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Reading Comprehension of Ambiguous Sentences by School-Age Children with Autism Spectrum Disorder

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Abstract

Weak central coherence (processing details over gist), poor oral language abilities, poor suppression, semantic interference, and poor comprehension monitoring have all been implicated to affect reading comprehension in individuals with autism spectrum disorder (ASD). This study viewed the contributions of different supporting skills as a collective set of skills necessary for context integration—a multi-component view—to examine individual differences in reading comprehension in school-age children (8–14 years) with ASD ($n = 23$) and typically developing control peers ($n = 23$). Participants completed a written ambiguous sentence comprehension task in which participants had to integrate context to determine the correct homonym meaning via picture selection. Both comprehension products (i.e., offline representations after reading) and processes (i.e., online processing during reading) were evaluated. Results indicated that children with ASD, similar to their TD peers, integrated the context to access the correct homonym meanings while reading. However, after reading the sentences, when participants were asked to select the meanings, both groups experienced semantic interference between the two meanings. This semantic interference hindered the children with ASD's sentence representation to a greater degree than their peers. Individual differences in age/development, word recognition, vocabulary breadth (i.e., number of words in the lexicon), and vocabulary depth (i.e., knowledge of the homonym meanings) contributed to sentence comprehension in both children with ASD and their peers. Together, this evidence supports a multi-component view, and that helping children with ASD develop vocabulary depth may have cascading effects on their reading comprehension.

Keywords

ASD; reading; comprehension; weak central coherence; oral language; semantics; eye tracking

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Reading Comprehension in ASD

The simple view of reading(Gough & Tunmer, 1986; Hoover & Gough, 1990; Tunmer & Chapman, 2012), a developmental model of reading, states that reading comprehension is the product of word reading and listening/oral language comprehension[1]. The simple view accounts for reading comprehension abilities in typically developing children and children with language impairment (Adlof, Catts, & Lee, 2010; Catts, Adlof, & Ellis Weismer, 2006; Catts, Hogan, & Fey, 2003; Hoover & Gough, 1990; Nation, Cocksey, Taylor, & Bishop, 2010). This conceptual framework has also been useful in investigating reading comprehension abilities in children with autism spectrum disorder (ASD) (Brown, Oram-Cardy, & Johnson, 2013; Cronin, 2014; Davidson & Ellis Weismer, 2014; Jacobs & Richdale, 2013; Nation, Clarke, Wright, & Williams, 2006; Norbury & Nation, 2011; Ricketts, Jones, Happé, & Charman, 2013). Understanding reading comprehension in ASD is important considering that approximately 65–73% of school-age children with ASD have reading comprehension difficulties (Henderson, Clarke, & Snowling, 2014; McIntyre et al., 2017; Nation et al., 2006).

The classic reading profile associated with ASD is that of the poor comprehender, or good word reading but poorer comprehension. However, word reading abilities are increasingly recognized as more variable than originally perceived (Brown et al., 2013; McIntyre et al., 2017; Nation et al., 2006). One proposed explanation for this shift is that previous studies over-relied on word recognition (i.e., the ability to use phonological and lexical-semantic processes to read real words) measures or collapsed word recognition and decoding (i.e., the ability to use phonological processing to read nonwords) measures, and this may have masked critical phonological decoding weaknesses in this population (Henderson et al., 2014). Therefore, Henderson et al. (2014) recommend separately assessing and evaluating the contributions of both word recognition and decoding measures in reading comprehension in children with ASD.

Vocabulary and morphosyntactic comprehension are two of the most foundational oral language abilities that predict reading comprehension in children without ASD (e.g., Adlof et al., 2010; Catts, Fey, Zhang, & Tomblin, 1999; Nation, Clarke, Marshall, & Durand, 2004; Oakhill, Cain, & Bryant, 2003). Morphosyntactic comprehension and vocabulary also predict reading comprehension in ASD (Åsberg & Dahlgren Sandberg, 2012; Cronin, 2014; Henderson et al., 2014; Jacobs & Richdale, 2013; Lucas & Norbury, 2014; Ricketts et al., 2013), and closely relate to profiles of reading abilities in ASD (McIntyre et al., 2017). Vocabulary can be further divided into vocabulary breadth (i.e., the number of items in the lexicon) and vocabulary depth (i.e., the richness of the semantic representation) (Ouellette, 2006; Ouellette & Beers, 2009). Vocabulary breadth is stronger than vocabulary depth in children with ASD (McGregor et al., 2012), and poor “deep” semantic knowledge may be particularly important for understanding language impairments in ASD (Naigles & Tek, 2017). Therefore, separately measuring the role of vocabulary breadth and depth may be

[1]The simple view of reading specifies listening comprehension in the model where listening comprehension is described as a parallel task of reading comprehension. However, listening comprehension has more generally been interpreted as oral language comprehension. Current evidence suggests that listening comprehension and oral language are tightly linked constructs (e.g., Kim, 2015; LARRC, 2017); therefore, oral language comprehension will be used in this study.

more pertinent and meaningful for understanding reading comprehension deficits in children with ASD.

As one final point when considering reading comprehension in ASD, the role of development is often overlooked. Word reading and oral language are important for reading comprehension throughout development, but their relative importance and relationships also change with development. For instance, word reading contributes more to reading comprehension abilities in younger children (~6–8 years) whereas oral language becomes a stronger predictor of reading comprehension in older children (~9 years and older) (Kim & Wagner, 2015; Vellutino, Tunmer, Jaccard, & Chen, 2007). Due to the recruitment challenges of a special population like ASD, studies examining reading comprehension in ASD recruit participants across wide age ranges (e.g., 6–16 years Cronin, 2014; 7–16 years in Henderson et al., 2014; 8–16 years in McIntyre et al., 2017; 6–16.5 years in Nation et al., 2006). Although this may be unavoidable, researchers should take greater care to attempt to account for potential developmental effects. In the current study, our purpose was not to evaluate developmental changes, but we attempted to capture development by assessing whether the child's chronological age, as a proxy for development, detected differences in performance.

Context Integration in ASD

Integrating context while reading, or context integration, is an important component for building coherent, meaningful representations (Oakhill, 1982; Oakhill, Hartt, & Samols, 2005; van der Schoot, Vasbinder, Horsley, Reijntjes, & van Lieshout, 2009). One way to evaluate the ability to integrate context is a homograph task. In the homograph task, participants read sentences in which the surrounding context biases the pronunciation of the homograph (i.e., words spelled the same with different pronunciations and meanings). The assumption is that if the context is integrated, then the correct meaning will be activated and the correct pronunciation will be said aloud.

Many studies found that participants with ASD performed more poorly on the homograph task than controls (Burnette et al., 2005; Frith & Snowling, 1983; Happé, 1997; Jolliffe & Baron-Cohen, 2001; López & Leekam, 2003; Snowling & Frith, 1986). The weak central coherence theory (Frith, 1989; Happé & Frith, 2006), which asserts that features of ASD are due to "a processing bias for featural and local information, and relative failure to extract gist or 'see the big picture' in everyday life" (Happé & Frith, 2006, p. 6), was proposed to account for this poor performance in context integration in ASD. Other studies evaluating the predictions of the weak central coherence theory using implicit priming methods, however, found that individuals with ASD could integrate context and did not differ from controls (Hahn, Snedeker, & Rabagliati, 2015; Hala, Pexman, & Glenwright, 2007; Henderson, Clarke, & Snowling, 2011; López & Leekam, 2003). In order to understand whether or not individuals with ASD have poor context integration, numerous explanations (oral language, suppression, semantic interference, and comprehension monitoring) have been contrasted with the predictions of the weak central coherence theory, and each of these will be considered in turn.

Some studies indicate that children with ASD are poor at context integration, and this is, at least partially, explained by their oral language abilities. Children (8–17 years) with language impairments, regardless of ASD diagnostic status, were poorer at context integration than those without language impairments on a listening comprehension task where children had to disambiguate the meanings of homonyms (i.e., words with the same pronunciation/spelling but different meanings) (Eberhardt & Nadig, 2016; Norbury, 2005). Similarly, children's (12–17 years) individual differences in eye movements while listening to contextually constraining sentences were related to language abilities rather than ASD status (Brock, Norbury, Einav, & Nation, 2008). Poor context integration is related to oral language abilities more generally. However, more work is needed to determine the role of specific aspects of oral language, such as vocabulary, morphosyntactic comprehension, and as proposed by López and Leekam (2003), familiarity with the rare pronunciations/meanings of the homographs.

In addition to weak central coherence and oral language abilities, suppression, or the ability to inhibit the incorrect meaning, has also been explored in context integration in ASD, but the results are unclear. In one study, children listened to sentences where a biasing context supported the meaning of the ambiguous word (a homonym), and then they were instructed to determine if a single picture representing the alternative meaning provided in the sentence "'fit' the meaning of the whole sentence" (Norbury, 2005, p. 155). Performance on ambiguous dominant (e.g., "Bill stole from the bank.") and subordinate (e.g., "Bill fished from the bank.") items were compared to unambiguous dominant (e.g., "Bill stole from the shop.") and subordinate (e.g., "Bill fished from the river.") items. Although the task was intended to measure suppression, the task demands in this condition actually required *both* context integration and suppression: the participants had to integrate the context to know that the dominant meaning was correct (relative to the sentence meaning) in order to know that the picture representing the subordinate meaning was incorrect. However, because only one picture was used and the correct answer was always "no" in this condition, participants only needed to activate the dominant meaning to correctly reject the picture. Performance was poorer for the children with language impairment, regardless of ASD status, but as Norbury (2005) cautions, these children may have been simply processing the individual meanings of the words rather than integrating the context and suppressing the meanings.

Henderson and colleagues (2011) contrasted the explanations above (weak central coherence, oral language, and suppression) with whether increased semantic interference during later stages of semantic processing contributed to context integration. Results for participants' (7–15 years) homonym processing in both the single-word and sentence-word priming tasks indicated that participants with ASD accessed the initial homonym meanings after 250 ms (the access stage) but could not select the meanings later after 1000 ms (the selection stage). This difference in the processing time-course of homonym meanings suggested that semantic interference between meanings during the selection stage of semantic processing may also play a role in context integration in some children with ASD. Notably, this study used a priming task, which may recruit different processing than non-priming tasks such as the homograph task (López & Leekam, 2003); the role of semantic interference in a non-priming task has not been evaluated.

