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Review

Working memory and autism: A review of literature

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ABSTRACT

Research studies that evaluated working memory with students with autism and other disorders were reviewed and summarized. Results suggest that persons with autism score lower on measures of working memory than do typical controls especially on tasks that require cognitive flexibility, planning, greater working memory load, and spatial working memory, and with increasing task complexity and in dual task conditions. Lower scores in verbal working memory were associated with greater problems in adaptive behavior and more restrictive and repetitive behavior. Children with autism were as likely as typical children to employ articulatory rehearsal (verbal WM). The format of WM tasks may determine whether or not performance is impaired. Implications for educational practice and future research are discussed.

Contents

1. Introduction

Current definitions of Autism Spectrum Disorders (ASD), as those first described by Kanner (1943), include students who Exhibit (1) social/communication deficits, and (2) fixated interests and repetitive behaviors (American Psychiatric Association, 2013). Additionally, in their textbook description of children with Autism, Scott, Clark, and Brady (2000) included challenges in cognitive and executive abilities. Numerous investigations have focused on social, language, and behavioral characteristics of children with autism. Fewer studies have explored the cognitive functions and executive

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abilities of this group. Working memory is a cognitive function/executive ability that has implications for social, behavioral, and academic performance; it is an important component of numerous educational tasks.

Working memory (WM) has been defined as the process by which information is stored and processed mentally (Baddeley, 1986). The most frequently used model of WM was presented by Baddeley who stated that WM consists of multiple components: (a) the *phonological loop*, which is responsible for maintaining speech-based information; (b) the *visuo-spatial sketchpad*, that functions in storing material by its visual or spatial features (Gathercole, Pickering, Ambridge, & Wearing, 2004); and (c) the *attention component*, that allows maintenance of task relevant focus, processing capabilities, and self regulation in the presence of external or internal distractions (Wolf & Bell, 2007). These components of WM that provide the ability to mentally hold and process information have been considered essential for daily activities such as planning, organization, cognitive flexibility (for reviews see Baddeley, 1986, 1992), and the learning of skills such as reading (Bayliss, Jarrold, Gunn, & Baddeley, 2003), comprehension (Friedman & Miyake, 2004), arithmetic (DeStefano & LeFevre, 2004), and problem solving (Beilock & DeCaro, 2007).

A recent review of the implications of WM deficits stated that the majority of children with poor WM are slow to learn in the areas of reading, math, and science, across both primary and secondary school years. These students have difficulties in following instructions, with learning activities that require both storage and processing, with place-keeping, and appear to be inattentive, to have short attention spans, and to be distractible (Gathercole, 2008). Thus, deficits in WM are closely associated with learning deficits observed in daily classroom activities. To this end, researchers have suggested that without early intervention, these deficits cannot be overcome and will continue to reduce the likelihood of academic success (Alloway & Gathercole, 2006).

WM deficits in individuals with Autism Spectrum Disorder (ASD) appear to result in numerous problems associated with behavior regulation, cognitive flexibility, abstract thinking, and focusing and sustaining attention (Hughes, Russell, & Robbins, 1994; Ozonoff & McEvoy, 1994; Ozonoff, Pennington, & Rogers, 1991). However, previous research has been inconsistent and inconclusive on identifying the factors that influence WM performance or its academic implications for individuals with ASD. This is possibly due to the large variation in the characteristics of individuals with ASD and the implications of these characteristics on the WM assessment procedures.

Primarily, there are two subgroups of individuals with ASD, those that coexist with intellectual disability, and those with average or above average intellectual functioning. Individuals with ASD with average or above average functioning include those who are diagnosed with High Functioning Autism (HFA) or those with Asperger's (ASP), and their characteristics vary in terms of social, linguistic, and cognitive abilities from individuals with ASD who have intellectual disability. Koyama, Tachimori, Osada, Takeda, and Kurita (2007) compared the performances of individuals with ASP with higher (mean full-scale IQ, 98.3) and participants with HFA with lower (mean full-scale IQ, 94.6) intellectual functioning on the Wechsler Intelligence Scales and autism rating scales, and found that, consistent with previous studies, their participants with ASP had higher verbal IQ and scored significantly higher than participants with HFA on verbal subtests of Vocabulary and Comprehension, although neither group of participants in this study had below average IQ.

Although we have glimpses of the cognitive performances of children with ASD from these intelligence tests, many questions remain unanswered. Without fully understanding the cognitive challenges faced by individuals with Autism Spectrum Disorders (ASD) we are challenged in developing educational interventions. How do students with ASD perform on WM? How does their performance compare to children with other disabilities that also show difficulties in WM, such as those with ADHD, Tourette Syndrome, and intellectual disability? The information about WM is important for researchers to develop interventions that can better target the challenges for this population. Therefore, the purpose of this review is to evaluate existing WM research on individuals with ASD within the context of individual existing characteristics with linguistic and cognitive challenges.

2. Method

To search for articles for this review, we accessed the databases Academic Search Premier, ERIC, and Psych Info. We utilized the search words "Autism," "Asperger's," "Pervasive Developmental Disorders," "High Functioning Autism," "Working memory," "spatial working memory," and "auditory working memory." Research studies were included in this review if they were (a) published in peer-reviewed journals in English, (b) included individuals with ASD, Asperger's Syndrome, or High Functioning Autism, and (c) included experimental or quasi experimental methodologies that evaluated WM. We also included articles that had test results from the working memory subtests from the Wechsler Intelligence Scale for Children (WISC-III and IV). Both computer and hand searches were conducted to locate articles that met these criteria. We excluded studies that exclusively evaluated working memory using medical procedures, such as fMRI scans.

This search produced 24 studies that evaluated WM performance for individuals with ASD. The articles were obtained from 11 different journals and were published between 1996 and 2013. Twenty of the studies assessed child and teenaged populations. Four studies assessed adult populations and one study assessed both child and adult populations.

2.1. Participants and setting

The 24 studies that evaluated WM with individuals with ASD classified their participants into three main categories – HFA, ASP, and autism. The participants were diagnosed based on their ratings on one of the following instruments: the

Autism Diagnostic Interview – Revised (ADI-R; Lord, Rutter & LeCouteur, 1994), the Autism Diagnostic Observation Schedule (ADOS; Lord et al., 1989), the Autism Diagnostic Observation Schedule – Generic (ADOS-G; Goldberg et al., 2005; Goldstein, Beers, Siegel, & Minshew, 2001; Lord et al., 2000), clinical diagnosis in a hospital setting using DSM-IV criteria (Gilotty, Kenworthy, Sirian, Black, & Wagner, 2002), or the Diagnostic Interview Schedule for Children for DSM-IV, parent version (PDISC-IV; Geurts, Verte, Oosterlaan, Roeyers, & Sergeant, 2004). See Table 1 for more information on the participants of each study.

The number of participants in these studies ranged from 20 to 520, with sample sizes varying in each study. In each of these WM studies, participants were selected because their intellectual functioning was 66 or higher (range 90–132) as measured on the Wechsler Adult Intelligence Scale-Revised (WAIS-R) or the Wechsler Intelligence scale for Children (WISC).

The studies classified the participants as having autism (AUT) or Asperger's (ASP), or High Functioning Autism (HFA) and compared their performances to typical comparisons, students with learning disabilities (LD), those with attention deficit hyperactivity disorders (ADHD), Pervasive Developmental Disorder Not Otherwise Specified (PDD-NOS), or Tourette Syndrome (TS). None of the studies compared the three groups with AUT, ASP, and HFA simultaneously.

