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J Autism Dev Disord. Author manuscript; available in PMC 2019 October 01.

Published in final edited form as:
J Autism Dev Disord. 2018 October ; 48(10): 3524–3541. doi:10.1007/s10803-018-3617-7.

Reading Comprehension in Children With and Without ASD: The Role of Word Reading, Oral Language, and Working Memory

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Abstract

Word reading and oral language predict reading comprehension, which is generally poor, in individuals with autism spectrum disorder (ASD). However, working memory (WM), despite documented weaknesses, has not been thoroughly investigated as a predictor of reading comprehension in ASD. This study examined the role of three parallel WM N-back tasks using abstract shapes, familiar objects, and written words in children (8–14 years) with ASD ($n = 19$) and their typically developing peers ($n = 24$). All three types of WM were significant predictors of reading comprehension when considered alone. However, these relationships were rendered non-significant with the addition of age, word reading, vocabulary, and group entered into the models. Oral vocabulary emerged as the strongest predictor of reading comprehension.

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[1]The results of the analyses including and excluding this participant were equivalent; therefore, only the analyses including this participant are reported.

Compliance with Ethical Standards

Ethical approval:
All procedures performed in this study involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent
Informed consent was obtained from all individual participants included in the study by the children's parents or legal guardians.

Conflict of Interest
The authors declare that they have no conflicts of interest.

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Keywords

reading comprehension; vocabulary; working memory; word reading; autism

A substantial number of individuals with autism spectrum disorder (ASD) have poor reading comprehension; estimates from recent studies range from 38–73% (Davidson and Ellis Weismer 2014; Henderson et al. 2014; Jones et al. 2009; McIntyre, Solari, Grimm, et al. 2017; Nation et al. 2006; Ricketts et al. 2013). Similar to children without autism, word reading and oral language abilities predict reading comprehension across the lifespan in children on the autism spectrum who have average to above average nonverbal cognition (Brown et al. 2013; Cronin 2014; Davidson and Ellis Weismer 2014; Henderson et al. 2014; Jacobs and Richdale 2013; McIntyre, Solari, Gonzales, et al. 2017; Nation et al. 2006; Norbury and Nation 2011; Ricketts et al. 2013). However, one predictor of reading comprehension—working memory (WM; i.e., the ability to process and store relevant information)—has not been thoroughly investigated in relation to reading comprehension deficits in ASD, despite documented WM weaknesses (Wang et al. 2017). The purpose of this study was to evaluate the role of WM in reading comprehension in children (8–14 years) with ASD and their typically developing (TD) peers in addition to the roles of word reading and oral language.

The Simple View of Reading and Related Predictors

The simple view of reading specifies that reading comprehension is the product of decoding (i.e., word reading) and listening comprehension (i.e., spoken language comprehension) (Gough and Tunmer 1986; Hoover and Gough 1990). This model has been widely supported in the reading development literature for individuals not on the autism spectrum (Adlof et al. 2010; Catts et al. 2003, 2006; Hoover and Gough 1990; Nation et al. 2010). The simple view of reading is also supported in individuals on the autism spectrum with average to above average nonverbal cognition across the lifespan (Brown et al. 2013; Cronin 2014; Davidson and Ellis Weismer 2014; Henderson et al. 2014; Jacobs and Richdale 2013; McIntyre, Solari, Grimm, et al. 2017; Nation et al. 2006; Norbury and Nation 2011; Ricketts et al. 2013).

Word reading abilities generally fall in the average to above-average range, in individuals with ASD (Calhoon 2001; Cardoso-Martins and Ribeiro da Silva 2008; Gabig 2010; Huemer and Mann 2010; Newman et al. 2007; Norbury and Nation 2011; Saldaña et al. 2009); although, some children with ASD display poor word reading abilities in addition to poor comprehension (Brown et al. 2013; McIntyre, Solari, Grimm, et al. 2017; Nation et al. 2006). In particular, word reading deficits are more common in those children with ASD who have co-occurring language impairments than those children with ASD who do not have co-occurring language impairments (Lindgren et al. 2009; Lucas and Norbury 2014; Norbury and Nation 2011). A further consideration in determining word reading abilities in children with ASD is that most studies consider both word recognition (i.e., ability to read known, real words) and word decoding (i.e., ability to read unknown words, or nonwords) to index word reading abilities together. However, Henderson et al. (2014) recommended not

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collapsing word recognition and decoding measures, given that children with ASD in their study had stronger word recognition than decoding abilities.

The two strongest predictors of reading comprehension in individuals with ASD in a meta-analysis were word reading abilities and semantic knowledge (Brown et al. 2013). Morphosyntactic knowledge also appears to play some role in predicting reading comprehension in individuals with ASD (Cronin 2014; Jacobs and Richdale 2013). Taken together, this evidence indicates that word reading (word recognition and decoding) and oral language abilities (vocabulary and morphosyntactic knowledge) predict reading comprehension both in individuals without ASD and in individuals with ASD. However, the role of WM in addition to word reading and oral language has not been evaluated in children with ASD.

Working Memory and Reading Comprehension

Working memory has long been implicated as a predictor of individual differences in reading comprehension (Daneman and Carpenter 1980; Daneman and Merikle 1996; Just and Carpenter 1992). The construction-integration model (CI model) further theoretically motivates the involvement of WM in reading comprehension (Kintsch 1998). In the CI model, a situation model (i.e., a mental representation of the text information and the reader's relevant knowledge) is attained through cycles of construction and integration while reading a text. WM supports comprehension of texts by acting as a buffer to hold recently read information in mind to integrate with the situation model of the text so far. WM also holds the information activated from long-term memory (i.e., background knowledge) to make inferences that are additionally integrated into the situation model. According to the CI model, good comprehenders use effective retrieval strategies to integrate text information and stored knowledge to bolster their WM capacities. Poor comprehenders do not use effective retrieval strategies, and therefore, are limited by their WM capacities.

Typical measures of WM used to establish the WM-reading comprehension relationship include the reading span task, or more commonly in children the listening span task (e.g., Christopher et al. 2012; Nouwens et al. 2016; Pimperton and Nation 2010; Seigneuric and Ehrlich 2005; St. Clair-Thompson and Gathercole 2006; Swanson and Berninger 1995), letter or digit span (e.g., Arrington et al. 2014; Cantin et al. 2016; Christopher et al. 2012; Goff et al. 2005; St. Clair-Thompson and Gathercole 2006; Swanson and Berninger 1995), and the letter N-back task (e.g., Potocki et al. 2015). It is notable, however, that these measures are primarily *verbal* WM tasks.

While it has been established that WM is related to reading comprehension, there is considerable debate as to whether WM is related to reading comprehension purely because of the linguistic nature of the tasks used. The majority of the evidence suggests that the relationship is specifically verbal in nature (Berninger et al. 2010, 2016; Daneman and Merikle 1996; Jarvis and Gathercole 2003; Jerman and Swanson 2005; Oakhill et al. 2011; Seigneuric et al. 2000; Seigneuric and Ehrlich 2005; Swanson and Berninger 1995). However, some studies show contributions of both verbal and visuospatial/nonverbal WM and reading comprehension, suggesting a domain-general relationship (Goff et al. 2005; St.

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Clair-Thompson and Gathercole 2006). Additionally, some studies found that verbal or numerical WM predicted reading comprehension above and beyond attention, word reading, fluency, and vocabulary (Cain, Oakhill, and Bryant 2004; Cutting et al. 2009; Oakhill et al. 2011; Whitney Sesma et al. 2009).