Comprehension monitoring (i.e., processes used by readers to evaluate their understanding of the text to identify and repair misunderstandings (Connor et al., 2015; van der Schoot, Reijntjes, & van Lieshout, 2012)) may also contribute to weaknesses in context integration. Caruana and Brock (2014) examined the role of weak central coherence versus poor comprehension monitoring using eye tracking in adults that varied in non-clinical autism traits (based on the Autism Spectrum Quotient). The authors argued that the results did not support either view. However, regressions, or looks backward while reading, are the signature eye movement interpreted to indicate a comprehension failure and monitoring (Rayner, 1998; Sereno, O'Donnell, & Rayner, 2006), and were not analyzed by Caruana and Brock (2014). Therefore, poor comprehension monitoring in this case cannot be ruled out.

Finally, in addition to the above previously considered explanations, we contend that word reading abilities may also account for some variation in context integration in a written task. Many studies showing intact context integration in ASD, except for children with language impairments, used *listening* comprehension tasks (Beversdorf et al., 1998; Brock et al., 2008; Eberhardt & Nadig, 2016; Hahn et al., 2015; Henderson et al., 2011; López & Leekam, 2003; Norbury, 2005). Alternately, studies finding poor context integration used *written* comprehension tasks (Burnette et al., 2005; Frith & Snowling, 1983; Happé, 1997; Jolliffe & Baron-Cohen, 1999, 2000; López & Leekam, 2003; Snowling & Frith, 1986). Although listening and reading comprehension should closely align, it is possible that poorer performance on the homograph task could be related to participants' word reading abilities.

Previous studies using written tasks differ in how they accounted for word reading abilities: several studies did not account for word reading abilities (Brock & Bzishvili, 2013; Burnette et al., 2005; Jolliffe & Baron-Cohen, 2000, 2001; Snowling & Frith, 1986), two studies asked participants to read the homographs in isolation (Happé, 1997; López & Leekam, 2003), and two studies matched groups on decoding abilities, but the ASD participants' average word reading abilities in these studies were impaired relative to their chronological ages (Frith & Snowling, 1983; Hala et al., 2007). One study, which excluded participants with inadequate word reading skills, did not find that individual variability in word reading abilities predicted homograph task performance in Hebrew-speaking children with ASD (Brock, Sukenik, & Friedmann, 2017). However, context integration on written tasks improves with word reading development in typically developing children (Booth, Harasaki, & Burman, 2006), and we expect also contributes to context integration on a written task in English-speaking children with ASD.

Although context integration in ASD has been extensively investigated, we note four gaps in knowledge. First, the contribution of oral language and semantic interference to context integration has primarily been established using listening comprehension tasks. Processes in listening and written comprehension closely align, but we argue that examining these effects in a written comprehension context integration task is necessary to understand the weaknesses originally documented in the homograph task, a written task.

Second, previous studies viewed the contributions of different supporting skills as opposing views rather than a collective set of skills necessary for context integration—a multi-component view. More specifically, a multi-component view is that foundational oral language abilities, knowledge of both ambiguous meanings, interference of meanings during initial access, interference of meanings in later selection, and comprehension monitoring abilities all must be in place for successful context integration to occur. Therefore, depending on a child's abilities, a weak link in any of these skills could potentially contribute to poor context integration.

Third, previous studies relied on group comparisons and broad measures (collapsing all aspects of oral language into a single measure), but given the heterogeneity in ASD, this may be masking important individual differences. Brock and Caruana (2014) in their review of the Frith and Snowling (1983) homograph task and studies that followed, particularly emphasize accounting for individual differences as well as determining specific aspects of oral language and other factors that contribute to variation in reading comprehension in ASD. Only a single recent study has examined individual differences in Hebrew-speaking children with ASD; findings indicated a wide range of homograph pronunciation related to age and picture naming abilities (above and beyond age), but autism severity, word reading abilities, or knowledge of meanings did not account for individual variability in homograph reading (Brock et al., 2017).

Lastly, previous studies on context integration in ASD primarily evaluated what some have termed comprehension products (i.e., how the text is represented after reading is completed), not processes (i.e., how cognitive activity changes while reading) (Rapp & van den Broek, 2005). These terms largely align with the terms offline and online comprehension, but we prefer comprehension products and processes to better distinguish the resulting text representation from the processing that occurs while reading. Reading comprehension researchers recommend examining both comprehension products and processes to better identify the locus of comprehension failures (Rapp & van den Broek, 2005; van den Broek et al., 2005; van den Broek, Kendeou, Lousberg, & Visser, 2011), which we do in the current study.

Prior studies have evaluated eye movements during context integration in adults and children without ASD. Monitoring eye movements in skilled adult readers during context integration (where the context appears before the target word) shows what is known as the subordinate-bias effect (Pacht & Rayner, 1993; Rayner, Pacht, & Duffy, 1994). The subordinate-bias effect occurs because of increased competition between the two word meanings: the dominant meaning is initially accessed because of frequency (i.e., the dominant meaning is more common than the subordinate meaning), but the subordinate meaning is accessed because of the preceding biasing context. This consistently results in longer looking times at target words and regressions (i.e., looks from the target back to the preceding context) in biased-subordinate sentences relative to sentences with matched unambiguous words (Duffy, Morris, & Rayner, 1988; Rayner & Duffy, 1986; Sereno et al., 2006). In an eye tracking study examining comprehension processes in context integration in children (10–12 years), poor comprehenders, like good comprehenders and adults, integrated context to determine the correct sentence meaning during the access stage (i.e., lexical ambiguity resolution), but only the good comprehenders monitored their comprehension and reanalyzed the context after encountering the ambiguous word (van der Schoot et al., 2009). Therefore, we might expect children with ASD to perform similarly to the poor comprehenders given their shared reading comprehension weaknesses.

No study has evaluated eye movements during context integration in children with ASD. Other eye tracking studies with individuals with ASD revealed that although comprehension products did not differ from peer controls, ASD readers have been consistently found to have longer overall reading times (Au-Yeung, Kaakinen, Liversedge, & Benson, 2015; Howard, Liversedge, & Benson, 2017; Sansosti, Was, Rawson, & Remaklus, 2013) and overall increased regressions (Au-Yeung et al., 2015; Micai, Joseph, Vulchanova, & Saldaña, in press; Sansosti et al., 2013). Some have interpreted these group differences to suggest an inability to integrate world knowledge (Sansosti et al., 2013), to build a sufficient situation model or inefficient use of text (Micai et al., in press), or alternately, as a more cautious or deliberate reading strategy (Au-Yeung et al., 2015; Howard et al., 2017; Micai et al., in press). However, as Howard et al. (2017) note, participants with ASD in these studies have generally higher looking times and increased regressions across the task manipulations, suggesting that these group differences are *not* related to the cognitive or linguistic demands of the task. Continued investigation of comprehension processes in ASD is needed to shed light on the nature of these differences.

Current Study

In the current study, we evaluated comprehension of ambiguous sentences (i.e., sentences containing words with more than one meaning) in children (ages 8–14 years) with ASD and their typically developing peers. First, to build on the gaps in knowledge previously described, we used a written rather than listening comprehension task. Second, we improved on the Norbury (2005) design to simultaneously evaluate integration and interference in a sentence task. Third, we evaluated both comprehension products (as done in most of the previous studies) and comprehension processes to better assess where comprehension breakdowns may be occurring. Lastly, we assessed individual differences in multiple factors that were considered together: age/development, word reading (word recognition and decoding), oral language, including vocabulary breadth, morphosyntactic comprehension, and vocabulary depth (i.e., comprehension of the meanings of ambiguous words). This led us to three research questions:

1. Are children with ASD able to integrate context and/or do they experience more semantic interference than their peers on a *written* ambiguous sentence comprehension task?

2. Do children's ambiguous sentence comprehension processes align with their products, and do children with ASD's eye movements differ in a way that indicates more comprehension difficulties during processing (e.g., longer durations, more regressions)?

3. Do individual differences in age/development, word reading (decoding and word recognition), oral language (vocabulary breadth, morphosyntactic comprehension, and vocabulary depth) also contribute to written ambiguous sentence comprehension and are any of these effects specific to the ASD group?

To address our first research question and simultaneously evaluate context integration and interference, we used the sentences from Norbury (2005). However, rather than presenting a single picture after each sentence, we presented two pictures after each sentence—one representing the dominant meaning and one representing the subordinate meaning for the biased conditions or two neutral pictures in the neutral conditions. Presentation of both of the pictures representing the meanings of the target ambiguous words naturally creates interference, but if participants adequately integrate the context, they should overcome this interference to select the correct meaning.

Comparisons between accuracy performance in the biased-dominant (BD) and biased-subordinate (BS) conditions were made to test for the context integration effect, and comparisons between the biased conditions and their paired neutral conditions were made to evaluate the interference effect. The specific predictions for the context integration effect were that if participants integrated the context, then no differences in performance between the biased-dominant and biased-subordinate conditions (BD = BS) were expected because integrating the context means arriving at the correct meaning each time (assuming both word meanings are known). Alternately, if participants did not integrate the context, then the dominant (higher frequency) meaning should be activated regardless of context, which would result in lower performance on the biased-subordinate condition (BD > BS).

Turning to the specific predictions for the interference effect, if interference occurred when participants were presented with both meanings, then performance in the dominant-neutral (DN) condition would be higher than the biased-dominant condition (DN > BD) and likewise performance in the subordinate-neutral (SN) condition should be higher than performance in the biased-subordinate condition (SN > BS). Alternately, if no interference occurred, performance should not differ for the biased-dominant and dominant neutral conditions (BD = DN), and likewise, biased-subordinate and subordinate-neutral conditions (BS = SN). Crossing the predictions for context integration and interference lead to the predictions in Table 1. If any of these patterns were specific to the ASD group, then we predicted group by condition interactions for these comparisons.

