RESEARCH ARTICLE

Discourse Comprehension in Autism Spectrum Disorder: Effects of Working Memory Load and Common Ground

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Pragmatic language impairments are nearly universal in autism spectrum disorders (ASD). Discourse requires that we monitor information that is shared or mutually known, called "common ground." While many studies have examined the role of Theory of Mind (ToM) in such impairments, few have examined working memory (WM). Common ground impairments in ASD could reflect limitations in both WM and ToM. This study explored common ground use in youth ages 8–17 years with high-functioning ASD ($n = 13$) and typical development ($n = 22$); groups did not differ on age, gender, IQ, or standardized language. We tracked participants' eye movements while they performed a discourse task in which some information was known only to the participant (e.g., was privileged; a manipulation of ToM). In addition, the amount of privileged information varied (a manipulation of WM). All participants were slower to fixate the target when considering privileged information, and this effect was greatest during high WM load trials. Further, the ASD group was more likely to fixate competing (non-target) shapes. Predictors of fixation patterns included ASD symptomatology, language ability, ToM, and WM. Groups did not differ in ToM. Individuals with better WM fixated the target more rapidly, suggesting an association between WM capacity and efficient discourse. In addition to ToM knowledge, WM capacity constrains common ground representation and impacts pragmatic skills in ASD. Social impairments in ASD are thus associated with WM capacity, such that deficits in domain-general, nonsocial processes such as WM exert an influence during complex social interactions. ***Autism Res*** *2016, 9: 1340–1352.*

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As individuals engage in conversation they develop and continuously update a representation of "common ground" [Clark, 1992; Glucksberg, Krauss, & Higgins, 1975; Krauss & Fussell, 1991]. Common ground knowledge may encompass both long-held information, such as the fact that someone has a toddler, or new information revealed during the course of a conversation, such as the fact that this toddler just learned to climb stairs. Common ground is incorporated seamlessly into conversations; the concept reflects discourse principles suggesting that a speaker will provide information, but avoid redundancy [Grice, 1975].

Referential communication—referring to objects and events—relies on the ability to maintain and update such common ground representations. There are significant individual differences in the ability to monitor conversational [Harris, 1996] and visual [Farrant, Fletcher, & Maybery, 2006] perspective during communication. Tracking common ground involves making inferences about the knowledge of conversational partners; this ability likely depends in part on theory of mind [ToM; that is, the ability to attribute mental states to others; Baron-Cohen, 1991]. Referential communication, and discourse more generally, also require a speaker to inhibit her *own* perspective and to continuously update her representation of her interlocutor's perspective; executive function abilities, including inhibition and working memory (WM), undergird the allocation of attentional and cognitive resources, and may be relevant to these discourse processes. The goal of this eyetracking study was to determine whether individual differences in discourse were driven by ToM or by WM constraints, by assessing individuals with autism spectrum disorder (ASD). ASD is characterized by significant variability in both ToM and executive skills, enabling the detection of even relatively subtle correlations.

Although ASD comprises a broad range of intellectual and linguistic abilities, pragmatic language deficits are present across the spectrum. Studies report significant

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pragmatic impairments for individuals with ASD of all ages and at all functional levels [Paul, 2007]. Deficits are evident early in development [Landa & Goldberg, 2005] and are characterized by fewer spontaneous bids for communication [Stone & Caro-Martinez, 1990], fewer purely social speech acts [Wetherby, 1986], fewer demonstrative gestures [Mundy, Sigman, Ungerer, & Sherman, 1987], and difficulty with turn-taking (Loveland, Landry, Hughes, Hall, & McEvoy, 1988). Adolescents with ASD have difficulty comprehending nonliteral statements despite intact receptive language [Asberg, 2010], and show deficits in turn-taking [Capps, Kehres, & Sigman, 1998], prosody [Eigsti, Schuh, Mencl, Schultz, & Paul, 2012; Paul, Augustyn, Klin, & Volkmar, 2005], comprehension of indirect requests and other such indirect language [Paul & Cohen, 1985; Rajendran, Mitchell, & Rickards, 2005; Uchiyama et al., 2006], and the integration of gestures with speech [de Marchena & Eigsti, 2010; Garcia-Perez, Lee, & Hobson, 2007].

One study of common ground use in high-functioning ASD found that while the typically developing group reduced story length when an interlocutor was familiar with story content, consistent with prior studies of common ground, the ASD group failed to do so [de Marchena & Eigsti, 2015]. Additional analyses suggested this pragmatic skill may have been delayed, rather than absent altogether.