Two studies directly comparing the relation of verbal, numerical, and spatial WM measures to reading comprehension found that verbal WM measures accounted for the most variance in reading comprehension above and beyond word reading and vocabulary (Oakhill et al. 2011; Seigneuric et al. 2000). To a lesser degree numeric WM measures also accounted for some variance in reading comprehension, but the spatial WM measures did not. These findings were interpreted in line with the conclusions of Daneman and Merikle (1996) that verbal and numeric WM are related to reading comprehension because both require the storage and processing of symbols. However, an alternative interpretation is that the relationship exists because both tasks are linguistic.

Some would also argue that the relationship between verbal, and particularly numeric WM tasks and reading comprehension is observed because both tasks, WM and reading comprehension, inherently involve word reading and orthographic processing. Studies investigating WM and word reading relationships, however, are mixed. Nonverbal WM does not appear to be related to word reading (Messer et al. 2016; Oakhill et al. 2011), although, children with dyslexia were poorer at both nonverbal and verbal WM relative to good readers (Reiter et al. 2005). Verbal WM was related to word reading in some studies (Arrington et al. 2014; Booth et al. 2014; Christopher et al. 2012; Seigneuric et al. 2000), but other studies either found no significant relationship (Swanson 2008; Swanson and Berninger 1995; Whitney Sesma et al. 2009) or no significant relationship after accounting for age, general abilities, and/or verbal abilities (Messer et al. 2016; Oakhill et al. 2011). The latter suggests that if a significant relationship is found between verbal WM and word reading, the relationship may be spuriously related through language abilities.

Task demands are another consideration in understanding the WM-reading comprehension relationship. Oakhill et al. (2011) improved on the comparability of the measures across type (verbal, numerical, and spatial) relative to the measures used by Seigneuric et al. (2000) and other studies. However, they did not control for presentation modality, which could lead to recruitment of different processes across tasks (Meegan et al. 2004). A review of WM task type differences based on positron emission tomography (PET)/magnetic resonance imaging (MRI) data suggests that verbal, spatial, and object WM recruit different regions of the prefrontal cortex (Smith and Jonides 1999). However, in studies controlling for task-demand differences by using parallel tasks, it seems that these differences in neural activation patterns may be due to additional recruitment of other processes when demands are high because parallel tasks result in less content-specific variation (Nystrom et al. 2000; Oberauer et al. 2003; Wilhelm et al. 2013).

Studies examining WM deficits in children who are poor comprehenders (i.e., children who have intact word reading abilities but poor listening and reading comprehension) demonstrate that verbal WM is deficient in poor comprehenders (Cain 2006; Cain, Oakhill, and Bryant 2004; Cain, Oakhill, and Lemmon 2004; Gathercole et al. 2006; Nation et al.

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1999; Oakhill et al. 2005; Pimperton and Nation 2010; Swanson and Berninger 1995). However, children who are poor comprehenders do not differ from good comprehenders on visuospatial/nonverbal tasks (Nation et al. 1999; Pimperton and Nation 2010; Swanson and Berninger 1995). Further support that poor comprehenders' WM weaknesses are related to the nature of the WM task (or the stimuli used in the task) comes from an investigation comparing children with reading-based learning disabilities to children with math-based learning disabilities on a word and number WM task; this study found that poor performance on the WM task was specific to the child's learning disability weakness (Pelegrina et al. 2015).

In summary, many studies point to a verbal WM and reading comprehension relationship (Berninger et al. 2016; Carretti et al. 2009). However, these studies have not always controlled for task demands or presentation modality of the WM tasks. Furthermore, some argue that verbal WM cannot be separated from language processing (MacDonald and Christiansen 2002; Mainela-Arnold and Evans 2005; Nation et al. 1999). In line with this argument, several findings have indicated that vocabulary mediated all WM-reading comprehension relationships in children and adults (Chrysochoou et al. 2011; Van Dyke et al. 2014). In addition, a meta-analysis examining the role of executive function, including WM, in children with reading disability (collapsed across children with word reading and reading comprehension difficulties) concluded that there were not clear results regarding the contribution of verbal versus nonverbal response type (Booth et al. 2010). The authors suggest that the effect size may be a function of the degree of the language demands of the tasks, and that nonverbal tasks should be used in future work to detect WM effects separate from language processing effects.

Working Memory and Reading Comprehension in ASD

The evidence is mixed regarding WM strengths and deficits in ASD. Studies show both poor (e.g., Gabig 2008; Hill et al. 2015) and intact (e.g., Cui et al. 2010; Joseph et al. 2005; Macizo et al. 2016; Williams et al. 2005) verbal WM. Similarly, for nonverbal WM, studies have found both poor (e.g., Corbett et al. 2009; Happé et al. 2006; Joseph et al. 2005; Landa and Goldberg 2005; Steele et al. 2007; Williams et al. 2005) and intact nonverbal WM (e.g., Ellis Weismer et al. 2017; Happé et al. 2006; Hill et al. 2015; Macizo et al. 2016). A recent meta-analysis indicated that individuals with ASD exhibited a medium to large overall WM impairment ($d = -0.61$) with a larger degree of impairment for nonverbal ($d = -.72$) compared to verbal ($d = -.44$) WM type (Wang et al. 2017). The results of the meta-analysis did not find effects of task demands, age, or IQ; however, there were medium effects related to diagnostic criteria (Wang et al. 2017).

One explanation for the inconsistent results in the ASD WM literature not considered in Wang et al. (2017) is the participants' language abilities. Several studies demonstrated that WM abilities, particularly verbal WM abilities, were related to language abilities (Akbar et al. 2013; Gabig 2008; Happé et al. 2006; Hill et al. 2015; Macizo et al. 2016); however, other studies have not found a relationship (Joseph et al. 2005; Landa and Goldberg 2005). Hill et al. (2015) compared children matched on age who had co-occurring structural language deficits (ASD-LI) to children with ASD with no structural language deficits (ASD-

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NL) as well as to children with specific language impairment (SLI; i.e., children without ASD diagnoses but who have structural language deficits) on several measures of verbal and nonverbal WM. The ASD-LI children had more verbal WM impairments than the ASD-NL children, but the ASD-LI and SLI children only differed on the narrative WM task with the ASD-LI group performing worse than the SLI group. (Hill et al. 2015) also compared these same children on nonverbal WM tasks, and found no significant group differences. Together, this evidence suggests that verbal WM deficits in ASD may be constrained by the individuals' language abilities.

Ricketts and colleagues (2011; 2013) suggested that WM weaknesses may contribute to reading comprehension deficits in ASD; however, few studies have investigated this to date. One study claimed that both vocabulary and verbal WM were significant predictors of inferencing ability in children with ASD (Lucas and Norbury 2015). It is unclear, however, whether the verbal WM measure, the *Clinical Evaluation of Language Fundamentals* Recalling Sentences subtest, indexed WM, language, or both. In a second study, poor comprehenders without ASD had lower WM compared to typically developing controls and adolescents on the autism spectrum, and were also affected to a greater degree than the ASD group by a memory load manipulation during an online inferencing task (Tirado and Saldaña 2016). In summary, the overall role of WM in reading comprehension in ASD (as opposed to inferencing, specifically) has not been investigated. Furthermore, the role of different types of WM has also not been assessed.

Current Study

The purpose of this study was to investigate the contribution of word reading, oral language (vocabulary and morphosyntax), and WM to reading comprehension in a sample of children (8–14 years) with ASD and their typically developing peers. Most critically, we wanted to assess the role of WM in addition to the well-established roles of word reading and oral language in reading comprehension. We also evaluated the role of three different types of WM in reading comprehension.