As in previous studies, the hypotheses above are for the sentence comprehension products. For the sentence comprehension processes, our predictions relate to the time spent looking at the target word. According to the subordinate-bias effect, as described above, we predicted that if context integration occurred during comprehension processing, then time spent looking at the target word should be longer in the biased-subordinate condition relative to the subordinate-neutral condition (BS > SN) and the dominant-neutral and biased-dominant conditions should not significantly differ (DN = BD). Alternately, if interference occurs during lexical access, then both biased conditions should have longer looking times relative to their paired neutral conditions (BS > SN and BD > DN). Again, if either pattern is specific to the ASD group, we predicted a group by condition interaction.

In line with the previous studies examining eye movements in ASD, we also predicted longer reading times for the ASD group when reading the context. In addition, we predicted the ASD group would look back from the target to the context (i.e., make more regressions) on more trials than the controls. If participants' eye movements are related to the task demands, we would also expect increased context reading times and regressions in the biased conditions relative to the neutral conditions, and if the biased-subordinate condition was the most difficult condition, we would observe increased context reading times and regressions for this condition specifically.

In comparing children's comprehension products and processes, we predicted based on the results of Henderson and colleagues (2011) that semantic interference would not affect lexical access (determined by looking times at the target word). However, semantic interference may occur later when the meanings have to be recalled and selected during the picture selection portion of the task. The time spent looking at the target word determined interference during the lexical access stage and the comprehension product determined interference during the selection stage.

Following Brock and Caruana's (2014) recommendations, we considered individual differences in our study on written ambiguous sentence comprehension in ASD. Specifically, we examined individual differences in age/development, word reading skills, oral language abilities, and knowledge of ambiguous meanings (vocabulary depth). We predicted that age would account for developmental differences in written ambiguous sentence comprehension because reading more generally develops from 8–14 years. More specifically, context integration has been shown to improve with age in typically developing children (Booth et al., 2006; Khanna & Boland, 2010), in younger children with ASD (Hahn et al., 2015), and in a cross-sectional sample of older children with ASD (Brock et al., 2017). In line with the simple view of reading, we also hypothesized that word reading abilities would predict ambiguous sentence comprehension on a written task. We separately measured word recognition and decoding per the recommendation of Henderson et al. (2014), but we did not have specific predictions about which would be a better predictor. We also expected that vocabulary breadth, morphosyntactic comprehension, and vocabulary depth may all pay a role in ambiguous sentence comprehension, but that vocabulary depth may be the strongest predictor because the sentence comprehension task specifically requires knowledge of both ambiguous word meanings. If any of these effects were specific to the ASD group, then we predicted an interaction between group and the particular effect to be significant.

Method

Participants

Participants who were comparable in age to participants in other studies on reading comprehension and context integration in ASD (ages 8–14 years) were recruited from a larger project upon additional informed parental consent and child assent. The university institutional review board approved both research protocols. The larger project recruited children for both the ASD and control groups through local schools, community centers, or clinics using flyers and website postings. The participants with ASD were also recruited through a research registry at the Waisman Center consisting of families who indicated an interest in having their child participate in research studies. For the current study, when scheduling families for their next visit in the larger project, we provided families with relevant details and asked if their child would be interested in participating in an additional study after their upcoming visit. Families who agreed were recruited and scheduled for the current study.

We excluded participants with known chromosomal abnormalities (e.g., Fragile X syndrome, Down syndrome), cerebral palsy, uncorrected hearing/visual impairments, or other disorders. Control participants were excluded if they had 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, Bailey, & Lord, 2003)) administered during their visit. All participants were monolingual English speakers and passed a standardized pure tone audiometry hearing screening (American Speech-Language-Hearing Association, 1997). Fifty participants met the exclusionary criteria above and were recruited for participation. After data collection, we excluded four additional participants due to technical difficulties with the eye tracker (ASD: $n = 1$), insufficient eye tracking data (ASD: $n = 1$; Control: $n = 1$), and high performance resulting in significant skew for most variables (Control: $n = 1$), which resulted in 46 participants total ($n = 23$ in each group). Both groups were mostly white (ASD: $n = 19$, Control: $n = 20$). Additional participant characteristics are summarized in Table 2.

Participants with ASD previously received either a medical or educational community diagnosis of ASD when entering the study. A licensed psychologist confirmed ASD diagnoses (*Child Autism Rating Scale-Second Edition, High Function form* total raw scores ≥ 25; Schopler et al., 2010) for all participants except one who was included with a score of 24[2]. On the parent-report autism screener (SCQ) none of the control group scores ($M = 3.87$, $SD = 3.29$, Range: 0–16) indicated concern and they were significantly lower than the ASD group's scores ($M = 18.17$, $SD = 6.02$, Range: 9–35), $F(1, 44) = 99.95$, $p < .001$, $\eta^2_G = .694$).

Standardized Measures

A battery of standardized measures was used to evaluate cognition, oral language, and reading. The autism confirmation/screening measures, hearing screening, nonverbal cognition, and oral language measures were administered as part of the larger project protocol. Participants were tested separately after consent and assent were obtained to administer the reading standardized tests and experimental tasks. Nonverbal cognition was assessed using the *Wechsler Intelligence Scale for Children-Fourth Edition* (WISC-IV; Wechsler et al., 2003) Perceptual Reasoning index. Vocabulary comprehension breadth was assessed using the *Peabody Picture Vocabulary Test-Fourth Edition* (PPVT-4; Dunn & Dunn, 2007). Participants completed either Form A or Form B for this study, depending on the respective year they were tested in the larger project. Morphosyntactic comprehension was assessed using the *Test of Oral Language Development, Intermediate Version, Fourth Edition* (TOLD:I-4; Hammill & Newcomer, 2008) Morphological Comprehension subtest, which requires participants to listen to sentences, and then identify them as grammatically

[2]Exclusion of this participant did not change the results of any analyses, except for regressions. Specifically, after excluding this participant, the Group × Condition: BD-BS interaction was no longer significant but trending towards significance. After comparing this participant's mean regressions to the ASD and TD group means by condition, it appears that this participant made more regressions than the average of both groups. We included the participant in all analyses because increased regressions appear to be more common in ASD and this participant fit this feature. However, we cautiously interpret the Group × Condition: BD-BS interaction in these analyses.

correct or incorrect. The *Woodcock-Johnson Reading Mastery Tests, Third Edition (WRMT-III*; Woodcock, 2011) Word Identification subtest evaluated word recognition (i.e., reading familiar words). The WRMT-III Word Attack subtest (i.e., reading nonwords) evaluated word decoding, which assesses the ability to apply phonological knowledge to the pronunciation of unfamiliar words. The WRMT-III Passage Comprehension subtest assessed reading comprehension ability, which requires participants to read a short passage of two to three sentences in length and then identify key information from that passage by saying the word belonging in the blank.

Separate one-way analyses of variance (ANOVAs) and generalized eta-squared effect sizes (η_G^2) (see Bakeman, 2005; Fritz, Morris, & Richler, 2012 for details) were used to evaluate group differences. ASD and control groups did not significantly differ in mean age, socioeconomic status (SES), nonverbal cognition, or morphosyntactic comprehension (see Table 2). The group difference for vocabulary breadth was significant but small. Groups significantly differed for word decoding, word recognition, and passage comprehension (listed in order of increasing effect sizes).

Experimental Tasks

We used two experimental tasks in this study. The first task (Word task) was based on the Norbury (2005) words in isolation task (Experiment 1), which we used as a measure of vocabulary depth, or how well children knew the meanings of the ambiguous words used in this study. The second task (Sentence task) was based on the Norbury (2005) sentences from the suppression condition (Experiment 2) to assess children's ambiguous sentence comprehension. The design and procedure for the ambiguous word and sentence comprehension tasks were analogous. Participants silently read words or sentences while their eye movements were monitored. Participants then determined whether one picture (Word task) or which of two pictures (Sentence task) aligned with the word or sentence meaning. The key difference between each task was that we evaluated participants' comprehension of words in isolation (Word) or with context added prior to the same words (Sentence).

Design—The tasks assessed comprehension of the dominant and subordinate meanings of ambiguous words and unambiguous, neutral words. Adding neutral words confirmed basic understanding of the task and increased item variability to make the nature of task less apparent (Brock & Bzishvili, 2013). Neutral words were paired with each semantic meaning of the ambiguous words. Crossing type of word (ambiguous v. unambiguous, neutral) and meanings (dominant v. subordinate) created four conditions (see examples in Figure 1): biased-dominant (ambiguous word, dominant meaning), biased-subordinate (ambiguous word, subordinate meaning), dominant-neutral (neutral word, paired-dominant meaning), and subordinate-neutral (neutral word, paired-subordinate meaning).

Word and Sentence tasks were presented separately, and each task had 88 items total with 22 items per condition. Trials were presented across conditions and pseudo-randomized so that there were no consecutive appearances of two of the same ambiguous items, three items from the same condition, or three correct responses in a row. Order of presentation for the

Word and Sentence tasks was counterbalanced across participants with some participants receiving the Word task then Sentence task and others receiving the Sentence task then Word task.

In line with Norbury (2005), the correct answer for the biased-dominant and biased-subordinate conditions was always "yes" in the Word task. Rather than present the ambiguous word for a third time as in Norbury (2005), the correct pictures were switched to be incorrect pictures for the dominant-neutral and subordinate-neutral conditions such that for a dominant-neutral word, the participant saw the picture representing the paired subordinate-neutral word and vice-versa. In this way, the pictures did *not* "go with" the presented words, so the correct answer for these two conditions was always "no." In the Sentence task, participants chose between pictures representing the dominant or subordinate meanings in the biased conditions or between pictures representing the neutral items in the neutral conditions.

Stimuli—We used the Norbury (2005) word and sentence stimuli with some adjustments to adapt them from British English to American English (see the supplementary material S1 for a complete account of these changes and to view a list of all stimuli). All ambiguous target words were homonyms. All sentences consisted of the context followed by the target word. In the biased sentences, the verb biased the sentence to lead to the appropriate meaning of the ambiguous target words. In the neutral sentences, the same context as the respective biased condition was presented but with the paired-neutral words.