Some accounts of ASD conceptualize pragmatic language deficits as reflecting broader impairment in ToM [Baron-Cohen, Leslie, & Frith, 1985]. That is, difficulties in inferring another person's beliefs limit the affected individual's ability to make predictions about how those around them will behave, and lead to pragmatic difficulties. Several studies [reviewed in Loukusa & Moilanen, 2009] support the suggestion that difficulties with discourse are directly related to limitations in ToM. For example, de Villiers and colleagues reported an association between the comprehension of relevance implicature and ToM performance in ten children with ASD [de Villiers, de Villiers, Coles-While, & Carpenter, 2009]. Specifically, children with higher ToM scores demonstrated better comprehension of interactions like the following: Dad asks, "what happened to the ham?" and Joe answers "the dog sure looks happy" (i.e., the dog has eaten the ham).

There is empirical evidence for a connection between ToM and common ground. When in the speaker's role, typically-developing children who pass ToM false-belief tasks tend to provide more disambiguating information to their listeners [James, 2002]. In one large ($n = 74$) study of typically-developing children age four and a half years [Resches & Perez Pereira, 2007], children were paired by level of ToM performance, and participated in a referential communication task. Dyads differed in pragmatic functions, descriptive accuracy, and message ambiguity, according to their ToM competence; for example, the pairs with better ToM produced more directive statements.

Children with ASD are capable of altering their utterances to account for listener knowledge, although not to the same degree as typically-developing peers [Geller, 1991]. Their descriptions may be under- or over-informative; particularly when perspective-taking demands increase, children with ASD provide more irrelevant information [Dahlgren & Sandberg, 2008; Nadig, Vivanti, & Ozonoff, 2009; Volden, Mulcahy, & Holdgrafer, 1997]. Somewhat surprisingly, children's ability to understand and interpret utterances as *listeners* is unrelated to their ToM [Resches & Perez Pereira, 2007]. These studies suggest an association between ToM and perspective-taking in the speaker but not the listener role.

There are a number of studies, however, suggesting that ToM limitations cannot fully explain pragmatic difficulties in ASD. For example, Japanese children with ASD showed intact semantic plausibility (e.g., comprehension of active versus passive sentences, given semantic cues to support syntactic status) despite impaired false belief (ToM) performance [Naito & Nagayama, 2004]. Youth with high-functioning ASD similarly showed no associations between ToM and the ability to process prosodic (voice) cues to a speaker's physical state, basic emotions, social emotions, or second order mental states [Chevallier, Noveck, Happe, & Wilson, 2011]; there were no group differences in interpreting these vocal cues, despite the presence of group differences in ToM. In a study of narrative production, high-functioning adolescents with ASD showed no impairments in ToM despite narrative deficits including fewer gist descriptions, more ambiguous pronominal referents, and idiosyncratic language [Suh et al., 2014]. Dahlgren and colleagues [2008] reported that success on a ToM task did not predict performance on a referential communication task in a large group of school age children with ASD; some children who failed the ToM task performed *better* on referential communication compared to children who passed. These studies all suggest that discourse deficits cannot be wholly accounted for by impairments in ToM. It is also possible that relationships between discourse and ToM reflect moderator effects of general development, such that children with more sophisticated abilities in one domain are found to have strong abilities in the second domain, without a causal relationship.

Beyond ToM, studies suggest that executive functions play an important role in discourse. In adults, individual differences in WM [Horton & Gerrig, 2005a,2005b] and verbal inhibitory control [Brown-Schmidt, 2009; Rubin, Brown-Schmidt, Duff, Tranel, & Cohen, 2009] are associated with the ability to access shared information. A study of children ages 3–5 years found an association between the ability to incorporate a partner's perspective and inhibitory control, but not WM [Nilsen & Graham, 2009]. WM demands in this study were low, so findings may have been limited by floor effects. Preliminary data from our lab suggests that children, with more limited WM capacity, and slower than adults to integrate common ground information, suggesting that WM is relevant to perspective-taking (manuscript in preparation).