We designed three parallel measures of WM including the: Shape WM task, Object WM task, and Word WM task. All three tasks were presented visually (no auditory information was provided), and all three tasks were N-back tasks (specifically, the 2-back). By restricting all tasks to the visual modality, we avoided the potential confound of auditory processing. In the Shape WM task, children viewed abstract shapes that were not easily labeled—a nonverbal WM task. In the Object WM task, children viewed pictures that could be labeled —a verbal WM task. In the Word WM task, children read single words. By using written words, as opposed to letters or numbers, this task was comparable to the Object WM task in the type of linguistic knowledge activated but differed by using orthographic representations; therefore, the Word WM task tapped both verbal and orthographic processing.

In the control group, we predicted that the verbal WM tasks (Object and Word WM) would be more strongly related to reading comprehension than the nonverbal WM task (Shape WM). Additionally, if the basis for the association of the verbal WM tasks was related to presentation similarities, then we predicted that the Word WM measure would be more

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strongly related to reading comprehension than the Object WM measure because both tasks require reading. However, if the relationship was due to processing of verbal information, then we predicted similar relationships for the word and object tasks. Although the verbal WM measures may be related to reading comprehension, a more stringent test is whether these measures predict reading comprehension in addition to word reading and oral language abilities. For this, the prediction is less clear. On the one hand, there is some evidence that verbal WM predicts reading comprehension above and beyond word reading and oral language (e.g., Cain, Oakhill, and Bryant 2004). On the other hand, the verbal WM-reading comprehension relationship may be explained by shared variance with word reading and oral language and not predict reading comprehension after accounting for these variables.

For the participants with ASD, the WM-reading comprehension relationships may be different than those for the control children. If verbal WM is stronger relative to nonverbal WM in individuals on the spectrum, as suggested in a recent meta-analysis (Wang et al. 2017), then verbal WM (Object and Word WM) performance in the ASD group should be superior to nonverbal WM (Shape WM). If this is upheld in our data, then we predict that the relationship of the Object and Word WM tasks (verbal WM) with reading comprehension may be weaker relative to the relationship of the Shape WM task (nonverbal WM) because nonverbal WM may better tap into individual processing differences in the ASD group. Note that this is the opposite of our prediction for the control group.

When considering the role of WM in addition to word reading and oral language, the following predictions can be made. If nonverbal WM is related to reading comprehension in this group, it follows that there may be less shared variance between reading comprehension and word reading as well as oral language, and nonverbal WM (Shape WM) *would* predict reading comprehension after accounting for these variables. Again, this differs from our prediction for the control group. Essentially, we predict that the different profiles across verbal and nonverbal WM often found in ASD would also alter the relationships of verbal and nonverbal WM with reading comprehension in ASD. The alternative hypothesis is that WM profiles will not differ between the ASD and the control group, and the relationships of verbal and nonverbal WM with reading comprehension will also be the same across groups.

Method

Participants

Participants were recruited through local schools, community centers, or clinics using flyers and website postings and through a research registry at the Waisman Center (ASD group only) for a larger project examining the relationship of oral language and executive function abilities across monolingual typically developing (TD), bilingual TD, children with specific language impairment, and children with ASD (see Ellis Weismer et al. 2017; Gangopadhyay et al. 2016; Haebig et al. 2015; Kaushanskaya et al. 2017 for published studies including some of these participants). Following participation in the larger study, the monolingual TD participants and participants with ASD were recruited for the present study on reading abilities upon additional informed parental consent and child/adolescent assent (see Davidson and Ellis Weismer 2017 for a published study including this similar subset of

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participants). On average, the time between studies was 8.1 months (SD = 6.49). The university's institutional review board approved both research protocols.

Twenty-five participants per group between the ages of 8–14 years were recruited for the current study. Of these, 19 participants with ASD and 24 TD controls did not display any of the exclusionary criteria and completed all three WM tasks. Exclusionary criteria for both groups included: non-native English/multi-lingual speaker, nonverbal cognition < 85, known chromosomal abnormalities (e.g., Fragile × syndrome, Down syndrome), cerebral palsy, uncorrected hearing/visual impairments, or other disorders. Additional exclusionary criteria for the control group included: language or learning disabilities or other developmental delays, including risk for ASD as indicated by an autism screening measure [the *Social Communication Questionnaire* (SCQ(Rutter et al. 2003)] administered during their visit.

A certified and licensed psychologist used the *Child Autism Rating Scale-Second Edition* (CARS-2(Schopler et al. 2010) via observational methods to confirm previous medical or educational community ASD diagnoses. Participants were considered to meet criteria for ASD if their total raw scores were greater than or equal to 25, as this corresponds to the 10^{th} percentile of CARS2-HF scores among individuals with ASD in the standardization/norming sample. All, except one, ASD participants' community diagnoses were confirmed. The one participant who did not meet the preset criteria was close to the cutoff with a score of 24 and was therefore included.

TD Control participants included almost equal males ($n = 13$) and females ($n = 11$). ASD participants were mostly male ($n = 15$). Both groups were also mostly white (TD: $n = 21$; ASD: $n = 17$) with the remainder reporting "Other". All participants passed a pure tone audiometry hearing screening performed at 20db HL at the frequencies 1000, 2000, and 4000 Hz, per American Speech-Language-Hearing Association (ASHA) guidelines (American Speech-Language-Hearing Association 1997). See Table 1 for additional participant characteristics.

Procedure

The autism confirmation/screening measures, hearing screening, nonverbal cognition, oral language measures, and WM measures were administered as part of the protocol of the larger research study. The reading measures were administered as part of the current research study protocol. All participants were tested individually in a quiet room at a research center.

Standardized Measures

A battery of standardized measures was used to evaluate nonverbal cognition, oral language, and reading abilities. Nonverbal cognition was assessed using the *Wechsler Intelligence Scale for Children-Fourth Edition* (WISC-IV; Wechsler et al. 2003) perceptual reasoning index. Vocabulary comprehension was evaluated using the *Peabody Picture Vocabulary Test-Fourth Edition* (PPVT-4; Dunn and Dunn 2007). Morphosyntactic comprehension was determined using the *Test of Oral Language Development, Intermediate Version, Fourth Edition* (TOLD:I-4; Hammill and Newcomer 2008). Reading abilities were measured using the *Woodcock Reading Mastery Test, Third Edition* (WRMT-III; Woodcock 2011). For word

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reading abilities, the WRMT-III Word Identification subtest measured word recognition of real words and the WRMT-III Word Attack subtest assessed decoding of nonwords. The scores from these two subtests, which were strongly correlated (see Tables 3 and 4), were combined into the Basic Skills cluster score to collectively reflect recognition and decoding as word reading abilities. The WRMT-III Passage Comprehension subtest measured participants' ability to read a short passage of two to three sentences in length and identify key information from that passage by stating the word belonging in the blank. Responses were scored as correct if they matched any of the correct answers provided for each item in the manual.

We selected the WRMT-III because this measure (or similar versions) is commonly used in the United States to index reading comprehension both clinically and in research (e.g., Adlof et al. 2010; Berninger et al. 2016; Catts et al. 2003, 2006; Christopher et al. 2012; Cronin 2014; Cutting et al. 2009; Huemer and Mann 2010; Ouellette 2006; Quinn et al. 2015; Swanson and Berninger 1995). Additionally, the WRMT Passage Comprehension and similar cloze tests of reading comprehension have been used to define good and poor comprehender groups that then demonstrate lower WM in poor comprehenders (e.g., Swanson and Berninger 1995), and verbal WM, compared to other executive function measures, was a significant predictor of a reading composite, including a measure of word reading, spelling, and passage comprehension (Berninger et al. 2016). Finally, one study suggested that poor working memory may account for the poor reading comprehension on a similar measure to the WRMT in children in ASD (Newman et al. 2007).