Norbury (2005) reported ratings for the meaning frequencies of the ambiguous words; however, additional stimuli information such as frequency, age of acquisition, familiarity, and imagery were not reported or analyzed. In order to keep our reading comprehension tasks comparable to the listening comprehension task in Norbury (2005), we did not alter the stimuli beyond the adaptations noted above. Detailed post-hoc analyses of the stimuli are reported in S1. To summarize these comparisons, conditions only differed for imagery (biased-dominant ratings lower than dominant-neutral) and number of characters per word (more characters per word in the subordinate-neutral condition). Given that the difference in number of characters could affect the eye movement data, we chose to control for differences in the number of characters across items (both target words and sentences) by dividing the fixation durations by the number of characters for the given item (a similar approach to van der Schoot et al. (2009)).

The original picture stimuli from Norbury (2005) were not used because the clipart images included additional visual information not pertaining to the stimuli (e.g., the picture of the animal bat contained a picture of the moon in the background). In pilot testing, the original clipart picture stimuli were compared to new photograph picture stimuli. Four adults selected the photograph items ($M = 0.83$, $SD = 0.38$) with slightly higher accuracy than the clipart items ($M = 0.81$, $SD = 0.40$), but the difference was not significant ($t(580.97) = -0.77$, $p = .444$). Given that there was no difference in adults but that children tend to be better at recognizing photographic images (e.g., Simcock & DeLoache, 2006; Tare, Chiong, Ganea, & DeLoache, 2010), we used the photographic images in this study.

Apparatus—The Word and Sentence tasks were presented using E-Prime software (Schneider, Eschman, & Zuccolotto, 2002) via a Tobii T60 XL eye-tracking device (average gaze position: 0.5°; spatial resolution: 0.2°; Tobii, 2010). The Tobii T60 XL does not require a chin rest or other device to reduce head movements, which increases compliance of participants with ASD. The Tobii T60 XL 60 Hz sampling rate is relatively tolerant of head movements, and has been used in previous studies with children with ASD (e.g., Lucas & Norbury, 2013).

Procedure—All stimuli were presented on a 1920 × 1200 pixels resolution screen with a white background. Written stimuli were presented in size 30 black New Courier font. All sentences fit on a single line. Participants viewed the screen from approximately 60 cm, and a 5-point standard calibration and validation procedure was conducted for each task prior to testing. After calibration, participants' eye movements were monitored throughout each task. To begin each task, participants listened to and read the instructions and viewed corresponding example images (see full instructions in Supplementary Material S2). In each task, we familiarized participants with six practice items before beginning the test items.

See Figure 2 for a visual depiction of the trial presentation in each task. For each trial, participants saw the word "Ready?" (2000 ms), and then, a black crosshair (+) appeared in the center of the screen (Word) or 100 pixels from the left edge of the screen (Sentence). When a stable fixation was achieved, the screen automatically advanced to the word/ sentence screen with the target word or first letter of the sentence replacing the crosshair. Participants pushed a button (the "go"-button) on a serial response button box (SRBox) when they were done reading to advance to the image screen (5000 ms maximum display time). For the Word task, a single image was displayed in the center of the screen, and for the Sentence task, two images were displayed equidistance from the right and left edges of the screen (screen side was randomly assigned). After a selection was made via the SRBox (or the screen automatically advanced), the next trial proceeded with no feedback on accuracy.

Accuracy measures—For the word task, accuracy was determined from the participant's response on the SRBox during the picture verification to index vocabulary depth. Similarly, for the sentence task, accuracy was determined from the participant's response on the SRBox during the two-choice picture identification to index the ambiguous sentence comprehension product.

Eye-tracking measures and data extraction—Eye-fixation measures were obtained for two areas of interest (AOI) in each sentence: the context and the target word. First-pass duration (i.e., the sum of all fixations on the target word during first-pass reading divided by the number of non-space characters) measured lexical access. First-pass refers to the participant's initial time spent reading the target word after reading the sentence; if a participant re-read the target word (i.e., moved their gaze out of the target AOI and then back), these fixations were not included. The first-pass duration data were log (base 10; $\log_{10}$) transformed because this transformation best corrected for high skewness and kurtosis. Total gaze duration (i.e., the sum of all fixations in the context divided by the number of non-space characters) measured the time spent reading the context, including both first-pass eye movements and any looks back to the context after reading the target word. The total gaze duration data were square-root transformed because this transformation best corrected for high skewness and kurtosis. Regressions (i.e., whether the participant looked back to the context or not after reading the target word) measured comprehension monitoring, or the participant's awareness that they did not understand. For regressions, trials were coded as a binary variable to capture whether there was (1) or was not (0) a regression on each trial.

For each eye tracking measure, raw data was extracted using a custom-written Python script (Python, 2009) based on the fixations algorithm in Blignaut (2009). Only eye-gaze data with eye-tracker assigned validity codes less than two were included for analysis because only these data points are considered reliably measured by the eye tracker (Tobii, 2010b). Individual fixations were identified if gaze points were within the maximum allowable distance of 50 pixels and if they met an 80 ms minimum or 1000 ms maximum duration criteria. To account for blinks in the raw data, we used a 100 ms per fixation criteria as the allowable dropout duration. In other words, if a participant's raw gaze data was missing for less than 100 ms and their gaze was at the same fixation point afterwards, we counted this as a blink that was classified as a continuation of the fixation before the blink. However, if the duration of missing data was longer than 100 ms or on a different fixation point afterwards, this was classified as a new fixation.

Trials were required to have at least one fixation on the target and one fixation on the context for inclusion in all data analyses. This resulted in 326 (8.1%) excluded trials overall (Control: 174 (8.6%); ASD: 152 (7.5%)). All analyses were run on this filtered dataset. To assess eye data quality, a global measure of the overall number of fixations and fixation duration for each group was compared. Control (raw: $M = 6.60$, $SD = 2.95$, Range: 2–22; square-root transformed: $M = 2.51$, $SD = 0.54$, Range: 1.41–4.69) and ASD (raw: $M = 8.02$, $SD = 4.38$, Range: 2–25; square-root transformed: $M = 2.73$, $SD = 0.74$, Range: 1.41–5.00) groups did not significantly differ in global number of fixations (square-root transformed), $F(1, 44) = 3.07$, $p = .087$, $\eta_G^2 = 0.07$. Control (raw: $M = 1407.97$ ms, $SD = 797.76$ ms, Range: 168–4747 ms; $\log_{10}$-transformed: $M = 3.08$, $SD = 0.24$, Range: 2.23–3.68) and ASD (raw: $M = 1517.12$ ms, $SD = 889.21$ ms, Range: 166–4695 ms; $\log_{10}$-transformed: $M = 3.11$, $SD = 0.25$, Range: 2.22–3.67) groups also did not significantly differ in global fixation duration ($\log_{10}$-transformed), $F(1, 44) = 0.36$, $p = .551$, $\eta_G^2 = 0.01$.

Analysis Approach

Linear mixed-effects models are considered an improvement over traditional analysis of variance (ANOVA) approaches to account for the covariance of participants and items in repeated-measures designs (Barr, Levy, Scheepers, & Tily, 2013; Richter, 2006) as well as evaluate individual variability (Richter, 2006). In addition, generalized linear-mixed effects models using a binomial distribution better model accuracy data (Dixon, 2008). For these reasons, we used linear and generalized-linear mixed effects models as our analysis approach, which have also been used in eye tracking studies with adults with ASD (Au-Yeung et al., 2015; Howard et al., 2017).

Generalized mixed-effects models with a logit link function and binomial distribution for the outcome were fitted using the lme4 package (Bates, Mächler, Bolker, & Walker, 2015, 2016) in R (R Core Team, 2016) with a bobyqa optimizer and maximum iterations set at 500,000 to examine vocabulary depth accuracy and sentence comprehension product accuracy as well as the regressions eye sentence comprehension process measure. To examine the first pass duration and total gaze duration sentence comprehension process measures, linear mixed-effects models with a bobyqa optimizer and maximum iterations set at 500,000 were fitted using the lme4 package. *P*-values were determined using the Satterthwaite approximation from the lmerTest package (Kuznetsova, Brockhoff, & Christensen, 2016) for the linear mixed-effects models and the lme4 summary function from the lme4 package for the generalized-linear models. The intraclass correlation coefficient (ICC) for the random effects of participant and item are reported for all models with values closer to 1 indicating larger effects of participant or item clustering.

Initial models—The random effects structure for each dependent variable was determined using a backward-selection heuristic beginning with the maximal random effects structure and iteratively reducing the random effects structure until a further reduction implied a significant loss in the goodness-of-fit (Matuschek, Kliegl, Vasishth, Baayen, & Bates, 2017). Additional details about this model selection process and the results are in the Supplementary Material S3. The selected models are presented here:

$$\begin{matrix} Vocabulary\ Depth \\ Sentence\ Comprehension\ Product \end{matrix} \quad \begin{matrix} Intecept + Group * Condition + \\ (Condition|Participant) + (1|Item) \end{matrix}$$

$$\begin{matrix} First\ Pass\ Duration \\ Total\ Gaze\ Duration \\ Regressions \end{matrix} \quad \begin{matrix} Intercept + Group * Condition \\ +\ (1|Participant) + (1|Item) \end{matrix}$$

Contrasts for the categorical Group fixed effect were coded using simple coding to test the performance for control (reference group) versus ASD participants. Contrasts for the categorical Condition fixed effect were coded using forward difference coding. Conditions were ordered and coded to compare the dominant-neutral to the biased-dominant condition; this is the Condition: DN-BD contrast effect reported in the analyses. Next, the biased-dominant condition was compared to the biased-subordinate condition (Condition: BD-BS effect), and the biased-subordinate condition was compared to the subordinate-neutral condition (Condition: BS-SN effect). The random-effects term [$(Condition|Participant)$] allows the coefficients for intercept and condition to vary by participant whereas the random-effect term [(1|Participant)] allows the coefficients for intercept to vary by participant. The random-effects term [$(1|Item)$] allows the coefficient for intercept to vary by item.

Additional models—First, the additional variables were simultaneously entered into the sentence comprehension product, first pass duration, total gaze duration, and regressions models described above. Second, we reduced models by retaining fixed effects with significant or trending toward significant (≤ .1) *p*-values[3]. Finally, we tested whether the additional variables were related to group by adding an interaction for relevant fixed effects. The reduced and added group interaction models are presented together as the results between steps did not differ. Age, Word Recognition, Word Decoding, Vocabulary Breadth, and Morphosyntax were all grand mean centered. A missing morphosyntax score for a participant with ASD was replaced by the ASD group mean to include all participants and make the models comparable. Vocabulary Depth was the children's accuracy performance from the Word task, and was entered as a bivariate, categorical variable.