The majority of reviewed studies assessed their participants across multiple sessions in undefined settings but some identified their settings as a university lab (3) or a hospital setting (6). During these sessions, the investigators administered various tests to the participants either through standard testing procedures or computer programs.

2.2. Tasks and procedures

The studies evaluated WM in spatial working memory by using the Spatial Working Memory Span Test (Ozonoff & Strayer, 2001), the Stockings of Cambridge task, the Intra-Dimensional/Extra-Dimensional set-shifting task, and the Spatial working memory computerized task from the Cambridge Automated Neuropsychological Test and Battery (CANTAB), (Cambridge Cognition, 1996; Goldberg et al., 2005; Steele, Minshew, Luna, & Sweeney, 2007), the Behavior Rating Inventory of executive functioning completed by parents (Gilotty et al., 2002), word span, block span, the Tower of London (Joseph, McGrath, & Tager-Flusburg, 2005), problem solving and set shifting using the Wisconsin Card Sorting test (WCST; Geurts et al., 2004), and WAIS-R profile (Goldstein et al., 2001).

3. Results

In the studies reviewed, comparisons were made between the performances of individuals with Autism Spectrum Disorders to those of typical comparisons and to those with other disorders. In comparisons with typical children, most studies reported lower performances in WM for persons with autism compared to typical controls. Individuals with HFA consistently made more errors, used fewer strategies, and showed poorer performance than typical children on tasks that involved cognitive flexibility, planning, higher working memory load, and spatial working memory, especially with increasing task complexity (Guerts, Verte, Oosterlaan, Roeyers, & Sergeant, 2004; Goldberg et al., 2005; Landa & Goldberg, 2005). Similarly, individuals with ASP also performed lower than comparisons on dual task conditions compared to single task conditions (Garcia-Villamistar & Sala, 2002) and scored lower on the WM-Math component of IQ tests, such as digit symbol (Nakahachi et al., 2006). Additionally, based on parent ratings on the Vineland Adaptive Behavior Scale (Sparrow, Balla, & Cichetti, 1984) and the Behavior Rating Inventory of Executive Functioning-Parent Rating Questionnaire (BRIEF: Gioia, Isquith, Guy, & Kenworthy, 2000), one of the studies indicated that, for persons with ASP and HFA, WM performance was negatively correlated with problems in adaptive behavior, communication, and socialization (Gilotty et al., 2002). That is, the lower the scores in working memory (especially verbal working memory) the higher the problems in adaptive behavior. This finding is supported by Lopez, Lincoln, Ozonoff, and Lai (2005) who compared the performances of 17 average functioning adults with autism to an equal number of typical controls on a new executive function battery (i.e., Delis-Kaplin Executive Function Scales), the Wisconsin Card Sorting test, Wechsler Adult Intelligence Scale (WAIS), and behavioral ratings from the Autism Diagnostic Observation Schedule, Autism Diagnostic Interview – Revised, Gilliam Autism Rating Scale, and the Aberrant Behavior Checklist. They found that the executive processes (i.e., cognitive flexibility, working memory, and response inhibition) were highly related to the level of restrictive and repetitive behaviors engaged in by participants with autism. However, there were no group differences in working memory, but this was attributed to the lack of sufficient power to detect a medium-sized effect.

In comparisons of the WM performances of individuals with HFA and those with specific learning disabilities (LD), similarities were found. Goldstein et al. (2001) compared the performances of 35 adults with HFA and 102 adults with LD on the WAIS and the Wide Range Achievement Test (WRAT) and concluded that the cognitive profile of individuals with HFA was similar to that of individuals with LD who were not significantly impaired in reading but who had academic difficulties in other areas, such as mathematics.

In two studies with children (6–12 years), Russell, Jarrold, and Henry (1996) assessed WM through the use of articulatory rehearsal (i.e., repeating back pairs of long and short words), and the capacity of WM through computerized variations of counting and computational tasks. Comparisons were made between typical students, those with autism, and those with moderate learning difficulties. The authors reported that the participants with autism were as likely as typical children to employ articulatory rehearsal (verbal WM) and they had spans superior to those of participants with moderate learning difficulties, but they performed lower than students with moderate learning difficulties in their total capacity of WM.

Table 1

Authors	Participants	Diagnosis criteria	Assessments	Main results
Benetto, Pennington, and Rogers (1996)	*ASD*: $n = 19$ Age: $M = 15.95$ yrs FSIQ: $M = 88.89$ *Clinical Comparisons*: $n = 19$ (including those with learning and attention disorders) Age: $M = 15.23$ yrs FSIQ: $M = 91.74$ Sample recruited for the research project	DSM-III-R criteria for Autism or PDD Childhood Autism Rating Scale WISC-R Stanford Binet Test of Intelligence	*Working Memory (WM) Measures* Sentence Span. Counting Span WISC-included subtest of working memory such as Digit span *Measures of Executive Functioning* Wisconsin Card Sorting Test (WCST). Tower of Hanoi *Memory Measures* Temporal order versus recognition Memory California Verbal Learning Test	Students with ASD performed significantly lower than comparisons on measures of temporal order memory, source memory, supra-span, free recall, working memory, and EF, but not on short- and long-term recognition, cued recall, or new learning ability. Significant correlation in the scores of Digit Span Forward (from WISC) and other WM subtests: Counting Span, and Sentence Span.
Bodner, Beversdorf, Saklayen and Christ (2012)	*ASD*: $n = 14$ (71% male) Age: $M = 18.9$ yrs, Mean FSIQ = 103.9 Of these, 7 met criteria for Autistic disorder and 7 met criteria for Asperger's disorder. *NC*: $n = 13$ (69% male) Age: $M = 19.2$ yrs Mean FSIQ = 108.7 Participants were receiving clinical services in an academic medical center specializing in diagnosis and treatment of ASD.	Diagnostic interviews, DSM-IV criteria, Autism Diagnostic Interview – Revised; Wechsler Abbreviated Scale of Intelligence (WASI)	Participants attended two testing sessions over the course of a week. Each participant received 40 mg of propranolol (norepinephrine) upon arrival at one testing session and a placebo (sugar) pill at the other session, with the order of drug administration counterbalanced within each group. Following a 60-min delay (to allow for complete absorption and maximization of plasma levels), participants completed the AX-Continuous Performance Test (CPT).	Individuals with ASD performed more poorly than controls in the working memory condition (BX trials). The ASD group performed significantly better in the propranolol condition than the placebo condition. Working memory performance of the control group was unaffected by propranolol/placebo administration.
Cui et al. (2010)	*ASP*: $n = 12$ Age: $M = 7.46$ yrs FSIQ: $M = 100.03$ Boys: girls 11:1 *Controls*: $n = 29$ Age: $M = 7.37$ yrs FSIQ: $M = 108.31$ Boys: girls 23: 6 Participants were outpatients in a child developmental behavior center.	Clinical diagnosis using DSM-IV criteria WISC – Chinese version	*Verbal Storage-Only Tasks* Digit recall and word list recall examining the phonological loop *Complex Memory Span Tasks* backward digit recall and counting recall involving both the function of central executive (for processing) and that of phonological loop (for storing) *Visuospatial Storage Tasks* Block recall and variant-visual-pattern test measuring the visuospatial sketchpad; n-back tests	Children with ASP performed better than controls in digit and word recall tasks (consistent with the view that they had better rote memory skills), but worse in a block recall task and variant-visual-patterns test, suggestive of deficits in representing visual and spatial information. In n-back test, ASP group had similar accuracy as controls but took longer and showed larger effects of task load.
Gabig (2008)	*ASD*: $n = 15$ (13 boys, 2 girls,) Age: $M = 6$ yrs 6 m. NVIQ: $M = 95$ *TD (Control)*: $n = 10$ Age: $M = 6$ yrs 8 m. NVIQ: $M = 106$ Participants recruited from a larger, ongoing study of language and cognitive-linguistic processing ability in verbal children with autism.	Clinical diagnosis using DSM-IV criteria. Autism Diagnostic Interview – Revised (ADI–R); NV intelligence – Differential Ability Scale (DAS) Peabody Picture Vocabulary Test; Word Articulation subtest of the Test of Language Development – Primary; Social Communication Questionnaire	*Verbal WM with Increasing Complexity* Nonword repetition (NWR) required encoding the phonological representation of a nonsense word and repeating it. Memory for digits span (MD) required encoding phonological and semantic representations and storing and recalling a series of numbers in sequence. Sentence imitation (SI) required encoding phonological and semantic representations of words and constructing phrases and clause structures to aid in the organization, temporary storage, and recall of a sentence.	ASD group scored significantly below controls on NWR, MD, and SI and hierarchy of memory task complexity influenced performance outcomes for the ASD group only. ASD group performed better on NWR than on MD or SI, consistent with previous research on verbal WM function in autism with the a pattern of escalating memory deficits with increasing task complexity reported in older children and adults with autism.