Standard scores are reported in Table 1 for ease of interpretation; however, these scores did not meet normality assumptions. Growth scale value scores (GSVs), when available, are preferable to raw scores in statistical analyses because they are on an equal-interval scale (Dunn and Dunn 2007). GSVs for the reading (word decoding, word recognition, word reading, and passage comprehension) and vocabulary measures were normally distributed; therefore, these scores were used in all analyses. For the morphological comprehension subtest, GSVs were not available. Raw scores were normally distributed and used in all analyses. These scores also better capture variability across the large age range in this sample. Chronological age was examined and controlled, as necessary.

Experimental Working Memory Measures

Working memory was measured using three variations of the classic N-back task (Smith and Jonides 1999; Szmalec et al. 2011). These three N-back tasks were consistent in presentation but differed in the type of stimuli presented (see Figure 1). The Shape WM task was designed to be non-linguistic in that participants viewed abstract shapes that had been shown not to invite labels (Attneave and Arnoult 1956; Vanderplas and Garvin 1959). The Object WM task was designed to be linguistic in that participants viewed pictures of familiar objects that easily could be named. The Word WM task was also linguistic, but participants saw single words rather than pictures. Whole words were used rather than single letters or numbers as is common in letter or number N-back tasks in order to equate the type of information accessed by both the Object and Word WM tasks. In this way, the Word WM task only differed (from the Object WM task) by its orthographic presentation. The words in

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the Word WM task were not the same as the names for the objects in the Object WM task. Across the two tasks (see Table 2), the words did not differ in age of acquisition, word concreteness, familiarity, imageability, frequency, number of letters, or number of syllables (*ps* > .388).

The computerized WM tasks were run using E-Prime Studio 2 (Schneider et al. 2002). Shape, Object, or Word items were presented visually (participants did not hear the objects named or the words read) so that a single item appeared on the screen for each trial. All three N-back tasks consisted of three levels (0-back, 1-back, and 2-back) where the participants decided if the current item matched an item presented *n* positions before. Performance in this sample was at ceiling for the 0- and 1-back levels across all WM types; therefore, only the 2-back level was used in the current study. In the 2-back condition, participants were instructed to press the green button when the item was the same as the one that appeared two trials before the target item and to press the red button if the item was different. Participants completed eight practice trials before completing the task. Each stimulus was presented for 500 ms with an inter-stimulus interval (ISI) of 1500 ms. Across 40 trials, the stimuli were presented so that the number of "hits" occurred for 30% of the trials in order to ensure that participants carefully monitored the series of shapes. A fixed pseudo-random presentation sequence was used such that the N-2 sequences were not repeated more than 10 times. The presentation order of the Shape, Object, and Word WM tasks was randomized across participants. Accuracy scores (proportion correct) indexed WM for each WM task. For the Shape, Object, and Word WM tasks, the accuracy scores were arcsine-transformed to correct for substantial skewness and kurtosis and used in all analyses.

Analysis Approach

First, we compared the groups using Analysis of Variance (ANOVA) across the relevant measures to determine any significant group differences. Second, correlations for all measures of interest were examined separately for each group to assess the patterns of relationships with reading comprehension in both groups and to theoretically and empirically select the measures to use in the regressions. Lastly, a series of hierarchical linear regressions was used to investigate the role of each WM type (Shape, Object, and Word). For each WM type, the respective WM was entered as a single predictor of reading comprehension at Step 1. In Steps 2–5, an additional predictor was added to the model in the following order: age, word reading, vocabulary, and group membership (ASD v. TD control peers), and change in variance accounted for at each step was compared to the previous model. In this way, we could examine the effect of each WM type in reading comprehension in relation to each of the additional predictors. Given the relatively small sample, bootstrapping for estimate confidence intervals with 5000 iterations was completed to confirm the reliability of the results (Field et al. 2012). In the robust regression, the data are simulated across 5000 samples and the average of those results is returned. We have more confidence in the original results when the bootstrapped confidence intervals are narrow and comparable to the results for the original sample. All analyses were run in *R* (R Core Team 2016).

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Results

Group Comparisons

Group comparisons (see Table 1) indicated that the ASD group had significantly more characteristics of autism than the control group, as expected. The groups were well matched and did not significantly differ with respect to age, socioeconomic status, nonverbal cognition, vocabulary comprehension, or morphosyntactic comprehension. However, the groups were not balanced with respect to gender (TD 54% males, ASD 79% males). We examined possible gender differences in WM and reading abilities using Wilcoxon rank sum tests with continuity corrections (Mann-Whitney U tests). For the sample as a whole there were no significant gender differences on the three WM measures or two reading measures. For the TD group there was a marginal effect of gender for word reading with females performing better than males (p=.05), but no other significant effects. For the ASD group, there was a significant gender effect for word reading (p=.04) and object WM (p=.02) with males scoring higher than females; there were no significant gender differences within the ASD group for the other three measures. Inspection of individual scores revealed that there was one outlier (female) score on both of the measures on which a gender effect was observed. Given the lack of significant gender differences for the overall sample, TD group and the majority of measures for the ASD group, we did not include gender in our statistical models. The control group performed significantly higher on all reading measures, including word reading, word recognition, word decoding, and reading comprehension. The TD control and ASD group's performance did not significantly differ on the Shape, Object, or Word WM tasks.

Correlations

The patterns of association were relatively similar in the ASD and TD control groups (see Table 3). The word reading cluster, word recognition, vocabulary, and morphosyntax measures were all related to reading comprehension in both groups, as expected. Unexpectedly, word decoding was not significantly related to reading comprehension in the TD control group; however, the relationship was significant in the ASD group. Age was significantly related to reading comprehension in the TD control group and was trending towards significance for the ASD group ($p = .056$). Lastly, the patterns of association for WM type were similar across both groups—Object WM was significantly and more strongly related to reading comprehension than Shape and Word WM, which were both not significantly related to reading comprehension.

Given the similar patterns of correlations for both groups, we next examined the correlations collapsed across groups (see Table 4). Group membership was dummy coded (0 = TD Control; 1 = ASD), and negatively associated with reading comprehension. All other variables were significantly and positively associated with reading comprehension, including all three WM measures. In addition to Age and Group, the word reading cluster measure (given that both word recognition and decoding were significantly related across both groups) and vocabulary comprehension (because this relationship with reading comprehension was stronger than for morphosyntactic comprehension) were selected as the additional variables for the regression analyses.

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Regression Analyses

The initial models were fit including all participants. However, model fit checks indicated one participant with ASD as a potential outlier (this was not the participant who did not meet CARS ASD criteria identified above). Models were refit excluding this participant, and model fit checks indicated reasonably good fit. After reviewing the scores for the outlier participant, it appeared that this participant was an outlier for two reasons: (1) the participant had low word reading and even lower reading comprehension scores, but a vocabulary score in the average range and (2) this participant was one of the oldest participants. The results including all participants and excluding the outlier were comparable, with one exception: age was trending toward significance in the models including all participants, but was significant in the models excluding the outlier. Given the comparable results and the better fit of the models excluding the outlier, the results of these analyses are reported.

The results were similar across all three WM types. At Step 1, Shape WM (see Table 5), Object WM (see Table 6), and Word WM (see Table 7) were significant predictors, and accounted for 15%, 29%, and 16%, respectively, of the variance in reading comprehension. The addition of Age at Step 2 significantly accounted for 18–27% of additional variance in reading comprehension. Similarly, adding Word Reading at Step 3 significantly accounted for an additional 15–29% of the variance and adding Vocabulary at Step 4 significantly accounted for an additional 6–8% of the variance in reading comprehension. Finally, Group Membership in the final models (Step 5) significantly accounted for an additional 10–12% of the variance in reading comprehension.