Results

Vocabulary Depth and Sentence Comprehension Product

Table 3 summarizes descriptive data, fit indices, and fixed effect estimates for vocabulary depth and the sentence comprehension product. The ASD and control group did not significantly differ in their accuracy for vocabulary depth. Both groups knew significantly fewer biased-subordinate word meanings relative to the biased-dominant meanings (Condition: BD-BS effect), and similarly, both groups knew significantly fewer of the biased-subordinate meanings relative to the subordinate-neutral words (Condition: BS-SN effect). None of the interaction effects were significant, meaning that these condition effects were similar across both groups.

For sentence comprehension, a significant Group fixed effect showed lower ASD performance than the control group. Both groups performed significantly lower in the biased-dominant condition relative to the dominant-neutral condition (Condition: DN-BD effect), and both groups performed significantly lower in the biased-subordinate condition than the subordinate-neutral condition (Condition: BS-SN effect). The performance in the biased-dominant and biased-subordinate conditions (Condition: BD-BS effect) did not significantly differ. Again, none of the interaction effects were significant, meaning that these condition effects were similar across both groups.

Sentence Comprehension Processes

See Table 4 for descriptive data, fit indices, and fixed effect estimates for all sentence processes (i.e., eye tracking measures). For first-pass durations for the target word, the Condition: BS-SN fixed effect was significant, supporting the subordinate-bias effect of longer looking times in the biased-subordinate condition relative to the subordinate-neutral condition. None of the fixed effects were significant for total gaze durations for the context. For regressions to the context, the group fixed effect was significant, indicating that the ASD group made regressions from the target word to the context on more trials than the control group. A significant Group X Condition: BD-BS interaction indicated that the ASD group made more regressions in the biased-dominant condition than the biased-subordinate condition.

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[3]This approach is similar to the step function in the lmertest package that reduces non-significant effects from models (Kuznetsova et al., 2016). However, because this method cannot be applied to generalized linear models, we applied a more general approach by hand to reduce both linear and generalized linear models.

Additional Variables Explaining Sentence Comprehension

For the sentence comprehension product (Table 5), the full model would not converge, but after removing the Group × Condition interaction, the model was able to converge. Although not ideal, we concluded that this reduction was appropriate given that the interaction was not significant in the original model, and the original model did not significantly differ from a model without the interaction in a model comparison, $\chi^2(3) = 2.44$, $p = .487$. Similar to the original model, the Group, Condition: DN-BD, and Condition: BS-SN fixed effects all remained significant. In addition, the Age and Vocabulary Depth fixed effects were significant and the Word Recognition effect was trending toward significance. When the model was reduced, Age was a significant fixed effect, suggesting that children's sentence comprehension improves with age. The Word Recognition fixed effect was also significant, meaning that children's sentence comprehension improved with higher word reading. Finally, the Vocabulary Depth fixed effect was significant, indicating that the better children's comprehension of the words at the single-word level, the better their comprehension at the sentence level. An interaction with group was initially added for both Word Recognition and Vocabulary Depth, but the model would not converge with the Group × Word Recognition interaction; therefore, only the Group × Vocabulary Depth interaction was entered. This interaction was trending toward significance, suggesting that vocabulary depth may have contributed more to the ASD group's sentence comprehension products than the control group. These significant effects for the sentence comprehension product are depicted in Figure 3.

For the sentence comprehension processes, the additional variable model results are provided in Table 6 and the reduced with group interactions model results are in Table 7. For first pass duration, the Condition: BS-SN fixed effect remained significant, the Vocabulary Breadth fixed effect was significant and the Age fixed effect trended towards significance. In the reduced model, Condition: BS-SN and Vocabulary Breadth were the only two significant fixed effects. When Group × Vocabulary Breadth was added to the model, the interaction was not significant. These results suggest that both groups were sensitive to the subordinate-bias effect, and across both groups and all conditions, time spent looking at the target word decreased slightly as vocabulary breadth abilities improved.

For total gaze duration, only Vocabulary Breadth trended toward significance when all variables were entered into the model. When the model was reduced, Vocabulary Breadth remained a significant fixed effect and did not interact with group. Similar to the first pass durations, time spent looking at the context also slightly decreased as vocabulary breadth abilities improved.

Lastly, when the additional variables were added to the regressions model, the original Group and Group × Condition: BD-BS fixed effects remained significant. In addition, Vocabulary Depth was a significant fixed effect. These effects remained significant in the reduced model, but the Group fixed effect was no longer significant when the Group × Vocabulary Depth interaction, which was not significant, was added. Based on this final model, if the child knew the word meaning, the less likely they were to make a regression back to the context. Yet, the ASD group made more regressions in the biased-dominant condition relative to the biased-subordinate condition than the control group.

Discussion

This study examined ambiguous sentence comprehension in children (ages 8–14 years) with ASD and their typically developing peers. To build upon the previous literature, we used a written rather than listening sentence comprehension task, simultaneously evaluated integration and semantic interference, assessed both comprehension products and processes, and determined the contributions of individual differences in age/development, word reading (word recognition and decoding), and oral language (vocabulary breadth, vocabulary depth, and morphosyntactic comprehension). Our results confirm the involvement of a collective set of skills necessary for context integration in both children with ASD and their peers.

For the sentence comprehension product, the ASD group performed significantly worse than the control group. Both groups performed worse in the biased-dominant and biased-subordinate condition relative to their respective neutral conditions, but performance did not differ between the biased-dominant and biased-subordinate conditions in either group. This result aligns with prediction A in Table 1, meaning that participants were integrating the context but semantic interference occurred during picture selection. Contrary to predictions, this same pattern occurred for both groups and was not specific to the ASD group. Although both groups were affected by the interference, the ASD group was impacted to a greater degree, resulting in their lower performance in the biased conditions relative to their peers.

Our interpretation for the sentence comprehension product that the participants were integrating the context is further supported by the first pass duration sentence comprehension process results. In both groups, we found the expected subordinate bias effect where the preceding context lead to competition between the subordinate and dominant meanings relative to the subordinate control condition. Therefore, this further supports that the participants with ASD were integrating the context while reading the sentences, but did not experience interference during this lexical access stage. However, as previously discussed, both groups experienced interference when we assessed the comprehension product during the picture selection stage. This comparison of the comprehension products and processes aligns with the results of Henderson et al. (2011) who found that that their participants with ASD displayed intact processing of homonyms during the lexical access stage, but increased semantic interference during the selection stage of semantic processing.

In addition to the effects described above, individual differences in age, word recognition, and vocabulary depth contributed to the sentence comprehension product. Older children were more likely to have better sentence comprehension products than younger children. Higher word recognition and vocabulary depth also improved children's sentence comprehension product.

The role of age reflects developmental changes in ambiguous sentence comprehension, which could be related to changes in any number of factors, including advances in word reading, oral language, or even interference, that all continue to develop during this age range. Development in ambiguous sentence comprehension aligns with previous studies of children with ASD (Brock et al., 2017; Hahn et al., 2015) and typically developing school-age children (Khanna & Boland, 2010). The goal of this study was not to examine these developmental effects, but based on this evidence, future studies should characterize these potential developmental changes.

The word recognition effect in the ambiguous sentence comprehension product was small, but significant. The small effect may reflect that children in this study did not have severe impairments in word recognition (all children's standard scores ≥ 80). That being said, even slight word reading deficits constrained sentence comprehension in this study as implied in the simple view of reading (Gough & Tunmer, 1986; Hoover & Gough, 1990). This result differs from the non-significant effect of word reading in Brock et al. (2017), but may be related to differences in English-speaking/reading versus Hebrew-speaking/reading participants and the inclusion of lower readers in the current study. Although word recognition was a significant predictor, we cannot directly conclude that word reading abilities account for the differences in findings across listening and written context integration tasks described in the introduction because this would require a more direct comparison of comparable tasks in each modality. Nonetheless, our finding that word recognition abilities contributed to performance on a written context integration task underscores the importance of accounting for word reading abilities in written comprehension abilities in ASD.

Finally, as López and Leekam (2003) predicted, whether or not participants knew the meanings of the words on an individual differences level contributed to their sentence comprehension products. Based on performance in the word comprehension task, we know that the ASD and control groups did not significantly differ but that both groups knew fewer subordinate word meanings. Therefore, we can interpret the word comprehension effect as indicating that more subordinate word meanings known, or deeper vocabulary knowledge, allowed for better context integration because to arrive at the correct meaning, the meaning itself must first be known. Similarly, richer vocabularies meant that participants were more likely to overcome interference. There was a nonsignificant trend that vocabulary depth was more likely to contribute to sentence comprehension in the ASD group than the controls.

Time spent looking at the context (i.e., total gaze duration) did not differ between groups or conditions on average, but there was a tremendous amount of individual variability overall. These results suggest that readers who spent more time reading the context appeared to do so consistently across items, and that there were "cautious readers" in both groups. This result is contrary to previous studies showing generally longer reading times in individuals with ASD relative to their peers (Au-Yeung et al., 2015; Howard et al., 2017; Sansosti et al., 2013). One explanation for this difference is that participants with poor word reading abilities were included in the sample (Sansosti et al., 2013). Another explanation is that this study examined comprehension in school-age children and the other studies assessed comprehension processes in adults (Au-Yeung et al., 2015; Howard et al., 2017). The age differences between these studies could reflect a developmental shift where school-age children with ASD do not differ from their peers, but if adults with ASD continue to use a "cautious reading strategy" this may distinguish them from other adults.

Vocabulary breadth was the only individual differences measure to account for some of the variability in time spent reading the context. Similarly, vocabulary breadth was the only individual differences measure to contribute to time spent looking at the target (i.e., first pass durations). Vocabulary breadth contributed to time spent reading the context and target for comprehension in both the ASD and control groups. The role of vocabulary breadth in accounting for individual differences in time spent reading the sentences for comprehension is consistent with the reading comprehension literature demonstrating that vocabulary knowledge considerably contributes to better reading comprehension (Adlof et al., 2010; Kendeou, van den Broek, White, & Lynch, 2009; Oakhill et al., 2003; Quinn, Wagner, Petscher, & Lopez, 2015; Tannenbaum, Torgesen, & Wagner, 2006; Verhoeven & van Leeuwe, 2008). In the case of these reading processes measures, the effect suggests that as children's vocabulary knowledge increased, they spent slightly less time reading the context and target. This reflects the contribution of oral language abilities in reading comprehension in that children with higher vocabularies, or more words in their vocabularies, need less time to process the sentences and have quicker access to word meanings.