Table 1 (*Continued*)

Authors	Participants	Diagnosis criteria	Assessments	Main results
Garcia-Villamistar and Sala (2002)	*ASD*: $n = 16$; Age: $M = 23.50$ yrs, *NC*: $n = 16$; Age: $M = 21.19$ yrs, 8 males,8 females in each group IQ: Required to score above the 35th percentile point on the Standard Progressive Matrices	Clinical diagnosis using DSM-IV criteria Total Score of Childhood Autism Rating Scale >30	*Single-task Conditions* Digit Recall: Present with lists of digits for 2 min then assess percentage of sequences correctly recalled. The Tracking Task: Cross out as many of the 80 1-square-cm boxes on sheets of white paper as possible with 2 min *Dual-task*: Perform the digit recall task and the tracking task simultaneously. The Dysexecutive Questionnaire completed by a relative Wisconsin Card Sorting Test Verbal fluency Test	For the digit span and tracking tasks, no significant differences between groups in single task conditions. Participants with ASD showed poorer dual-task performance than the control group. All executive function tests contributed to correctly predict participant's group (control or ASD)
Gilotty et al. (2002)	*HFA*: $n = 35$ Age: $M = 10.49$ yrs, ($SD = 3.04$) Boys = 30, Girls = 5 FSIQ: $M = 103.94$ yrs ($SD = 16.62$) Hospital-based setting	DSM IV criteria and hospital based diagnosis	Vinland Adaptive Behavior Scales (VABS); Behavior Rating Inventory of Executive Function-parent rating version (BRIEF) – utilizes verbal working memory descriptors.	Significant relationship between scores on VABS-communication and socialization, and working memory subscales of the BRIEF.
Goldberg et al. (2005)	*HFA*: $n = 17$ Age range: 8–12 yrs Age: $M = 10.3$ yrs, $SD = 1.8$ FSIQ: $M = 96.5$, $SD = 15.9$ *ADHD*: $n = 21$ Age: $M = 9.8$ yrs, $SD = 1.3$ FSIQ: $M = 113.8$, $SD = 10.3$ *NC*: $n = 32$ Age: $M = 10.4$ yrs, $SD = 1.5$ FSIQ: $M = 112.6$, $SD = 12.1$	Autism Diagnostic Interview – Revised; Autism Diagnostic Observation Schedule; Diagnostic Interview for Children and Adolescents Conner's Parents and Teacher Rating Scales – Revised. DSM-IV Criteria, clinical diagnosis	Stroop Color and Word Test (inhibition) Administered in 3 sheets of laminated paper, each with 5 columns of 20 items, each timed for 45 s. SOC, ID/ED, and SWM tasks from the CANTAB (planning, set-shifting, and working memory) Administered on a PC with a touch screen placed within arms' reach. An examiner read the instructions for each task verbatim from the CANTAB_ manual and encouraged participants by using the prompts. Participants responded by touching the screen.	No group differences on the response inhibition, planning, or set-shifting tasks. On the SWM task, children with HFA made significantly more between-search errors than controls on both the most difficult problems (8-box) and on the mid-difficulty problems (6-box); Conclusions suggest that spatial working memory is impaired in both ADHD and HFA, and more severely in the latter.
Guerts and Vissers (2012)	*HFA*: $n = 23$ including 16 ASP, 2 autism, 1 PDD-NOS, 4 ASD; *NC*: $n = 23$ Age range 51–83 yrs	Social Responsiveness Scale – Dutch version Diagnosis by an Autism specialist	Working Memory – Visuo-spatial WM-Spatial Span (forward problems) from the Wechsler Memory Scale-III The Dutch Adult Reading Test (DART) The Sustained Attention to Response Test (SART); Digit Symbol-copy from WAIS (Processing speed); Modified Card Sorting Test (Cog. Flexibility); Tower of London (Planning) Controlled Word Association Task (Fluency); Visual Reproduction of the WMS-III (Visual Memory); The Dutch version of the Rey Auditory Verbal Learning Task (RAVLT) (Verbal Memory)	Elderly with HFA had more problems with visio-spatial WM, sustained attention, and fluency than controls; other cognitive domains were intact. In previous studies, children and adults with autism demonstrated deficits in planning and cognitive flexibility. In this study, with the elderly with autism, these deficits did not seem to be present, suggesting that the deficits disappear with aging.

Guerts et al. (2004)	*HFA*: $n = 41$ Age: $M = 9.4$ yrs FSIQ: $M = 98.3$ *ADHD*: $n = 54$ Age: $M = 9.3$ yrs FSIQ: $M = 99.5$ *NC*: $n = 41$ Age: $M = 9.1$ yrs FSIQ: $M = 111.5$	Autism Diagnostic Interview – Revised (ADI-R); Child Communication Checklist (CCC); Disruptive Behavior Disorder rating scale (DBD); Diagnostic Interview Schedule for Children for DSM-IV, parent version (PDISC-IV); WISC-R: 4 subtests used for FSIQ – Vocabulary, Arithmetic, Picture Arrangement, and Block Design.	Self-Ordered Pointing task (Visual working memory); Circle Drawing Task (inhibition); Opposite Worlds of the Test of Everyday Attention for Children (TEA-Ch); Tower of London (planning); Wisconsin Card Sorting Test – Change task (cognitive flexibility, verbal fluency); Corsi Block Tapping Test (Short term memory)	Children with HFA demonstrated deficits in all executive functioning domains, except working memory. The HFA group showed more difficulties than the ADHD group with planning and cognitive flexibility.
Joseph et al. (2005)	*ASD*: $n = 37$ Boys = 35, girls = 2 Age: $M = 7.11$ yrs, $SD = 1.9$ Verbal IQ: $M = 87$, $SD = 19$ (Range 61–133) Nonverbal IQ: $M = 91$, $SD = 22$ (Range 49–133) *NC*: $n = 31$ Age: $M = 8.3$ yrs VIQ: $M = 88$ (Range: 64–122) Non-verbal IQ: $M = 91$, SD 17 (Range 51–114)	DSM IV criteria, Autism Diagnostic Interview–Revised, Autism Diagnostic Observation Schedule, Differential Ability Scales, Peabody Picture Vocabulary Test	Word Span Forward and Backward; Block Span Forward and Backward; working memory and inhibitory control NEPSY Knock-Tap, and planning (NEPSY Tower).	Findings suggest that executive dysfunction in autism is not directly related to language impairment per se, but rather involves an executive failure to use language for self-regulation and working memory tasks. ASD group performed lower than the NC group in all tests.
Kaufmann et al. (2013)	*ASP*: $n = 10$ Age: $M = 14.7$ yrs FSIQ: $M = 102.3$ Boys = 8, girls = 2 Verbal IQ = 107.6 Performance IQ = 95.8 Boys = 8, girls = 2 *NC*: $n = 10$ Age: M = 13.8 yrs FSIQ: $M = 109.5$ Verbal IQ: $M = 114.0$ Performance IQ: $M = 106$	DSM-IV-TR (APA, 2000) Autism Diagnostic Observation Scale (ADOS) Autistic Diagnostic Interview-Revised (ADI-R)	Various subtests of the PC-administered Cambridge Neuropsychological Test Automated Battery (CANTAB), including Spatial WM-requiring participants to find a token in each of a series of boxes located within a rectangle (stimulus duration being response bound) and use them to fill up an empty column on the right side of the screen. Task difficulty increased steadily (number of boxes 3, 4, 6, 8 indicating working memory load). At each level, participants were required to solve at least four trials.	Participants with ASP somewhat slower than controls in all but the SWM task. Participants with ASP solved the SWM task somewhat quicker but at the same time they committed numerically, but not statistically, more errors than controls.