In the final models, none of the WM measures were significant individual predictors of reading comprehension (*ps* > .610). Word reading was also not a significant individual predictor of reading comprehension in any of the models (*ps* > .903). The three significant individual predictors in all of the final models were age, vocabulary, and group membership. These predictors accounted for 81% of the total variance in reading comprehension.

Discussion

This study investigated the role of three types of WM in addition to word reading and oral language in reading comprehension in school-age participants with ASD and their TD peers. The groups were well matched in age, socioeconomic status, nonverbal cognition, and oral language abilities (vocabulary and morphosyntax). The groups differed in autism characteristics and reading abilities, particularly reading comprehension. This result is in line with numerous other studies documenting poorer reading comprehension in individuals with ASD compared with TD peers (e.g., Brown et al. 2013; Nation et al. 2006; Ricketts 2011).

Working Memory and Reading Comprehension in ASD and TD

We predicted possible group differences across the three WM tasks (Shape WM, Object WM, and Word WM) because of the documented WM weaknesses in individuals with ASD (Wang et al. 2017). However, in this sample, the ASD and TD control groups' performance did not significantly differ for any of the three WM measures. This result contrasts with the

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consensus of the literature (Wang et al. 2017), but may be explained in that our groups were well-matched across age, socioeconomic status, nonverbal cognition, and oral language. These findings indicate that when children with ASD are well matched to their TD peers across numerous factors known to affect WM, verbal and nonverbal WM performance can be indistinguishable between the two groups.

The relationships for WM and reading comprehension in the ASD group were similar to those found in the well-matched peer control group. As noted above, this might be anticipated given the lack of group differences in factors known to affect WM performance. Across both groups, all three types of WM were significantly related to reading comprehension, suggesting a domain-general relationship. Object WM accounted for the most variance in reading comprehension (29%) followed by Word and Shape WM (16% and 15%, respectively). The strength of Object WM, relative to Word WM, with reading comprehension was surprising. Examination of the correlations of the Object WM task with other variables shows that Object WM was moderately associated with all of the same variables as reading comprehension. Therefore, the strength of the Object WM-reading comprehension relationship likely reflects this shared variance and suggests that the strength of children's WM for verbal information was better tapped by this task. Exactly why the Object WM task versus the Word WM task better tapped into these processes is less clear, but children may have been relying on different sources of lexical information (e.g., phonological v. orthographic v. semantic) in the Word versus Object WM tasks. If we assume verbal mediation occurred (i.e., children named the visual objects as they viewed them) during the Object WM task, then it is possible that naming the objects provided stronger activation of the semantic representation than reading the words.

As noted, all three types of WM were related to reading comprehension and accounted for a significant amount of variance when entered as individual predictors of reading comprehension. However, these relationships were rendered non-significant with the addition of age, word reading, vocabulary, and group membership into the models. Each predictor accounted for a significant additional amount of variance when added, but at the final model, only age, vocabulary and group membership were significant individual predictors of reading comprehension. The models accounted for 81% of the variance in reading comprehension. We consider the role of each individual predictor in turn.

Predictors of Reading Comprehension in ASD and TD

We included age as a control variable in our models because the chronological age of the participants was significantly related to reading comprehension in our correlation analyses. The significant role of age in reading comprehension may reflect developmental shifts across our age span of 8 to 14 years. Age was also a significant predictor of ambiguous sentence comprehension in children with ASD and their TD peers across the same age span (Davidson and Ellis Weismer 2017). However, the separate collection timepoints for the WM and language measures versus the reading measures may also account for the significant effect of age. A post-hoc analysis indicated that older children tended to have longer lapses between data-collection timepoints compared to younger children ($r = .47$, $p = .002$). Future studies should further investigate potential developmental effects.

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Word reading was not a significant predictor of reading comprehension in this study after vocabulary was added to the models. Some evidence suggests that word reading abilities are related to vocabulary, or understanding word meaning (Harm and Seidenberg 2004; Nation and Snowling 1998; Ouellette 2006; Perfetti 2007; Protopapas et al. 2007; Tunmer and Chapman 2012). Also, studies have shown that in older children, like those in our sample, the unique contribution of word reading is negligible after vocabulary is taken into account (Protopapas et al. 2007), and more generally, that oral language abilities relative to word reading are a stronger predictor of reading comprehension later in reading development (Hoover and Gough 1990; Vellutino et al. 2007; Verhoeven and van Leeuwe 2008).

The significance of vocabulary aligns with many studies documenting the particularly strong and important role of vocabulary in predicting reading comprehension in TD individuals and children with poor comprehension not on the autism spectrum (Chrysochoou et al. 2011; Protopapas et al. 2007; Quinn et al. 2015; Tunmer and Chapman 2012; Van Dyke et al. 2014). The role of vocabulary knowledge in reading abilities of children with ASD is also becoming increasingly apparent (Brown et al. 2013; Davidson and Ellis Weismer 2017; Henderson et al. 2014; Lucas and Norbury 2014, 2015; Ricketts 2011). In addition, these results align with two investigations emphasizing the role of vocabulary over WM in reading comprehension (Chrysochoou et al. 2011; Van Dyke et al. 2014).

In the first study, vocabulary mediated the role of verbal WM in all reading comprehension measures evaluated, except one (a point we return to below), in 8- to 10-year-old TD children from Greece (Chrysochoou et al. 2011). In the second study, vocabulary was the only consistently significant predictor of reading comprehension out of a battery of 24 skills in young adults (18–24 years) (Van Dyke et al. 2014). The authors go on to suggest that "… previous findings emphasizing WM capacity may be spurious due to its shared variance with many other abilities" (Van Dyke et al. 2014, p. 389). However, as discussed further below, it is important to note that these results contrast with previous findings that WM accounted for additional variance above and beyond other variables, including vocabulary (Cain, Oakhill, and Bryant 2004; Cutting et al. 2009; Oakhill et al. 2011; Whitney Sesma et al. 2009) .

Finally, even after accounting for WM, age, word reading, and vocabulary, ASD group membership was a significant negative predictor of reading comprehension. In other words, after controlling for these important predictors of reading comprehension, having an ASD diagnosis adversely affects reading comprehension to a greater extent than can be accounted for by these variables. This result aligns with a recent study finding that reading comprehension weaknesses in ASD were specific when compared to peers with ADHD and TD (McIntyre, Solari, Gonzales, et al. 2017). Together, this evidence may suggest that additional ASD-specific factors beyond language, working memory, and word reading (all of which were well controlled in the current study) may be contributing to reading comprehension deficits in ASD. We hypothesize that one direction for further exploration is the role of insufficient background knowledge (e.g., social world knowledge) or inefficient retrieval of background knowledge from long-term memory, as predicted by the CI model.

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Factors Affecting the Working Memory-Reading Comprehension Relationship

Our results may diverge from previous studies, such as Oakhill et al. (2011), because of WM task-related differences, given that previous studies used measures such as the listening span or backward digit span. Our measures clearly differ in that all WM measures in this study were presented visually and at the single-item level (i.e., objects/words versus sentences). The WM-reading comprehension relationship, therefore, may have been significant in the previous studies because of modality differences (auditory v. visual presentation) or the degree to which those tasks tapped linguistic processing beyond the word level (Berninger et al. 2010).