Previous studies examining eye movements in ASD have found increased regressions in the ASD group that were not clearly related to the task demands (Au-Yeung et al., 2015; Sansosti et al., 2013), increased regressions related to the task demands (Micai et al., in press), and no increased regressions (Howard et al., 2017). Unfortunately, the results of our study do not help to clarify what is leading to differences in regressions. In this study, vocabulary depth significantly accounted for individual variability in regressions, and the ASD group made more regressions in the biased-dominant than biased-subordinate condition. On the surface, this result suggests that the ASD group evaluated their understanding of the sentence to identify and repair misunderstandings, which conflicts with the finding that poor comprehenders were poorer at monitoring their comprehension (van der Schoot et al., 2009). However, it is surprising that participants with ASD made more regressions on the biased-dominant condition than the biased-subordinate condition and that this effect remained significant even after accounting for vocabulary depth. Neither biased condition differed from the respective neutral conditions, implying that dominant (presumably easier) conditions had more regressions than the subordinate (presumably harder) conditions. Assuming regressions indicate comprehension monitoring, this suggests that the ASD participants better monitored their comprehension in the easier rather than harder conditions. Although this seems counterintuitive, it might suggest that participants with ASD were better able to monitor their comprehension (i.e., recognize that a comprehension failure had occurred) if comprehension was less demanding. In other words, the more a participant understood the sentence in the first place, the better able they were to monitor their comprehension of the ambiguous target word. However, this interaction effect was slightly unstable and should be interpreted cautiously.

Word decoding and morphosyntactic comprehension did not account for individual differences for the sentence comprehension product or processes. Previous studies have shown that word decoding and morphosyntactic comprehension contribute to reading comprehension in both children with ASD and typical development (Adlof et al., 2010; Catts et al., 1999; Cronin, 2014; Jacobs & Richdale, 2013; Nation et al., 2004; Ricketts et al., 2013). All of these studies, however, used standardized tests to measure reading comprehension. The texts in these tests differ in meaningful ways from the stimuli in the current study to explain the difference in results: the sentences in the current study were simple both in terms of word forms and sentence construction. Therefore, children could rely on word recognition abilities and foundational morphosyntactic knowledge to comprehend the sentences.

Strengths of this study include examination of *both* comprehension products and processes as well as an individual differences analysis approach. One limitation was that orthographic stimuli features (e.g., spelling regularity) were not controlled, which may be important in future studies given the contribution of word recognition to reading comprehension in the present study. Other stimuli characteristics (e.g., length in characters and imagery) should also be more carefully controlled. Additionally, future studies should consider manipulating the context to appear before and after the ambiguous word (as is often done in studies using written tasks for context integration), which will allow comparison of how individuals read and re-read the sentence by target location (beginning versus end of sentence). This may help determine potential processes underlying increased regressions in ASD. Finally, directly comparing listening *and* reading comprehension context integration tasks in the future would further elucidate modality (listening versus written) differences, and more specifically, determine the role of word reading abilities.

In summary, children with ASD, similar to their TD peers, integrated the context to access the correct homonym meanings while reading. After reading the sentences, when participants were asked to select the meanings, both groups experienced semantic interference between the two meanings. This semantic interference hindered the children with ASD's sentence representation to a greater degree than their peers, similar to a previous study using a listening comprehension task (Henderson et al., 2011). Individual differences in age/development, word recognition, vocabulary breadth, and vocabulary depth contributed to sentence comprehension in both children with ASD and their peers.

Together, this evidence supports a multi-component view that a collective set of skills is necessary for context integration, and reinforces the role of word reading and oral language abilities in reading comprehension as specified in the simple view of reading. One possible clinical and educational implication is that it is important to assess many components supporting reading comprehension to determine how a child's individual characteristics contribute to their reading comprehension difficulties. A second possible clinical and educational implication is that helping children with ASD develop vocabulary depth may have cascading effects on their comprehension.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Lay Summary

Like their peers, children with ASD were able to integrate context, or link words *while* reading sentences with ambiguous words (words with two meanings). *After* reading the sentences, both groups found it hard to pick the correct meaning of the ambiguous sentence and this decision was more difficult for the participants with ASD. Older children, children with better word reading abilities, and children with higher vocabularies were better at understanding ambiguous sentences. Helping children with ASD to develop richer vocabularies could be important for improving their reading comprehension.

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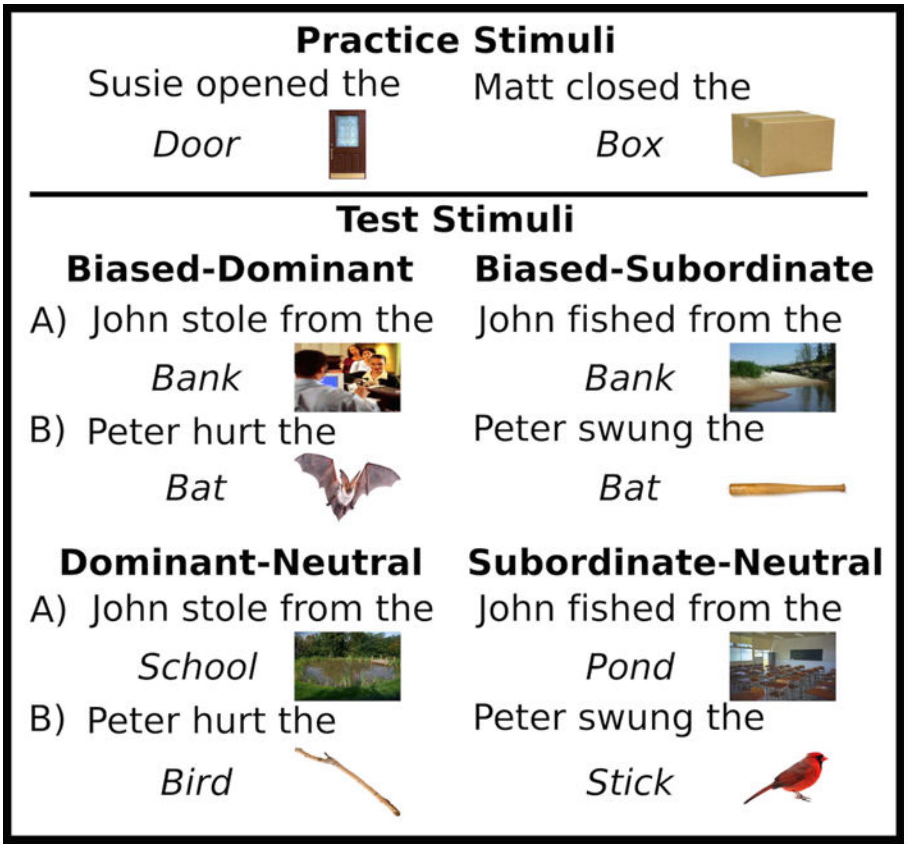

Figure 1.

Examples of practice and test stimuli for the word and sentence comprehension tasks presented by condition with the disambiguating region (top), target word (italicized), and image for the word comprehension task (both image pairs were presented in the sentence comprehension task). A complete stimuli list is in Supplementary Material S1.

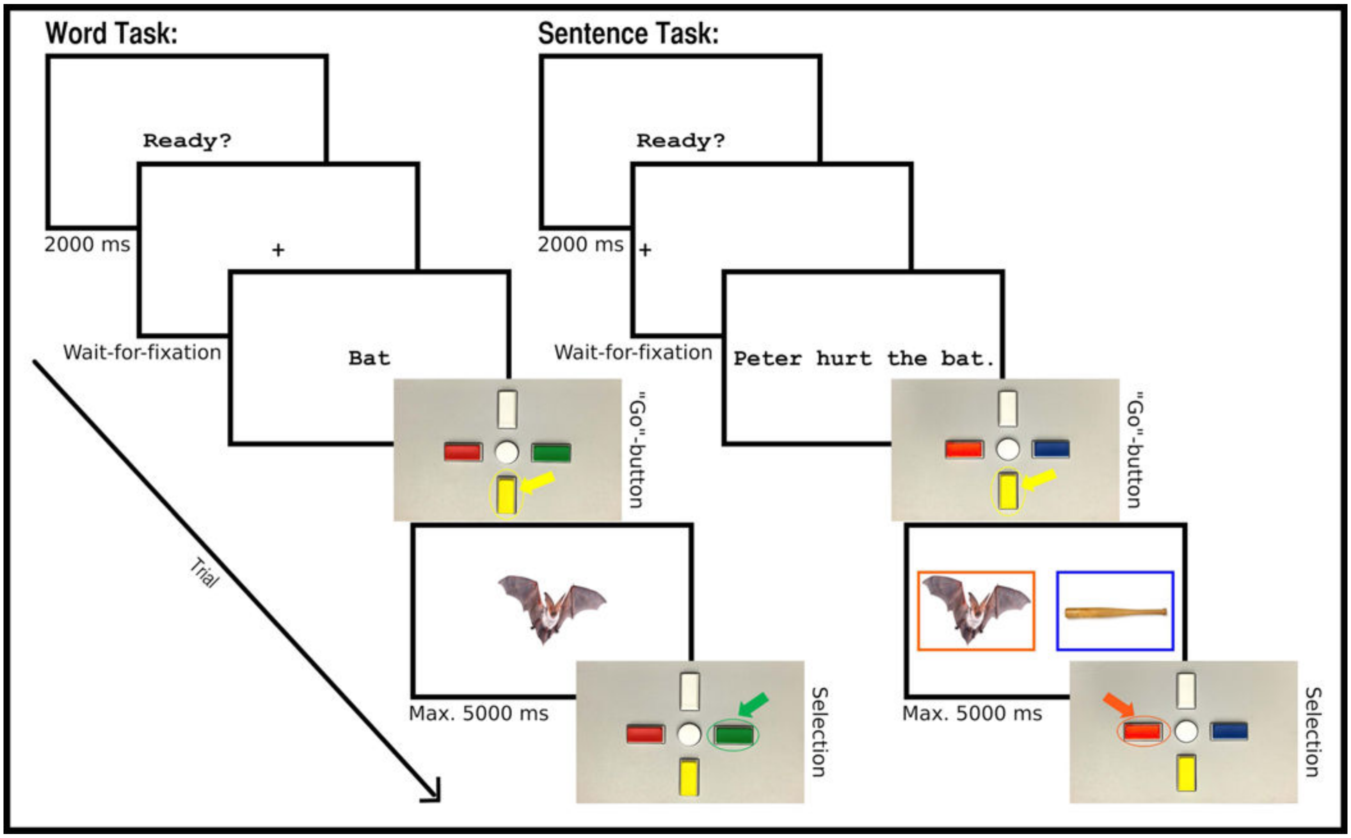

Figure 2.
Schematic of the word comprehension (lower diagonal) and sentence comprehension (upper diagonal) trials. Items in black squares were presented on the eye tracker screen. Serial-response button box (SRBox) images depict the selection choices for participants.