Table 1 (*Continued*)

Authors	Participants	Diagnosis criteria	Assessments	Main results
Landa and Goldberg (2005)	*HFA*: $n = 19$ Age: $M = 11.01$ yrs, $SD = 2.89$ FSIQ: $M = 109.7$, $SD = 15.80$ *NC*: $n = 19$ Age: $M = 11$ yrs, $SD = 2.85$ FSIQ: $M = 113.4$, $SD = 14.34$ Research Lab	Autism Diagnostic Interview-Revised, Autism Diagnostic Observation Schedule, or the Autism Diagnostic Observation Schedule-Generic	Cambridge Neuropsychological Test Automated Battery (CANTAB; Cambridge Cognition, 1996) to probe spatial working memory (SWM), planning (Stockings of Cambridge, hereafter SOC), and flexibility (set-shifting, using the intra-dimensional/extra-dimensional Shift Task, ID/ED Shift task) – Computerized test Clinical Evaluation of Language Fundamentals-Revised	VIQ correlated significantly with all the language assessment measures for the HFA group SWM deficits found for the HFA group on the tasks imposing the greatest WM load, and included preservation, and poorer search strategies compared to controls. HFA participants solved fewer problems in the min number of moves, regardless of task difficulty.
Lopez et al. (2005)	*AUT*: $n = 17$ Age: $M = 29$ yrs (range 19–42) VIQ: $M = 73$, $SD = 16$ FS IQ: $M = 77$, $SD = 15$ *NC*: $n = 17$ Age: $M = 29$ yrs, (range 18–29) VIQ: $M = 92$, $SD = 15$ FSIQ: $M = 89$, $SD = 13$	Wechsler Adult Intelligence Scale-Third edition. Diagnosis of autism by a licensed psychologist, board certified child adolescent psychiatrist, pediatrician, or neurologist. Autism Diagnostic Interview – Revised Autism Diagnostic Observation Schedule Gilliam Autism Rating Scale	Delis-Kaplin Executive Function Scales The following subtests were used- (a) California Verbal Fluency Test with 6 conditions, one a switching condition. Individual required to generate as many novel words to the letters F, A, and S. (b) California Design Fluency Test with 3 conditions that required participants to make unique designs by connecting dots with straight lines. (c) California Stroop Test required reading words of colors to name the dissonant ink color. (d) Tower of California test (spatial planning and cognitive flexibility) (e) California Trails Test consists of five conditions that assess visual-motor sequencing, visual scanning, number-letter switching, and motor speed. Wisconsin Card Sorting Test requires sorting stimulus cards based on 3 principles (color, form, number). Must ascertain the correct principle based on feedback about card sorting choices.	Several executive processes (i.e., cognitive flexibility, working memory, and response inhibition) were highly related to the restrictive, repetitive symptoms of autism; whereas, other executive process (i.e., planning and fluency) were not found to be significantly correlated with restricted, repetitive symptoms.
Mayes and Calhoun (2008)	*HFA*: $n = 54$ Age: $M = 8.2$ yrs (Range = 6–14 yrs) FSIQ: $M = 101$	DSM-IV criteria Checklist for Autism in Young Children; Child interview and Self report scale; clinical observations during testing; review of the child's developmental History; school transcripts	Wechsler Individual Achievement Test-2nd edition (WIAT-II) Word Reading, Reading Comprehension, Numerical Operations, and Written Expression subtests and 12 Wechsler Intelligence Scale for Children-Fourth edition (WISC-IV) subtests comprising the 4 indexes, including working memory (WMI), Perceptual Reasoning (PRI), Verbal Comprehension (VCI) and Processing Speed (PCI); and FSIQ, and General Ability Index	HFA had above normal scores on the WISC-IV Perceptual Reasoning and Verbal Comprehension Indexes and below normal scores on the Working Memory and Processing Speed Indexes norm.
Nakahachi et al. (2006)	*ASP*: $n = 16$ Male: $n = 12$, Female: $n = 4$ Age: $M = 28.0$ yrs (Range = 20–42) FSIQ: $M = 101$ Range:75–132) *NC*: $n = 28$ Male: $n = 12$, Female: $n = 7$ Age: $M = 28.3$ yrs (Range = 19–42) FSIQ: $M = 103$ (Range: 80–130)	DSM-IV Wechsler Intelligence Scale – Revised (WAIS-R)	Advanced Trail Making Test (ATMT) (Kajimoto, computerized version). Requires visuomotor coordination, visual scanning as in the digit symbol test, to quantitatively estimate working memory *Random (R) task* When a correct numbered button was pushed, the other buttons were rearranged randomly. *Fixed (F) task* When a correct numbered button was pushed, the location of the other buttons remained fixed. Reaction time could be shortened compared with task R by using working memory of subsequent buttons.	Discrepancy of scores among working memory-related tasks was demonstrated in ASP. The normal digit span and WMR in ATMT and lower score only in digit symbol for the ASP group suggests normal ability in retaining short-term information. Poor performance in the Digit symbol task may be due to the vagueness of task working memory requirement and delay of task performance.