Additionally, the relationship of WM and reading comprehension may depend on the reading comprehension measure and/or the aspects of reading comprehension tested in a given measure. From a theoretical view, the limited role of WM capacity and the stronger role of language and background knowledge in reading comprehension performance as captured by the Woodcock Reading Mastery Test (WRMT) is supported by the CI model (Kintsch 1998). WM's role was likely limited in reading comprehension on the WRMT because (1) the demands for holding text in WM were minimal (i.e., the passages were short and remained in front of the child while they determined their answer) and (2) the content of the texts required automatic knowledge access, not inferencing. Pearson and Hamm (2005) argued that cloze tests, like the WRMT Passage Comprehension, are not sensitive to "intersentential" comprehension (i.e. comprehension across multiple sentences), suggesting the limited need for WM to integrate text and background information across sentences.

Evidence from other studies also support this interpretation. For example, one study found that only oral language predicted WRMT passage comprehension (the same measure used in our study), but both oral language and an executive function composite including WM measures, predicted performance on a different standardized test of reading comprehension, the *Gray Oral Reading Test, Fourth Edition* (GORT-4) (Cutting et al. 2009). Other studies provide some evidence that WM may only be related to a specific aspect of reading comprehension—inferencing ability. Word reading and vocabulary predicted literal comprehension whereas word reading, WM, and planning predicted inferential comprehension in one study (Potocki et al. 2015). Similarly, vocabulary mediated all types of reading comprehension investigated except elaborative inferencing in another study (Chrysochoou et al. 2011). Our reading comprehension measure did not require inferencing, which could explain the lack of relationship in our study between WM and reading comprehension after accounting for the additional variables, particularly vocabulary. It could also explain why a relationship was found between WM and the inferencing measures for participants with ASD in Lucas and Norbury (2015) and Tirado and Saldaña (2016). Together, prior work and the results of this study, suggest that the WM-reading comprehension relationship may not only vary by WM task but also may depend on the reading comprehension measure.

Limitations

There are several important limitations and considerations to keep in mind regarding this investigation. The results of this study should be interpreted cautiously as the sample size

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was relatively small. Future studies will need to investigate the role of WM using several reading comprehension measures, including an inferencing measure. In addition, future studies with a more diverse sample of ASD participants—including participants with lower language, lower WM, or both—may be helpful in further determining whether and how WM impacts reading comprehension abilities in ASD. Finally, although the ASD and control samples were matched on a number of variables, they differed in terms of gender representation. Even though our examination of the breakdown of performance by males versus females revealed only minimal differences for the ASD group and none for the TD group, this factor may have had some effect on the findings.

Conclusion

This was the first study to investigate the role of three different types of WM via parallel tasks using abstract shapes, familiar objects, and written words in reading comprehension performance by children with ASD relative to their peers. Group membership was a significant predictor of reading comprehension, but the relationships of additional predictors were similar for both groups. Although all three WM types were significantly related to reading comprehension, they did not significantly predict reading comprehension after accounting for age, group membership, word reading, and vocabulary. In this sample of children with good nonverbal cognition and language abilities, vocabulary was the best predictor of reading comprehension. At this time, these results suggest that vocabulary knowledge is one area that should continue to be emphasized in clinical intervention though, admittedly, simply targeting vocabulary does not address higher-order linguistic comprehension skills. Future studies should continue to investigate the relationships of word reading, oral language, and WM with reading comprehension in ASD, particularly in samples with different language and WM profiles as well as across different reading comprehension measures.

Acknowledgments

This study was originally submitted in partial completion of MMD’s doctoral dissertation at the University of Wisconsin-Madison. Portions of these data were presented at the Society for the Scientific Study of Reading (SSSR) 2016 and the Symposium on Research in Child Language Disorders (SRCLD) 2017. Thank you to the participants and their families. We appreciate the support of the following funding agencies: National Institutes of Health National Institute on Deafness and Other Communication Disorders (NIDCD) R01 DC011750; National Institutes of Health Eunice Kennedy Shriver National Institute of Child Health and Human Development (NICHD) U54 HD090256; Council of Academic Programs in Communication Sciences and Disorders (CAPCSD) PhD Scholarship; American Speech-Language-Hearing Foundation New Century Scholars Award. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health. We acknowledge the help of Elizabeth Ales, Natalie Bowman, Ishanti Gangopadhyay, Eileen Haebig, Eva Lopez, Emily Murphy, Sarah Naumann, Stephanie Palm, Haliee Patel, Heidi Sindberg, and Lauren Utech for assistance with recruitment and data collection, and Ishanti Gangopadhyay and Eileen Haebig for the working memory task development.

MMD conceived of the study design and analysis approach, performed the statistical analyses, and drafted the manuscript. MK and SEW participated in the design and interpretation of the data and helped to draft the manuscript. All authors read and approved the final manuscript.

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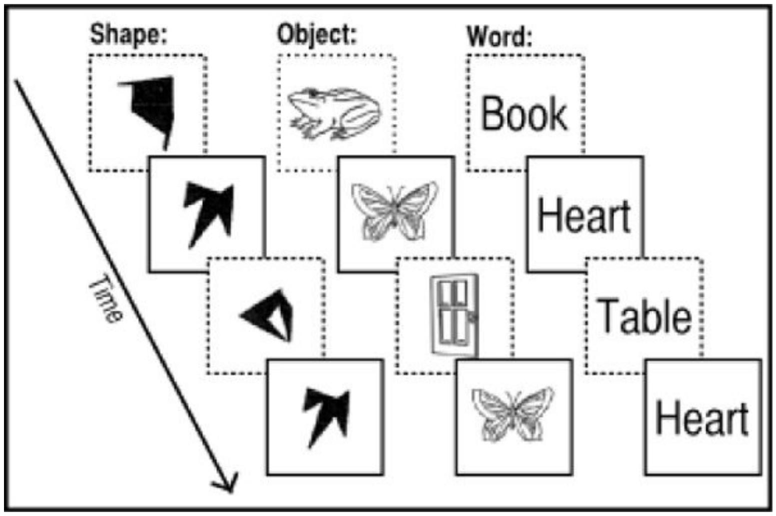

Figure 1.
Example stimuli and visual depiction of stimuli presentation for the Shape, Object, and Word working memory tasks. Participants decided if the current item matched the item presented two positions before (i.e., 2-back). Items with dotted borders indicate items that do not match and items with solid borders indicate items that do match.

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Table 1

Participant characteristics and group comparisons.