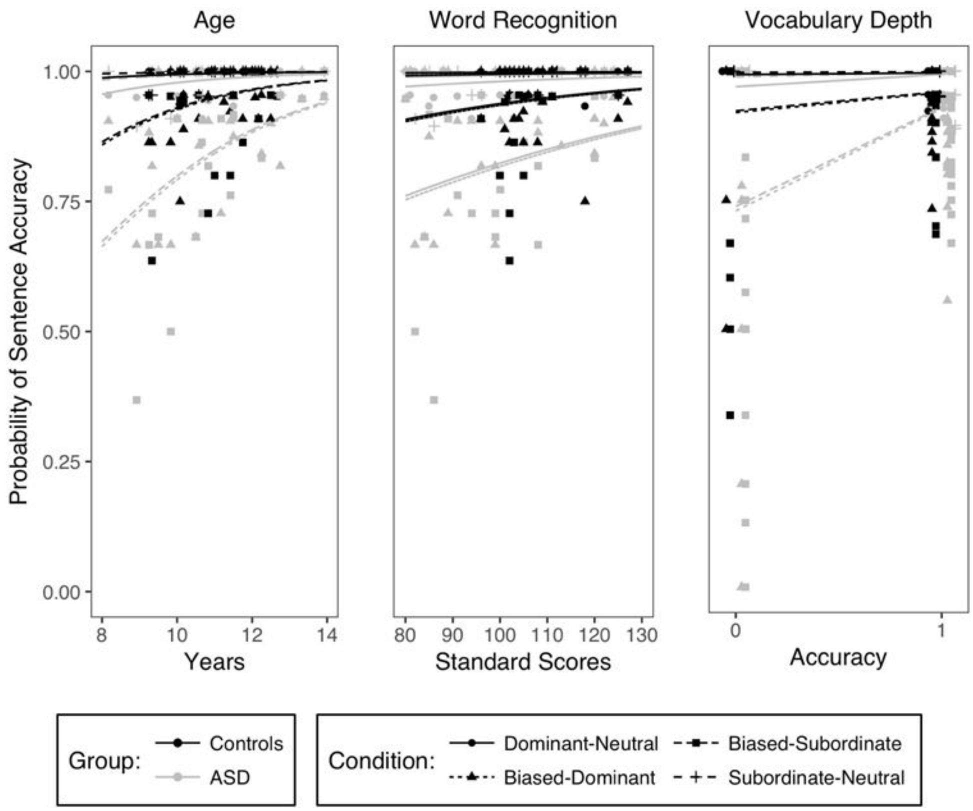

Figure 3.

Participant performance (points) by Age, Word Recognition, and Vocabulary Depth for Sentence Comprehension with the final model fixed effects predictions (lines) overlaid. Age and word recognition points are for each participant, and Vocabulary Depth points are for participant by item.

Table 1

Predictions for sentence comprehension products based on whether participants are integrating context, experiencing interference, both, or neither.

		Interference			
		Yes		No	
Integration	Yes	A)	• DN > BD • BD = BS • SN > BS	B)	• DN = BD • BD = BS • SN = BS
	No	C)	• DN > BD • BD > BS • SN > BS	D)	• DN = BD • BD > BS • SN = BS

Note. DN = Dominant-Neutral; BD = Biased-Dominant; BS = Biased-Subordinate; SN = Subordinate-Neutral.

Table 2

Participant characteristics and group comparisons.

	Control (*n* = 23; 13 males)			ASD (*n* = 23; 19 males)			Group Comparisons			
	M	***SD***	**Range**	***M***	***SD***	**Range**	***DF***	***F***	***p***	η_G^2
Age	11.07	1.01	9.25–12.67	11.07	1.57	8.17–13.92	(1, 44)	<0.01	.986	0
SES[a]	16.64	2.94	12–22	15.91	2.98	12–24	(1, 43)	0.67	.417	.015
Nonverbal Cognition[b]	114.22	10.14	94–135	107.57	14.68	86–137	(1, 44)	3.20	.081	.068
Morphosyntax[c]	10.96	3.39	5–16	9.50	3.22	5–16	(1, 43)	2.18	.147	.048
Vocabulary Breadth[d]	118.61	16.18	97–150	107.39	19.45	81–147	(1, 44)	4.52	.039	.093
Word Decoding[e]	103.43	12.07	86–132	92.00	14.85	73–122	(1, 44)	8.22	.006	.157
Word Recognition[f]	108.87	8.75	96–127	99.00	14.03	80–124	(1, 44)	8.20	.006	.157
Passage Comprehension[g]	116.30	12.53	91–134	95.96	15.75	68–126	(1, 44)	23.50	<.001	.348

Note. ASD = autism spectrum disorder; DF = Degrees of Freedom;

[a]Socioeconomic status based on mother's years of education (1 Control participant missing; *n* = 22);

[b]*Wechsler Intelligence Scale for Children-Fourth Edition (WISC-IV*) Perceptual Reasoning index scores;

[c]*Test of Oral Language Development,, Intermediate Version, Fourth Edition* (TOLD:I-4) Morphological Comprehension subtest scaled scores (1 ASD participant missing; *n* = 22);

[d]*Peabody Picture Vocabulary Test, Fourth Edition* (PPVT-4) standard scores;

[e]Woodcock Reading Mastery Test, Third Edition (WRMT-III) Word Attack standard scores;

[f]WRMT-III Word Identification standard scores;

[g]WRMT-III Passage Comprehension standard scores.

Table 3

Descriptive data for group by condition and model parameters for word and sentence comprehension products.

			Word				Sentence			
Group	**Condition**	***n* trials**	***M***	***SD***	**Range**		***M***	***SD***	**Range**	
Control	Dominant-Neutral	464	0.98	0.13	0–1		1.00	0.07	0–1	
	Biased-Dominant	458	0.94	0.23	0–1		0.93	0.25	0–1	
	Biased-Subordinate	463	0.90	0.30	0–1		0.93	0.26	0–1	
	Subordinate-Neutral	465	0.98	0.15	0–1		0.99	0.09	0–1	
ASD	Dominant-Neutral	470	0.96	0.20	0–1		0.98	0.14	0–1	
	Biased-Dominant	467	0.91	0.28	0–1		0.86	0.35	0–1	
	Biased-Subordinate	468	0.81	0.40	0–1		0.82	0.38	0–1	
	Subordinate-Neutral	467	0.97	0.16	0–1		0.99	0.11	0–1	
Fixed Effects			β	*SE*	*z*	*p*	β	*SE*	*z*	*p*
Intercept			3.86	0.25	15.30	< .001	4.54	0.33	13.73	<.001
Group-ASD			−0.59	0.36	−1.67	.095	−1.06	0.41	−2.60	.009
Condition: DN-BD			1.14	0.66	1.73	.084	2.69	0.69	3.90	<.001
Condition: BD-BS			1.18	0.45	2.60	.009	−0.11	0.49	−0.22	.825
Condition: BS-SN			−1.77	0.50	−3.51	<.001	−3.59	0.86	−4.17	<.001
Group-ASD × Condition: DN-BD			−0.70	0.78	−0.90	.367	−0.70	0.88	−0.80	.426
Group-ASD × Condition: BD-BS			0.63	0.42	1.51	.132	0.34	0.45	0.76	.448
Group-ASD × Condition: BS-SN			−0.61	0.60	−1.01	.311	−0.96	0.76	−1.26	.207
Fit Indexes										
Participant ICC			0.17				0.15			
Item ICC			0.22				0.28			
Deviance			1470.6				1311.2			
AIC			1508.6				1349.2			
BIC			1626.8				1467.5			

Note. ASD = autism spectrum disorder; DN = dominant-neutral; BD = biased-dominant; BS = biased-subordinate; SN = subordinate-neutral; ICC = intra-class correlation; AIC = Akaike’s Information Criteria; BIC = Bayes Information Criteria. The variance components table is located in Supplementary Material S4.

Table 4

Descriptive data for group by condition and model parameters for the sentence comprehension processes: first pass duration, total gaze duration, and regressions.