Oliveras-Rentas, Kenworthy, Roberson, Martin, & Wallace (2012)	Total Sample: $n = 56$ *HFA*: $n = 22$ *ASP*: $n = 22$ *PDD-NOS*: $n = 12$ Age: $M = 9.11$ yrs (6–15) Boys = 46 (82%) FSIQ: $M = 97.55$	Neuropsychological battery, Autism Diagnostic Interview (ADI) and the Autism Diagnostic Observation Schedule (ADOS)	WISC-IV which included the Working Memory Index Vineland Adaptive Behavior Scale, Second edition: Survey Interview Form	The Processing Speed Index (PSI) showed the greatest relative and normative weakness in the ASD group. No significant deficits were noted in WM. Adaptive communication abilities (Vineland) were significantly positively correlated with the WISC-IV including WM.
Ozonoff and Strayer (2001)	*Autism*: $n = 25$ Age: $M = 12.9$, $SD = 3.1$ Males = 21, Females = 4 FSIQ: $M = 96.3$, $SD = 17.8$ *TS*: $n = 15$ Age: $M = 13.4$ yrs, $SD = 2.5$ Males = 11, Females = 4 FSIQ: $M = 99.0$, $SD = 11.4$ *NC*: $n = 15$ Age: $M = 9.5$ yrs, $SD = 3.2$ Males = 9, Females = 6 FSIQ: $M = 107.1$, $SD = 10.5$ Experimental Setting – University – department	DSM-IV diagnostic criteria for Autism Autism Diagnostic Observation Schedule-Generic (ADOS-G) TS was diagnosed by a clinician.	Working memory tasks were performed on a computer with a touch screen. *Running Memory Task*: Match colored shapes from one or two screens back. *Spatial Memory-Span Task*: Match locations of 1, 3, or 5 colored shapes from previous screen; *Box Search Task*: Search and remember which boxes out of 6 had treasure behind them. Participants could only select new boxes if a box did not have treasure. If participants selected a box that had been checked before, a preservative error was counted.	No group differences were found across three tasks and five dependent measures of working memory. Performance was significantly correlated with both age and IQ. Authors concluded that working memory was not one of the executive functions seriously impaired in autism. The authors also suggested that the format of administration of working memory tasks may be important in determining whether or not performance falls in the impaired range.
Russell et al. (1996)	**STUDY 1** *AUT*: $n = 33$ Age: $M = 12.25$ yrs, $SD = 3.0$ VMA: $M = 6$yrs 3mths *Moderate LD*: $n = 33$ Age: $M = 10.75$ yrs, $SD = 2.0$ VMA: $M = 6$yrs *NC*: $n = 33$ Age: $M = 6.3$ yrs, SD = 1.3 **STUDY 2** *AUT*: $n = 22$ Age: $M = 12.5$ yrs, $SD = 2.8$ VMA: $M = 7$ yrs *Moderate LD*: $n = 22$ Age: $M = 11.1$ yrs, $SD = 2.0$ VMA: $M = 7$yrs *NC*: $n = 22$ Age: $M = 6.8$, yrs, $SD = 0.5$ VMA: $M = 7$ yrs	DSM-III PPVT- to calculate verbal mental age (VMA)	*STUDY 1*: All participants completed a short term memory task with both short and long syllables recalled aloud or by pointing (verbal vs non-verbal). All tasks were presented on a Macintosh computer using Hypercard. *STUDY 2*: Participants completed a capacity task that required the concurrent storage of information and performance of a relevant cognitive task. All participants were given the simple and complex versions of three tasks (a) counting (b) odd-man out and (c) sums.	STUDY1: Participants with Autism were at least as likely as controls to employ articulatory rehearsal (verbal working memory), and had superior spans than that of participants with moderate learning difficulties. STUDY 2: The performance of participants with Autism was inferior to that of control participants, but similar to those with moderate learning difficulties.

Table 1 (*Continued*)

Authors	Participants	Diagnosis criteria	Assessments	Main results
Scheirs and Timmers (2009)	Total sample: $n = 115$ *PPD-NOS*: $n = 55$ (75%) boys Age: $M = 10.1$ yrs FSIQ: 66–136 range *ADHD*: $n = 40$ (80% boys) Age: $M = 9.6$ yrs FSIQ: 76–123 range *PPD-NOS ± ADHD*: $n = 20$ (90% boys) Age: $M = 11.2$ yrs FSIQ: 76–116 range Archival outpatient mental health data from the Netherlands	DSM-IV-T Diagnostic criteria	Dutch version of the WISC-III This test consists of 13 subtests, the results of which can be combined into FIQ, VIQ (subtests Information, Arithmetic, Similarities, Vocabulary, Comprehension and Digit Span), PIQ (subtests Picture Completion, Substitution, Picture Arrangement, Block Design, Object Assembly, Symbol Search and Mazes), and the factor or index scores Verbal Comprehension Index (VCI), Perceptual Organization Index (POI) and Processing Speed Index (PSI) Subtests: Digit span is considered a measure of Working memory	Scores on all subtests including digit span (working memory)- PDD-NOS group attained the highest scores, whereas the scores of the ADHD and combined diagnosis groups were lower and highly similar to one another
Sinzig, Morsch, Brunning, Schmidt, & Lehmkuhl (2008)	*ASD and ADHD (ASD±)* $n = 19$ boys, 1 girl, included HFA – 5, ASP – 15 *Age*: $M = 10.9$ yrs *ASD w/out ADHD (ASD−)* $n = 20$ (16 boys, 4 girls) included HFA – 5, ASP – 15 Age: $M = 14.3$ yrs *ADHD* $n = 20$ (19 boys, 1 girl) Age: $M = 12.2$ yrs *NC* $n = 20$ (14 boys, 6 girls) Age: $M = 13.1$ yrs Recruited from the in and outpatient dept. of child and adolescent psychiatry	DSM-IV-TR criteria; Autism-Diagnostic Interview-Revised (ADI-R); Autism Diagnostic Obs Scale (ADOS); Diagnostic Checklist for Pervasive Developmental Disorders (DCL-TES); Diagnostic Checklist for Oppositional Defiant or Conduct disorders (DCL-SSV); The Diagnostic Checklist for Hyperkinetic Disorders/ADHD (DCL-HKS).	Battery of executive functioning tasks assessing inhibition, flexibility, spatial working memory (SWM), and planning	SWM – ADHD group made significantly more errors than the NC group and needed more strategies than children in the ASD+ group. ASD− group made more errors than the NC group. ASD+ and the ADHD group needed longer to perform the whole task compared to the ASD− group Participants with ASD were impaired in planning and flexibility. The ASD+ group, when compared to the ASD− group, showed more problems in inhibitory performance but not in the working memory task.

Steele et al. (2007)	*HFA*: $n = 29$, Age: $M = 14.83$ yrs, $SD = 5.4$ (Range: 8–29 yrs) FSIQ: $M = 107.7$, $SD = 10.9$ *NC*: $n = 29$ Age: $M = 16.93$ yrs, $SD = 5.47$ (Range: 8–29 years) FSIQ:$M = 110.7$, $SD = 9.9$	DSM IV criteria Autism Diagnostic Interview	Spatial working memory task from CANTAB presented on computer monitor.	HFA participants consistently made more errors than control; HFA increased their error rates at mid-level drastically, whereas controls increased error rates steadily. (3) HFA failed to effectively use the sequential search strategy.
Williams et al. (2005)	*Adults w/ASD*: $n = 31$, FSIQ: $M = 109$; Age: $M = 26.6$ yrs, $SD = 8.68$ *Adult Controls* $n = 25$, FSIQ: $M = 110$ Age: $M = 26.7$ yrs, $SD = 9.1$ *Children w/ASD*: $n = 24$, FSIQ: $M = 110$ Age: $M = 11.8$ yrs, $SD = 2.4$ *Children Controls* $n = 44$, FSIQ: $M = 110$ Age: $M = 12.4$ yrs, $SD = 2.2$	Wechsler Intelligence Scales (WISC-III), Kaufman Test of Educational Achievement, Autism Diagnostic observation Schedule, Autism Diagnostic Interview – Revised	*Verbal working memory tasks* N-back letter task: Keep track of the target letter on present screen, 1 letter back, or 2 letters back. Wechsler Memory Scale Wide Range Assessment of Memory and Learning (WRAML) (equivalent to WMS-III Number Letter Sequencing. *Spatial working memory tasks* WMS-III Spatial Span Subtest (adults) WRAML Finger Windows Subtest (children)	The children, adolescents, and adults with autism performed at similar levels relative to the cognitive and age-matched controls on the working memory tasks that involved the articulatory loop (verbal working memory) and performed poorer than the controls on the tasks that involved the visuospatial sketchpad (SWM).
Yerys, Wallace, Jankowski, Bollich and Kenworthy (2011)	*HFA*: $n = 28$ Age: $M = 10.9$ yrs, $SD = 1.5$ Including ASD: $n = 11$; ASP: $n = 12$; PDD-NOS: $n = 5$ *NC*: $n = 18$ Age: $M = 11.1$, $SD = 1.3$	DSM-IV criteria Autism Diagnostic Interview (ADI) or Autism Diagnostic Interview – Revised (ADI-R): Autism Diagnostic observation Schedule (ADOS)	Consonant Trigrams Test (CTT, verbal working memory): When presented with three consonant letters followed by a number, must count backwards from that number during a variable delay (0, 3, 9, or 18 s), then state the letters. ADHD Rating Scale-Parent Edition and the Behavior Rating Inventory of Executive Function-Parent Form–a test of everyday working memory	CTT performance lower in children with ASD than in controls suggesting divided attention as a relative weakness for children with HFA. Significant correlation between CTT performance and ratings of everyday working memory. Large variability in the performance of those with ASD.