Variable		TD Controls (n = 24)			ASD (n = 19)			ANOVA			
		M	*SD*	Range	*M*	*SD*	Range	*df*	*F*	*p*	n_g^2
Age[a]		10.97	1.04	9.25–12.67	11.21	1.48	9.25–13.92	1, 41	0.40	.531	0.01
SES[b]		16.83	3.01	12.00–22.00	15.47	3.13	12.00–24.00	1, 40	2.02	.163	0.05
Nonverbal Cognition[c]		113.88	10.53	94.00–135.00	106.58	14.91	86.00–137.00	1, 41	3.53	.067	0.08
Autism Characteristics[d]		4.00	3.28	0.00–16.00	16.58	5.80	9.00–35.00	1, 41	80.69	<.001	0.66
Vocabulary[e]	SS	119.12	16.20	97.00–150.00	109.11	20.89	81.00–147.00				
	GSV	194.96	15.43	171.00–220.00	187.42	20.39	149.00–231.00	1, 41	1.91	.175	0.04
Morphosyntax[f]	SS	11.00	3.40	5.00–16.00	9.61	2.85	6.00–16.00				
	Raw	27.29	12.23	7.00–45.00	21.28	11.39	9.00–45.00	1, 40	2.64	.112	0.06
Word Reading Cluster[g]	SS	104.79	11.37	83.00–132.00	93.42	12.65	77.00–120.00				
	GSV	518.21	15.07	489.00–549.00	504.89	19.35	458.00–549.00	1, 41	6.44	.015	0.14
Word Recognition[h]	SS	108.08	9.25	93.00–127.00	98.42	13.26	80.00–124.00				
	GSV	527.58	15.75	489.00–555.00	512.05	26.93	437.00–569.00	1, 41	5.59	.023	0.12
Word Decoding[i]	SS	101.04	13.74	69.00–132.00	89.47	11.97	73.00–116.00				
	GSV	508.29	17.13	467.00–550.00	497.37	14.21	475.00–528.00	1, 41	4.99	.031	0.11
Reading Comprehension[j]	SS	116.29	13.41	91.00–134.00	94.79	14.73	68.00–126.00				
	GSV	526.17	16.80	494.00–556.00	505.74	17.41	485.00–552.00	1, 41	15.18	<.001	0.27
Shape WM	Accuracy	0.73	0.11	0.52–0.95	0.68	0.15	0.32–0.88				
	Arcsine	1.03	0.12	0.81–1.35	0.98	0.16	0.60–1.22	1, 41	1.37	.248	0.03
Object WM	Accuracy	0.80	0.12	0.45–0.95	0.74	0.19	0.30–0.95				
	Arcsine	1.12	0.15	0.74–1.35	1.05	0.22	0.58–1.35	1, 41	1.24	.272	0.03
Word WM	Accuracy	0.77	0.11	0.50–0.95	0.71	0.17	0.32–0.88				
	Arcsine	1.09	0.13	0.79–1.35	1.02	0.18	0.60–1.22	1, 41	1.88	.178	0.04

Note. TD = typically developing; ASD = autism spectrum disorder; SES = socioeconomic status; SS = standard score; GSV = growth scale value; WM = working memory;

[a]Chronological age in years;

[b]Based on mother's years of education (TD: n = 23);

[c] *Wechsler Intelligence Scale for Children-Fourth Edition* Perceptual Reasoning Index;

[d] *Social Communication Questionnaire* total scores;

[e] *Peabody Picture Vocabulary Test-Fourth Edition*;

[f] *Test of Oral Language Development-Intermediate, Fourth Edition* (ASD: $n = 18$);

[g] *Woodcock Reading Mastery Test, Third Edition* (WRMT-III) Basic Skills Cluster;

[h] WRMT-III Word Identification;

[i] WRMT-III Word Attack;

[j] WRMT-III Passage Comprehension.

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Table 2

Object and word working memory stimuli characteristics.

	Object			Word			Task Comparisons			
Variable	***M***	***SD***	**Range**	***M***	***SD***	**Range**	***t***	***df***	***p***	***d***
Age of Acquisition[a,b]	4.00	0.94	2.89–5.53	4.14	0.77	2.74–5.38	−0.41	19.25	.689	−0.17
Concreteness[c]	597.09	32.09	522–635	606.11	8.13	595–623	−0.90	11.54	.388	−0.37
Familiarity[c]	560.09	57.86	474–636	577.67	43.07	506–643	−0.78	17.88	.447	−0.34
Imagability[c]	600.00	23.76	562–635	600.78	15.44	582–624	−0.09	17.25	.931	−0.04
Frequency[c,d]	112.00	183.55	1–591	131.00	127.12	10–431	−0.28	17.82	.784	−0.12
Number of Letters	4.82	1.72	3–9	5.18	1.33	4–8	−0.55	18.79	.586	−0.24
Number of Syllables	1.27	0.65	1–3	1.36	0.50	1–2	−0.37	18.88	.717	−0.16

Note.

[a]In years;

[b]From the Kuperman et al. database (Kuperman et al. 2012);

[c]From the MRC Psycholinguistic database (Wilson 1988);

[d]The Kucera-Francis written frequency.

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Table 3

Pearson correlations separately for the ASD group (below diagonal) and TD Control group (above diagonal).

	Age	RC	WRC	WR	WD	V	M	Shape	Object	Word
Age[a]	—	0.72***	0.49*	0.57**	0.33	0.58**	0.24	0.32	0.23	0.21
Reading Comprehension[b] (RC)	0.45‡	—	0.62***	0.76***	0.38	0.86***	0.52**	0.30	0.50*	0.32
Word Reading Cluster[c] (WRC)	0.48*	0.74***	—	0.91***	0.92***	0.73***	0.47*	−0.06	0.35	0.46*
Word Recognition[d] (WR)	0.39	0.68***	0.97***	—	0.67***	0.85***	0.47*	0.09	0.45*	0.57**
Word Decoding[e] (WD)	0.56*	0.72***	0.88***	0.74***	—	0.49*	0.39	−0.20	0.20	0.29
Vocabulary[f] (V)	0.45‡	0.70***	0.81***	0.83***	0.64**	—	0.58**	0.20	0.46*	0.46*
Morphosyntax[g] (M)	0.31	0.52*	0.28	0.24	0.32	0.58*	—	0.26	0.38	0.39‡
Shape WM	0.43	0.31	0.14	0.18	0.07	0.40	0.32	—	0.41*	0.34
Object WM	0.41	0.47*	0.61**	0.61**	0.51*	0.69***	0.21	0.71***	—	0.32
Word WM	0.06	0.35	0.32	0.36	0.19	0.53*	0.23	0.63**	0.77***	—

Note. ASD = autism spectrum disorder; TD = typically developing; WM = working memory;

[a]Chronological age in years;

[b]*Woodcock Reading Mastery Test, Third Edition* (WRMT-III) Passage Comprehension;

[c]WRMT-III Basic Skills Cluster;

[d]WRMT-III Word Identification;

[e]WRMT-III Word Attack;

[f]*Peabody Picture Vocabulary Test-Fourth Edition*;

[g]*Test of Oral Language Development-Intermediate, Fourth Edition* (ASD: $n = 18$);

‡ $p = .05$;

* $p < .05$;

** $p \leq .01$;

*** $p \leq .001$.

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Table 4

Pearson correlations collapsed across the ASD and TD Control groups.

	Group	Age	RC	WRC	WR	WD	V	M	Shape	Object	Word
Group	—										
Age[a]	0.10	—									
Reading Comprehension[b] (RC)	−0.52***	0.43**	—								
Word Reading Cluster[c] (WRC)	−0.37*	0.41**	0.73***	—							
Word Recognition[d] (WR)	−0.35*	0.39**	0.74***	0.94***	—						
Word Decoding[e] (WD)	−0.33*	0.37*	0.59***	0.90***	0.70***	—					
Vocabulary[f] (V)	−0.21	0.47**	0.75***	0.78***	0.84***	0.57***	—				
Morphosyntax[g] (M)	−0.25	0.24	0.56***	0.42**	0.38**	0.41**	0.59***	—			
Shape WM	−0.18	0.36*	0.35*	0.12	0.20	−0.01	0.34*	0.31*	—		
Object WM	−0.17	0.32*	0.49***	0.52***	0.57***	0.37**	0.61***	0.31*	0.60***	—	
Word WM	−0.21	0.09	0.39**	0.42**	0.47**	0.29	0.52***	0.34*	0.53***	0.61***	—

Note. ASD = autism spectrum disorder; TD = typically developing; WM = working memory;

[a] Chronological age in years;

[b] *Woodcock Reading Mastery Test, Third Edition* (WRMT-III) Passage Comprehension;

[c] WRMT-III Basic Skills Cluster;

[d] WRMT-III Word Identification;

[e] WRMT-III Word Attack;

[f] *Peabody Picture Vocabulary Test-Fourth Edition*;

[g] *Test of Oral Language Development-Intermediate, Fourth Edition* (ASD: $n = 18$);

‡ $p = .05$;

* $p < .05$;

** $p \leq .01$;

*** $p \leq .001$.

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Table 5

Hierarchical regression analysis results for Shape WM.