			First Pass Duration[1]				Total Gaze Duration[2]				Regressions			
Group	**Condition**	***n* trials**	***M***	***SD***	**Range**		***M***	***SD***	**Range**		***M***	***SD***	**Range**	
Control	Dominant-Neutral	464	1.76	0.31	1.07–2.78		8.39	2.50	2.43–16.32		0.63	0.48	0–1	
	Biased-Dominant	458	1.82	0.32	1.07–2.83		8.40	2.62	2.15–17.69		0.59	0.49	0–1	
	Biased-Subordinate	463	1.81	0.31	1.07–2.82		8.15	2.57	2.35–16.58		0.60	0.49	0–1	
	Subordinate-Neutral	465	1.74	0.32	1.01–2.91		8.05	2.46	2.34–16.41		0.65	0.48	0–1	
ASD	Dominant-Neutral	470	1.75	0.28	1.15–2.74		8.70	2.95	2.16–18.53		0.77	0.42	0–1	
	Biased-Dominant	467	1.80	0.30	1.08–2.90		8.79	3.04	2.36–17.32		0.76	0.43	0–1	
	Biased-Subordinate	468	1.83	0.31	1.07–2.83		8.35	2.90	2.42–17.41		0.70	0.46	0–1	
	Subordinate-Neutral	467	1.77	0.32	1.02–2.83		8.33	2.87	2.22–16.08		0.70	0.46	0–1	
Fixed Effects			β	*SE*	*t*	*p*	β	*SE*	*t*	*p*	β	*SE*	*z*	*p*
Intercept			1.78	0.03	60.86	<.001	8.31	0.27	31.10	<.001	0.84	0.13	6.70	<.001
Group-ASD			0.02	0.05	0.32	.749	0.32	0.52	0.61	.546	0.64	0.24	2.62	.009
Condition: DN-BD			−0.05	0.03	−1.63	.107	−0.05	0.20	−0.25	.806	0.14	0.14	1.01	.312
Condition: BD-BS			−0.01	0.03	−0.34	.738	0.33	0.20	1.66	.102	0.14	0.14	1.00	.317
Condition: BS-SN			0.07	0.03	2.10	.039	0.07	0.20	0.36	.722	−0.11	0.13	−0.79	.428
Group-ASD × Condition: DN-BD			0.01	0.02	0.41	.682	−0.08	0.19	−0.39	.695	−0.10	0.22	−0.48	.635
Group-ASD × Condition: BD-BS			−0.03	0.02	−1.35	.178	0.27	0.19	1.41	.159	0.42	0.21	2.00	.045
Group-ASD × Condition: BS-SN			−0.02	0.02	−0.81	.421	−0.09	0.19	−0.47	.640	0.23	0.21	1.08	.280
Fit Indexes														
Participant ICC			0.34				0.40				0.15			
Item ICC			0.10				0.04				0.02			
Deviance			45.3				16299.5				4325.0			
AIC			67.3				16321.5				4345.0			
BIC			135.7				16389.9				4407.2			

Note. ASD = autism spectrum disorder; DN = dominant-neutral; BD = biased-dominant; BS = biased-subordinate; SN = subordinate-neutral; ICC = intra-class correlation; AIC = Akaike's Information Criteria; BIC = Bayes Information Criteria;

[1] Log (base 10)-transformed values reported;

[2] Square-root transformed values reported. Tables for the variance components are located in Supplementary Material S4.

Table 5

Sentence comprehension product additional variables models parameters.

	All Additional Variables				Reduced Variables with Group Interactions			
Fixed Effects	β	*SE*	*z*	*p*	β	*SE*	*z*	*p*
Intercept	3.30	0.38	8.60	< .001	3.46	0.40	8.75	<.001
Group-ASD	−0.77	0.25	−3.01	.003	−1.55	0.49	−3.17	.002
Condition1: DN-BD	2.59	0.70	3.71	<.001	2.61	0.69	3.76	<.001
Condition2: BD-BS	−0.03	0.47	−0.07	.946	−0.05	0.47	−0.10	.918
Condition3: BS-SN	−3.70	0.94	−3.94	<.001	−3.60	0.91	−3.94	<.001
Age	0.41	0.10	4.26	<.001	0.38	0.09	4.26	<.001
Word Recognition	0.04	0.02	1.64	.101	0.02	0.01	2.21	.027
Word Decoding	−0.01	0.01	−0.54	.590	–	–	–	–
Vocabulary Breadth	−0.01	0.01	−0.58	.564	–	–	–	–
Morphosyntax	<0.01	0.04	0.02	.987	–	–	–	–
Vocabulary Depth	1.40	0.23	6.06	<.001	1.19	0.26	4.51	<.001
Group × Vocabulary Depth	–	–	–	–	0.94	0.49	1.92	.054
Fit Indexes								
Participant ICC	0.06				0.05			
Item ICC	0.30				0.30			
Deviance	1253.1				1249.8			
AIC	1297.1				1289.8			
BIC	1434.0				1414.2			

Note. ASD = autism spectrum disorder; DN = dominant-neutral; BD = biased-dominant;BS = biased-subordinate; SN = subordinate-neutral; ICC = intra-class correlation; AIC = Akaike's Information Criteria; BIC = Bayes Information Criteria. Age, Word Recognition, Decoding, Vocabulary, and Morphosyntax were grand mean centered. The variance components table is located in Supplementary Material S4.

Table 6

Sentence comprehension processes (first pass duration, total gaze duration, and regressions) additional variables models parameters.

	First Pass Duration[1]				Total Gaze Duration[2]				Regressions			
Fixed Effects	β	*SE*	*t*	*p*	β	*SE*	*t*	*p*	β	*SE*	*z*	*p*
Intercept	1.775	0.028	64.43	<.001	8.38	0.27	31.30	<.001	1.17	0.20	5.95	<.001
Group-ASD	−0.069	0.044	−1.56	.125	−0.35	0.49	−0.71	.481	0.57	0.26	2.17	.030
Condition: DN-BD	0.052	0.032	−1.64	.106	−0.05	0.20	−0.23	.816	0.15	0.14	1.13	.259
Condition: BD-BS	−0.011	0.032	−0.34	.734	0.33	0.20	1.68	.097	0.16	0.13	1.20	.231
Condition: BS-SN	0.067	0.032	2.10	.038	0.06	0.20	0.32	.750	−0.15	0.13	−1.11	.267
Age	−0.029	0.017	−1.70	.096	−0.14	0.19	−0.74	.464	0.03	0.10	0.34	.733
Word Recognition	−0.026	0.040	−0.67	.509	0.03	0.04	0.59	.556	0.03	0.02	1.13	.258
Word Decoding	−0.010	0.024	−0.42	.677	−0.04	0.03	−1.47	.149	−0.02	0.01	−1.62	.105
Vocabulary Breadth	−0.046	0.022	−2.05	.046	−0.05	0.02	−1.84	.073	−0.01	0.01	−0.56	.577
Morphosyntax	0.002	0.008	0.24	.815	0.03	0.09	0.31	.760	0.02	0.05	0.43	.670
Vocabulary Depth	0.003	0.017	0.21	.836	−0.06	0.15	−0.38	.707	−0.35	0.16	−2.13	.033
Group-ASD × Condition: DN-BD	0.009	0.022	0.41	.684	−0.08	0.19	−0.39	.695	−0.10	0.22	−0.48	.635
Group-ASD × Condition: BD-BS	−0.029	0.022	−1.36	.176	0.28	0.19	1.43	.154	0.44	0.21	2.08	.038
Group-ASD × Condition: BS-SN	−0.017	0.022	−0.80	.426	−0.10	0.19	−0.50	.620	0.20	0.21	0.96	.337
Fit Indexes												
Participant ICC	0.22				0.32				0.15			
Item ICC	0.12				0.05				0.02			
Deviance	17.2				16284.2				4317.7			
AIC	51.2				16318.2				4349.7			
BIC	157.0				16424.0				4449.3			

Note. ASD = autism spectrum disorder; DN = dominant-neutral; BD = biased-dominant; BS = biased-subordinate; SB = subordinate-neutral; ICC = intra-class correlation; AIC = Akaike’s Information Criteria; BIC = Bayes Information Criteria;

[1]Log (base 10)-transformed values reported;

[2]Square-root transformed values reported. Tables for the variance components are located in Supplementary Material S4.

Table 7

Sentence comprehension processes (first pass duration, total gaze duration, and regressions) reduced additional variables with group interactions model parameters.

	First Pass Duration[1]				Total Gaze Duration[2]				Regressions			
Fixed Effects	β	*SE*	*t*	*p*	β	*SE*	*t*	*p*	β	*SE*	*z*	*p*
Intercept	1.784	0.024	74.87	<.001	8.35	0.25	33.70	<.001	1.18	0.20	5.91	<.001
Group-ASD	−0.056	0.043	−1.30	.200	−0.23	0.48	−0.49	.628	0.44	0.39	1.14	.256
Condition: DN-BD	−0.052	0.032	−1.63	.107	0.05	0.20	−0.24	.808	0.15	0.14	1.14	.255
Condition: BD-BS	−0.011	0.032	−0.33	.740	0.33	0.20	1.66	.101	0.16	0.13	1.18	.238
Condition: BS-SN	0.067	0.032	2.09	.039	0.07	0.20	0.36	.723	−0.15	0.13	−1.10	.273
Age	−0.026	0.016	−1.62	.112	–	–	–	–	–	–	–	–
Word Recognition	–	–	–	–	–	–	–	–	–	–	–	–
Word Decoding	–	–	–	–	–	–	–	–	–	–	–	–
Vocabulary	−0.006	0.001	−5.35	<.001	−0.05	0.01	−3.69	<.001	–	–	–	–
Morphosyntax	–	–	–	–	–	–	–	–	–	–	–	–
Vocabulary Depth	–	–	–	–	–	–	–	–	−0.36	0.17	−2.19	.028
Group-ASD × Condition: DN-BD	0.009	0.022	0.41	.685	−0.08	0.19	−0.40	.692	−0.11	0.22	−0.52	.606
Group-ASD × Condition: BD-BS	−0.029	0.022	−1.35	.179	0.27	0.19	1.41	.158	0.43	0.21	2.01	.044
Group-ASD × Condition: BS-SN	−0.017	0.021	−0.81	.417	−0.09	0.19	−0.47	.638	0.23	0.21	1.06	.291
Group-ASD × Vocabulary Breadth	0.002	0.002	0.73	.472	0.01	0.03	0.34	.739	–	–	–	–
Group-ASD × Vocabulary Depth	–	–	–	–	–	–	–	–	0.20	0.32	0.61	.544
Fit Indexes												
Participant ICC	0.22				0.34				0.16			
Item ICC	0.12				0.05				0.02			
Deviance	18.2				16288.0				4320.3			
AIC	46.2				16313.5				4344.0			
BIC	133.3				16394.4				4418.6			

Note. ASD = autism spectrum disorder; DN = dominant-neutral; BD = biased-dominant; BS = biased-subordinate condition; SN = subordinate-neutral; ICC = intra-class correlation; AIC = Akaike's Information Criteria; BIC = Bayes Information Criteria;

[1] Log (base 10)-transformed values reported;

[2] Square-root transformed values reported. Tables for the variance components are located in Supplementary Material S4.