The performances of children with HFA (mean age 9 years) were also compared to those of children with attention deficit hyperactivity disorder (ADHD) on measures of planning, cognitive flexibility, and other cognitive tasks (Geurts et al., 2004). Results indicated that participants with HFA showed more difficulties with working memory tasks of planning and cognitive flexibility than those in the ADHD group.

In a comparison of 25 participants with ASD (ages 7–18), 15 typical comparisons (ages 8–19 yrs), and 15 students with Tourette Syndrome (ages 8–17 years), Ozonoff and Strayer (2001) reported that although performance was significantly correlated with both age and IQ, there were no significant differences between the experimental groups on working memory, and suggested that the format of administration of WM tasks may be important in determining whether or not performance falls in the impaired range. In this study, they used three computerized WM tasks, (a) a running memory task that asked participants to match colored shapes from a previous screen (one-back) or penultimate screen (two-back), (b) a spatial working memory-span task that required participants to match the locations of 1, 3, or 5 colored shapes from a previous screen, and (c) a box search task that asked students to search and remember which boxes (out of 6) had treasures behind them.

In summary, results suggest that persons with autism score lower on measures of working memory than do typical controls. They make more errors, use fewer strategies, and demonstrate lower performances on tasks that require cognitive flexibility, planning, greater working memory load, and spatial working memory, especially with increasing task complexity and in dual task conditions. They also score lower on the WM-Math component of IQ tests, such as digit symbol. Lower scores in working memory (especially verbal working memory) were associated with greater problems in adaptive behavior and more restrictive and repetitive behavior.

Similarities were found in the WM performances of individuals with autism and those with specific learning disabilities (LD) in mathematics. Children with autism were as likely as typical children to employ articulatory rehearsal (verbal WM) and they had spans superior to those of participants with moderate learning difficulties, but they performed lower than students with moderate learning difficulties in their total capacity of WM. Children with autism showed more difficulties with working memory tasks of planning and cognitive flexibility than children with ADHD. One study found no differences in the working memory of participants with ASD, Tourette Syndrome, and typical comparisons but scores were significantly correlated with both age and IQ.

4. Discussion

The purpose of this study was to review existing WM literature for individuals with autism spectrum disorders (ASD) to identify characteristics and challenges that would provide implications for academic assessment and intervention. We located and reviewed 24 studies and found that WM was mainly evaluated using clinical or neuropsychological test batteries and parent/teacher rating scales. Some of the assessments were presented in a computerized format, such as the Cambridge Automated Neuropsychological Test and Battery (Goldberg et al., 2005; Landa & Goldberg, 2005; Steele et al., 2007), running memory and spatial working memory tasks (Ozonoff & Strayer, 2001), and language and computational tasks, and that participants were required to either give verbal responses or type in their answers using a keyboard.

Though most of the reviewed studies reported challenges in WM for participants with ASD, there were differences in the components of WM that were related to difficulties. Though traditionally, individuals with ASD have been reported to have language impairments, authors in this review reported that verbal WM did not present a challenge, and that participants with ASD had similar articulatory rehearsal, or articulatory loop strategies (that require verbal working memory) to that of typically functioning comparisons (Russell et al., 1996; Williams, Goldstein, Carpenter, & Minshew, 2005). This finding may be due to the level of impairment of the participants with ASD or high functioning autism (HFA) in these studies, most of whom had average intellectual functioning, and had language or verbal IQs slightly lower than average, but not significantly impaired. This linguistic ability has previously been supported by prior studies that reported that individuals with Aspergers demonstrated milder impairment and their communicative competence was higher than in other variants of autism, including those with HFA (Frith, 1998).

However, linguistic abilities were a critical factor in debating the presence of spatial working memory deficits. Most authors suggested lower performance by participants diagnosed as ASD or HFA in spatial working memory tasks than participants without ASD. The authors suggested that there were similarities in spatial working memory performance of individuals with ASD and those with moderate learning difficulties. These deficits in spatial working memory resulted in poor performance on dual tasks and tasks that required higher cognitive load and flexibility (Goldberg et al., 2005; Landa & Goldberg, 2005). Even though a spatial working memory deficit was not found in one study (Ozonoff & Strayer, 2001), the authors suggested that the format of working memory assessment tasks may affect our ability to detect deficits. This was supported by Williams et al. (2005) who concluded that when spatial WM was assessed without verbal responses and coding (i.e., the use of the phonological loop requirement of WM), and used the visio-spatial sketchpad instead, it was more likely to reveal existing deficits for individuals with HFA. This report may be important because it contradicts prior research that reported heightened or superior visio-spatial abilities in individuals with ASD (Caron, Mottron, Rainville & Chouinard, 2004; Mitchell & Ropar, 2004).

Thus, the presence of verbal responses in the assessment of WM may be a confounding variable and should be considered in future research. This is especially relevant with the varied language abilities within the autism spectrum. Previous findings demonstrated that even the higher functioning groups, such as HFA and ASP, struggled with the functional use of language.

For example, they had difficulty explaining their correct answers, suggesting that they were not always aware of how they derived answers from context (LouKusa et al., 2007) and tended to use past tense significantly more frequently in their narratives (Seung, 2007). None of the studies reviewed compared the implications of linguistic abilities between the groups.

None of the studies in this review compared the WM performances of various groups of individuals with ASD (i.e., HFA, ASP, lower functioning students with Autism), and there were no developmental evaluations between the groups. Although the purpose of this study was not to assess developmental changes in ASD, one finding did emerge. Guerts and Vissers (2012) reported that elderly individuals with HFA had more problems with visio-spatial WM, sustained attention, and fluency than controls but deficits in planning and cognitive flexibility were not found, suggesting that these deficits disappear with aging. In auditory/verbal WM, children, adolescents and adults perform similarly, and seem to have problems with visio-spatial WM that continue into adulthood. In a review of neurodevelopment and executive functioning in autism, O'Hearn, Asato, Ordaz, and Luna (2008) concluded that some aspects of executive functions are impaired at different ages in autism but that "its developmental trajectory is not well defined, and it is not clear whether the development of executive function is delayed, persistently low, or truncated" (p. 1111). More studies will need to be conducted to verify if adults with autism improve with training in cognitive flexibility and planning. It is not clear if this normalization in cognitive flexibility and planning in adulthood is due to educational activities or to higher levels of intellectual functioning within the sample assessed.

