at his established span across the 3 recall (3-s, 12-s, 24-s) conditions.
Phonological Memory Task

Presentation Phase

Storage/Rehearsal

Recall Phase

2-Words

4-Words

6-Words

3-seconds delay

12-seconds delay

21-seconds delay

Central Executive

Auditory Input

Phonological Analysis

Phonological

STS

Inferior parietal lobe

Rehearsal Process

Phonological output buffer

Broca’s area-premotor cortex

Spoken Output
3 set size conditions at 3-s recall

Each child is performing at their established memory span

Stimuli Recalled Correctly

<table>
<thead>
<tr>
<th>Stimuli (words)</th>
<th>TD</th>
<th>ADHD</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>3</td>
<td>**</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>**</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td></td>
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</tbody>
</table>

~ 57% storage capacity deficit

% Correct

<table>
<thead>
<tr>
<th>Seconds</th>
<th>TD</th>
<th>ADHD</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>ns</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>**</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>**</td>
<td></td>
</tr>
</tbody>
</table>

ADHDs lose ~ 30% of words learned

TDs lose ~ 10% of words learned
Biological Influences, e.g., genetics

NEUROBIOLOGICAL SUBSTRATE

ENVIRONMENTAL/COGNITIVE DEMANDS

CORE FEATURES: INATTENTION, HYPERACTIVITY, IMPULSIVITY

SECONDARY FEATURES
Biological Influences (e.g., genetics)

Neurobiological Substrate

Environmental/Cognitive Demands

(Core Feature)
Working Memory Deficits

(Secondary Features)
Inattentiveness
Hyperactivity
Impulsivity

(Associated Features & Outcomes: Impaired
- Learning
- Cognitive Test Performance
- Academic Achievement
- Social Skills
- Organizational Skills
- Classroom Deportment
- Delay Aversion