		ΔR^2	ΔF	*B*	SE *B*	95% CI	Robust 95% CI	β	*p*
Step 1		0.15	6.89						.012
	Constant			465.31	20.19	424.49 – 506.12	434.78 – 506.54		<.001
	Shape WM			52.28	19.91	12.04 – 92.52	11.21 – 83.03	0.38	.012
Step 2	0.21	12.67							<.001
	Constant			399.41	25.66	347.50 – 451.31	359.38 – 448.23		<.001
	Shape WM			29.30	18.67	−8.47 – 67.06	−0.40 – 61.79	0.21	.125
	Age			8.08	2.27	3.49 – 12.67	3.15 – 11.96	0.49	.001
Step 3		0.29	30.92						<.001
	Constant			117.48	54.25	7.65 – 227.30	−13.81 – 225.01		.037
	Shape WM			32.80	14.06	4.33 – 61.26	10.58 – 65.32	0.24	.025
	Age			3.19	1.92	−0.70 – 7.08	−0.81 – 6.88	0.19	.106
	Word Reading			0.65	0.12	0.41 – 0.88	0.40 – 0.95	0.61	<.001
Step 4	0.06	7.72							.009
	Constant			222.40	62.67	95.42 – 349.38	48.62 – 342.44		.001
	Shape WM			19.23	13.85	−8.84 – 47.29	−7.72 – 43.23	0.14	.173
	Age			2.84	1.78	−0.76 – 6.44	−1.19 – 6.59	0.17	.118
	Word Reading			0.30	0.16	−0.03 – 0.64	−0.05 – 0.76	0.28	.076
	Vocabulary			0.47	0.17	0.13 – 0.82	0.11 – 0.85	0.44	.009
Step 5		0.10	20.14						<.001
	Constant			345.16	57.76	228.01 – 462.31	185.57 – 447.74		<.001
	Shape WM			2.21	11.87	−21.85 – 26.28	−19.81 – 23.18	0.02	.853
	Age			5.08	1.52	1.98 – 8.17	1.47 – 8.03	0.31	.002
	Word Reading			0.02	0.15	−0.28 – 0.32	−0.25 – 0.48	0.02	.903
	Vocabulary			0.58	0.14	0.30 – 0.87	0.20 – 0.88	0.54	<.001
	Group			−14.80	3.30	−21.49 – −8.11	−20.97 – −8.26	−0.38	<.001

Note.

WM = working memory;.

CI = confidence interval

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Table 6

Hierarchical regression analysis results for Object WM.

		ΔR^2	ΔF	*B*	SE *B*	95% CI	Robust 95% CI	β	*p*
Step 1		0.29	16.21						<.001
	Constant			456.29	15.49	424.97 – 487.60	433.46 – 477.77		<.001
	Object WM			56.70	14.08	28.24 – 85.15	35.01 – 78.84	0.54	<.001
Step 2		0.18	13.14						<.001
	Constant			390.27	22.72	344.33 – 436.22	352.60 – 432.95		<.001
	Object WM			43.06	12.90	16.97 – 69.14	22.41 – 66.21	0.41	.002
	Age			7.34	2.03	3.24 – 11.44	3.12 – 11.01	0.44	<.001
Step 3		0.15	15.01						<.001
	Constant			173.48	59.25	53.54 – 293.42	27.41 – 320.33		.006
	Object WM			19.59	12.61	−5.94 – 45.12	−5.68 – 50.84	0.19	.129
	Age			4.51	1.88	0.69 – 8.32	0.71 – 8.13	0.27	.022
	Word Reading			0.53	0.14	0.25 – 0.81	0.18 – 0.87	0.50	<.001
Step 4		0.07	9.08						.005
	Constant			257.44	60.59	134.66 – 380.21	98.38 – 399.02		<.001
	Object WM			6.85	12.21	−17.88 – 31.59	−18.21 – 30.82	0.06	.578
	Age			3.55	1.74	0.02 – 7.08	−0.42 – 6.96	0.21	.049
	Word Reading			0.22	0.16	−0.11 – 0.55	−0.16 – 0.65	0.21	.180
	Vocabulary			0.52	0.17	0.17 – 0.88	0.20 – 0.94	0.49	.005
Step 5		0.12	22.94						<.001
	Constant			352.95	51.98	247.52 – 458.38	213.17 – 457.53		<.001
	Object WM			4.98	9.68	−14.65 – 24.61	−13.60 – 28.45	0.05	.610
	Age			5.18	1.42	2.30 – 8.06	1.89 – 7.88	0.31	<.001
	Word Reading			0	0.14	−0.28 – 0.28	−0.29 – 0.40		0.999
	Vocabulary			0.57	0.14	0.29 – 0.85	0.23 – 0.91	0.53	<.001
	Group			−14.93	3.12	−21.26 – −8.61	−21.20 – −8.59	−0.38	<.001

Note.

WM = working memory;

CI = confidence interval.

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Table 7

Hierarchical regression analysis results for Word WM.

		ΔR^2	ΔF	*B*	SE *B*	95% CI	Robust 95% CI	β	*p*
Step 1		0.16	7.35						.010
	Constant			467.35	18.83	429.30 – 505.40	445.30 – 500.62		<.001
	Word WM			47.72	17.61	12.14 – 83.31	16.43 – 70.13	0.39	.010
Step 2		0.27	18.73						<.001
	Constant			378.28	25.87	325.96 – 430.60	339.18 – 419.87		<.001
	Word WM			41.08	14.74	11.27 – 70.88	13.72 – 67.46	0.34	.008
	Age			8.73	2.02	4.65 – 12.81	5.10 – 11.99	0.53	<.001
Step 3		0.18	17.60						<.001
	Constant			155.84	57.29	39.87 – 271.80	2.07 – 272.37		.010
	Word WM			16.85	13.63	−10.74 – 44.43	−8.42 – 45.80	0.14	.224
	Age			4.93	1.92	1.05 – 8.81	1.28 – 8.21	0.30	.014
	Word Reading			0.57	0.13	0.29 – 0.84	0.29 – 0.94	0.53	<.001
Step 4		0.08	9.72						.004
	Constant			252.58	60.27	130.47 – 374.69	87.68 – 383.68		<.001
	Word WM			1.24	13.27	−25.65 – 28.13	−31.4 – 33.0	0.01	.926
	Age			3.57	1.78	−0.05 – 7.18	−0.49 – 6.87	0.22	.053
	Word Reading			0.23	0.16	−0.10 – 0.56	−0.13 – 0.67	0.22	.159
	Vocabulary			0.55	0.18	0.19 – 0.91	0.16 – 0.98	0.51	.004
Step 5		0.12	23.07						<.001
	Constant			350.44	51.87	245.25 – 455.63	208.18 – 450.49		<.001
	Word WM			−2.21	10.53	−23.56 – 19.14	−25.86 – 24.87	−0.02	.835
	Age			5.12	1.45	2.19 – 8.06	1.64 – 7.86	0.31	.001
	Word Reading			0	0.14	−0.27 – 0.28	−0.29 – 0.42	0.01	.954
	Vocabulary			0.60	0.14	0.32 – 0.89	0.22 – 0.92	0.56	<.001
	Group			−15.04	3.13	−21.40 – −8.69	−21.60 – −9.08	−0.39	<.001

WM = working memory;

Note.

CI = confidence interval.