For educators, the implications of these findings are relevant if they affect educational performance. Unfortunately, few of the reviewed studies evaluated working memory with educational tasks. One study assessed counting abilities. Future research should provide clearer descriptions of the participants' characteristics within the context of school-based populations and use educational tasks to assess working memory. WM has implications for academic areas such as problem solving, listening and reading comprehension, mental math, and learning to spell. A list of the most commonly used tests of WM and possible educational implications are included (see Table 2). A student that struggles with auditory/verbal WM at a younger age may benefit from instruction that includes both auditory and written components. Children with WM deficits in planning and flexibility with environmental changes may have difficulty with time management, planning for an activity or assignment, sequencing or re-ordering a schedule due to changes, reacting to other children or adults, especially if something new happens, working through emergency situations such as drills, minor or major disasters, or asking questions.

Future researchers may want to identify developmental differences and investigate comparisons with individuals within other special populations, such as those with learning disabilities (LD). If there are similarities in WM performance in students with ASD and those with LD, there is a potential for numerous investigative opportunities that evaluate the feasibility of existing LD interventions to teach students with ASD within the school environment with implications for improving academic performance, language skills, and cognitive and behavioral flexibility.

This study identified WM characteristics and challenges for individuals with ASD with the implication that deficits can be remediated. Morrison and Chein (2011) published a review of intervention studies and answered the question, "Does working memory training work?" They concluded that increases in WM have been successfully demonstrated across a wide range of populations but there are differences in outcomes based on the training techniques employed. Core WM training seems to produce more far-reaching generalization effects than domain-specific strategies. Morrison and Chein's review included a variety of adult and child populations including those who experienced strokes and children with ADHD. Their review did not include the results of training WM in students with autism.

For students with ADHD, Klingberg et al. (2005) found treatment effects from computerized, systematic practice of WM tasks at post-intervention and follow-up using a span-board task (a visuospatial WM task). They reported secondary effects for response inhibition, and complex reasoning. Parent ratings showed significant reduction in symptoms of inattention and hyperactivity/impulsivity. Similarly, Beck, Hanson, Puffenberger, Benninger, and Benninger (2010) reported treatment effects from five weeks of intensive WM training for children with ADHD. They found significant improvements in parent ratings of inattention, ADHD symptoms, initiation, planning/organization, and working memory. Teacher ratings approached significance.

In another study, Van der Molen, Van Luit, Van der Moldn, Klugkist, and Jongmans (2010) attempted to train the WM of adolescents with mild to borderline intellectual disabilities using a computerized WM training. They found that verbal short-term memory improved significantly from pre- to post-testing and was maintained at follow-up. They concluded that WM can be effectively trained in adolescents with mild to borderline intellectual disabilities.

A limited number of studies have evaluated WM training in students with ASD. Baltruschat et al. (2011), reported results from three different single subject multiple baseline studies on students with Autism aged 6–9 years, demonstrating the positive effects of reinforcement, such as highly preferred tangible items (video game, candy, movie, drawing material, stickers) or edible food, on working memory performance in the tests of *Counting span*, in which participants were required to count quantities of circles mixed up with squares in a series of visual arrays, state the amount of time an array was presented and, then, recall each quantity in the correct order in which they were presented, *Complex span*, in which a sequence of visual stimuli are presented to the participant who is asked to provide a classification response that identifies a function of the object (e.g., Can you eat it?). At the conclusion of the sequence, the participants were asked to list the stimuli in the order in which they were initially presented, and *Digit span backwards*, in which, the participants had to memorize a series of numbers that were presented auditorally and then recall them backwards (Baltruschat et al., 2012).

Broadbent and Stokes (2013) reported improved performance in WCST, a test of visiospatial working memory, through the use of positive feedback. The WCST consists of four stimulus cards and 128 response cards that depict various symbols

Table 2
Commonly used tests of working memory and possible academic implications of test results.

Test	Description of the test	Academic implications
Advanced Trail Making Test (ATMT) **Measure:** Visiospatial working memory **Reference:** Kajimoto O. Technique for assessment of degree of fatigue. *Igaku no Ayumi 2003*; 204: 377–380 (in Japanese). Reitan, R. M. (1971). Trail making test results for normal and brain-damaged children. *Perceptual and motor skills, 33*(2), 575–581	Computerized version. Both parts A and B consist of a single sheet of paper with a sample printed on the front side and the test on the back. Circles are distributed and each encloses a number and/or letter. Connect the circles in sequence with a penciled line. Score is number of seconds for completion.	Speed of performance on a visual task, drawing, sequencing numbers from low to high
Wisconsin Card Sorting Test **Measure:** Visiospatial working memory A test of flexibility of thinking and complex problem-solving **Reference:** Chelune, G. J., Talley, J. L., Kay, G. G., & Curtiss, G. (1993). Wisconsin card sorting test manual. Odessa, FL: Psychological Assessment Resources	View four key cards on a computer screen. A single stimulus card that shares attributes with some or all of the key cards is presented. Match the stimulus card and the one key card that matches. Feedback is given from the computer about whether the sort was correct or incorrect. Using this feedback, they must determine the correct sorting rule. After they make a specified number of correct sorts using the first rule, the rule for sorting the cards changes without warning. They must then identify a new sorting rule and apply it consistently until the rule changes again.	Organizing, categorizing, problem solving, matching shapes, colors, etc., switching between various tasks (cognitive flexibility).
Cambridge Neuropsychological Test Automated Battery (CANTAB) **Measure:** Visiospatial working memory **Reference:** Cambridge Cognition (1996). CANTAB. Cambridge, England: Cambridge Cognition Limited	Begins with a number of colored boxes on the screen. Using a process of elimination, find one blue token in boxes and use them to fill an empty column on the right. The number of boxes is gradually increased, until it is necessary to search 8 boxes. The color and position of the boxes are changed to discourage the use of stereotyped search strategies.	Geometry
Continuous Performance Test **Measure:** Visiospatial working memory **Reference:** Conners, C. (2000). Conners' Continuous Performance Test II: Technical guide. Toronto, Canada: Multi-Health Systems	A long sequence of letters appears on a computer screen. Hit the space bar only when a letter appears that is not X. Rate varies. Omissions and commissions count as errors. Also records reaction times. All CPT scores represent T-scores normed on a large sample.	Differentiation between letters, spelling words etc. presented visually, speed of reading, response time.
Visuo-spatial WM – Spatial Span (forward problems) from the Wechsler Memory Scale-III **Measure:** Spatial working memory **Reference:** Wechsler, D. (1945/1997) Wechsler Memory Scale® – Third edition (WMS-III). San Antonio, TX: Harcourt Assessment.	A visual analog of the digit span test, the spatial span test requires participants to watch the examiner tap increasingly longer sequences of raised, blue blocks positioned arbitrarily on a white board. Participants tap the blocks in the same order they witnessed (forwards span) or in the reverse order (backwards span).	Identifying geometrical patterns
Self-Ordered Pointing task **Measure:** Visual working memory **Reference:** Petrides, M., & Milner, B. (1982). Deficits on subject ordered tasks after frontal- and temporal-lobe lesions in man. Neuropsychologia, 20, (3), 249–262	Pictures of familiar objects or abstract designs are arranged in a grid and presented in a different arrangement on each trial. The participant points to a picture as requested. The test requires executive abilities in order to organize and carry out a sequence of responses and retain and constantly monitor responses made.	Organizing, categorizing, problem solving, matching shapes, colors, etc., switching between various tasks (cognitive flexibility).
WMS-III Spatial Span Subtest (Adults) **Measure:** Spatial working memory **Reference:** Wechsler, D. (1997b). *Wechsler Memory Scale-III*: Administration and scoring manual. San Antonio, TX: The Psychological Corporation. Williams, D. L., Goldstein, G., Carpenter, P. A., & Minshew, N. J. (2005). Verbal and spatial working memory in autism. *Journal of Autism and Developmental Disorders, 35*(6), 747–756.	Forward and backward span conditions. 10 cubes in fixed locations are presented and the examiner taps the cubes in a specified sequence starting with a 2-block sequence, gradually increasing to a 9-block sequence. Two trials of different combinations are given at each level. The participant is asked to repeat the sequence forward and backward.	Organizing visual materials presented sequentially, such as shapes, sizes, figures, etc.

Table 2 (*Continued*)

Test	Description of the test	Academic implications
WRAML Finger Windows Subtest (children) **Measure:** Spatial working memory **Reference:** Sheslow, D., & Adams, W. (1990). *WRAML: Wide range assessment of memory and learning.* Wilmington, DE: Jastak Assessment Systems	A card with window-like openings is presented. The examiner puts a pencil into a sequence of these windows and the participant is asked to use his or her finger to repeat the sequences.	Organizing visual materials presented sequentially, such as shapes, sizes, figures, etc.
Letter-Number Sequencing (LNS) – One of the ubtests of the Wechsler's Working Memory Index **Measure:** Auditory/Verbal working memory **Reference:** Wechsler, D. (1997). Wechsler Memory Scale (3rd ed.). San Antonio, TX: The Psychological Corporation	A series of intermixed letters and single digits are read aloud at one item per second. The participant verbally reports the numbers in numerical order, followed by letters in alphabetical order. Sequences begin with three items (two letters and one number or two numbers and one letter) and become increasingly longer until the participant fails all three trials of a given sequence length.	Spelling, listening comprehension, verbal learning of math facts
N-back test of working memory **Measure:** Verbal working memory **Reference:** Kirchner, W. K. (1958), Age differences in short-term retention of rapidly changing information. Journal of Experimental Psychology, 55(4), 352–358	A series of digits appear on a computer screen. Task is to signal when a digit is identical to the digit that came immediately before it (1-back), and then 2-back or 3-back. For example, if the following sequence appeared during a 3-back trial (2, 4, 5, 2, 6, 5, 9, 3, 0, 9), the participant should respond affirmatively after seeing the second 2, the second 5, and the second 9 in the sequence.	Spelling, matching visually presented numbers, number patterns
Nonword repetition (NWR) Subtest from the Comprehensive Test of Phonological Processing **Measure:** Auditory/Verbal working memory **Reference:** Wagner, R. K., Torgensen, J. K., & Rashotte, C. A. (1999). *Comprehensive test of phonological processing.* Austin, TX: Pro-Ed Gathercole, S. E., Willis, C. S., Baddeley, A. D., & Emslie, H. (1994). The children's test of nonword repetition: A test of phonological working memory. *Memory, 2(2)*, 103–127.	Requires encoding the phonological representation of a nonsense word and repeating it.	Listening/comprehension, listening and learning alphabets, spelling, sentences,
PASAT **Measure:** Auditory/Verbal working memory **Reference:** Gronwall, D. M. & Sampson, H. (1974). The Psychological Effects of Concussion. Auckland, New Zealand: Aukland Universithy Press	Participants hear a sequence of single digit numbers. They add adjacent digits together and verbally report the sum. While calculating the sum, they must also remember the last digit heard in order to add it to the next number presented. Example: if the participant hears 3, 5, 6, 2, 8, during part of a trial, correct responses would be 8 (3 + 5), 11 (5 + 6), 8 (6 + 2) and 10 (2 + 8). The digits occur 3 s apart during the first trial and 1.2 s apart during the second trial.	Mental math calculation and problem solving
WISC – Digit Span – One of the Subtests of the Wechsler's Working Memory Index **Measure:** Verbal Working Memory **Reference:** Wechsler, D. (2004). The Wechsler intelligence scale for children – fourth edition. London: Pearson Assessment.	Presents participants with increasingly longer sequences of single digit numbers. Participants first repeat the sequence out loud in order of presentation. Then, they recite the sequence in reverse.	Remembering formulae in mathematics, reciting/ sequencing of numbers either *n* order or possible pattern of numbers (such as even/odd/prime numbers)
Working Memory Span Test – Counting Span **Measure:** Verbal working memory **Reference:** Case, R., Kurland, M. D., & Goldberg, J. (1982). Operational efficiency and the growth of short-term memory span. *Journal of Experimental Child Psychology, 33*, 386–404	In the children's version of this test, orally counted (and point their finger at) the green dots presented against a white background. Yellow dots, interleaved with the green dots, disrupted the visual patterns of the green dots (Case et al. did not report a range of values for the number of green or yellow dots presented). The task presented three items of each size from one to five, in ascending order	Counting, sequencing, reading through distractions

Table 2 (*Continued*)

Test	Description of the test	Academic implications
Working Memory Span Test – Operation Span **Measure:** Verbal working memory **Reference:** Turner, M. L., & Engle, R. W. (1989). Is working memory capacity task dependent? *Journal of Memory & Language, 28*, 127–154	Solve mathematical operations while trying to remember words. There were 84 mathematical operation strings in Turner and Engle's (1989) first operation span task. Each string consisted of a mathematical equation with two arithmetic operations on one side of the equation and a stated solution on the other side of the equation. The first operation was a simple multiplication or division problem and was followed by a simple addition or subtraction operation. The stated solution was correct on half of the trials.	Math problem solving, mental math
Working Memory Span Test – Reading Span **Measure:** Verbal working memory **Reference:** Daneman, M., & Carpenter, P. A. (1983). Individual differences in integrating information between and within sentences. *Journal of Experimental Psychology: Learning, Memory, & Cognition, 9*, 561–584	Read aloud sentences while remembering the last word of each sentence for later recall in the order in which they were presented. Increasing number of sentences presented in ascending order. Items presented until the subject fails to recall all 3 items of a given size.	Reading and reading comprehension
Behavior Rating Inventory of Executive Function – parent rating version (BRIEF) – utilizes verbal working memory descriptors. **Measure:** Parental perception of verbal working memory **Reference:** Roth, R. M., Isquith, P. K., & Gioia, G. A. (2005). *BRIEF-A: Behavior Rating Inventory of Executive Function – adult Version*: Professional Manual. Psychological Assessment Resources.	The BRIEF-P consists of a single rating form with 63 items in 5 scales: inhibition (to stop own behavior), shifting (to make a transition and change focus from one mindset to another), emotional control (to modulate emotional responses), working memory (to hold information in mind for the purpose of completing a task), and planning/organization (to manage current and future-oriented task demands within the situational context).	Parent perception of working memory

(crosses, circles, triangles, or stars), in different colors (red, blue, yellow, or green) and numbers of figures displayed (one, two, three, or four). Participants are required to sort/categorize the cards according to six predetermined sorting principles in the order of color, form, number, color, form, number. In the traditional administration of the WCST, participants' are given feedback using "right" or "wrong" commands. In this study, 50 high functioning individuals with Asperger's (aged 14–70 years) and matched typically developing peers were placed in the traditional format of the WCST as well as the modified format of feedback, where they were given only "right" feedback. Result showed that individuals with Aspergers, who received only the positive feedback, had better performance and were similar to the typically developing peers than the traditional format (which included negative feedback).

Additional studies on working memory assessments and interventions, especially that have implications for academic and behavior activities, need to be conducted.

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