In the Dahlgren study cited above, where children with poor ToM nonetheless performed well on referential communication, verbal memory and full-scale IQ were correlated with referential task performance [Dahlgren & Sandberg, 2008]. These findings suggest that high-functioning children with ASD, who have intact cognition and language functioning on standardized tests, may draw on additional resources during discourse [Frith & Happe, 1994; Nadig et al., 2009]. ToM may be a necessary but not sufficient component of successful discourse processing; while ToM performance correlates with discourse abilities, these findings seem to suggest it may not be critical. Tager-Flusberg [2001] proposed that ToM in ASD may reflect more effortful, explicit processing. Children with ASD have the capacity for perspective-taking, but seem to have difficulty in *selecting* appropriate or efficient strategies for conveying information.

Executive skills, including WM and inhibition, may relate to ToM beyond intellectual or language abilities [Joseph & Tager-Flusberg, 2004; Pellicano, 2010], suggesting that domain-general processes mediate perspective-taking, at least in ASD. A wide range of executive functioning deficits has been noted in ASD, including limitations in WM [for reviews see Eigsti, 2011; Sanders, Johnson, Garavan, Gill, & Gallagher, 2008]. Adolescents and adults with ASD have greater difficulty than mental age-matched controls at making inferences when complex situational contexts change over time [Reed, 1994]. Adolescents with ASD also have greater difficulty attending to multiple cues and combining complex information than peers with other developmental delays [Oswald & Ollendick, 1989]. These studies suggest that WM constrains perspective-taking.

Successful and efficient referential communication during discourse, and specifically, responding to common ground, requires the speaker to: (1) perceive and update relevant common ground knowledge; and (2) flexibly modify utterances based on this knowledge. A study of high-functioning youth with ASD indicated that some were able to modify their descriptions to fit an addressee's perspective when it differed from their own, although the ASD group's utterances were less informative [Nadig et al., 2009]. Interest, complexity, or other processes appear to modulate discourse abilities in ASD [e.g., Nadig, Lee, Singh, Bosshart, & Ozonoff, 2010]. To date, few studies have described discourse with participants with ASD in the role of *listener*.

Research on common ground often makes use of referential communication tasks [Clark, 1992; Clark & Wilkes-Gibbs, 1986; Epley, Morewedge, & Keysar, 2004; Hanna & Tanenhaus, 2004; Hanna, Tanenhaus, & Trueswell, 2003; Keysar, Barr, Balin, & Brauner, 2000; Nadig & Sedivy, 2002]. In such tasks, a trained "partner" gives instructions to the participant; on critical trials, the instructions are temporarily ambiguous (e.g., *Pick the red ones*). In the current study, the goal was to explore the influence of WM and ToM skills on discourse in children and adolescents with ASD and typical development using eyetracking. WM was manipulated via changes in the number of objects in discourse that the listener was required to track. Ambiguity was manipulated by having a target object (known to both speaker and participant and therefore part of common ground) and a competing object, identical in shape and color to the target. On 50% of critical trials, both the speaker and participant knew about this competitor object (i.e., it was in common ground); in these trials, the speaker provided clarifying information about the exact location of the target object. For the remaining trials, only the participant knew about the second competing object (i.e., the competitor was in privileged ground), requiring the participant to draw upon common ground knowledge to resolve the ambiguity.

Previous studies of typical development suggest that by the mental age of six, children are capable of accurately selecting objects by drawing on common ground knowledge [Ackerman & Silver, 1990; Ackerman, Szymanski, & Silver, 1990; Nadig & Sedivy, 2002; Schuh et al., revisions]. Given this, we predicted that all participants would ultimately choose the correct item (i.e., response accuracy would be high). However, eye movements can reveal more subtle differences in on-line processing. We predicted less efficient eye movement patterns in conditions of high WM load and when the competing object was in privileged ground, as participants would be required to draw upon common ground knowledge to determine that the speaker could only be referring to the target object. We further predicted that WM deficits would constrain performance in the ASD group to a greater extent, such that less rapid and efficient responding would be observed particularly in high WM load and high perspective-demanding conditions. Finally, we anticipated that task performance would correlate with off-line WM and ToM task performance, consistent with prior studies.

Methods

Participants

Participants included 20 individuals with high-functioning ASD or Pervasive Developmental Disorder/Not Otherwise Specified and 22 individuals with typical

Table 1. Participant Demographics

	ASD; $n = 13$	TD; $n = 22$	χ^2 or F	p	η^2_p
Age (years)	13.0 (2.7); 8–17	13.1 (2.7); 8–17	.003	.96	<.001
Male: Female	11:2	15:7	1.16	.43	
SES	49 (8); 39–59	46 (9); 30–58	.18	.68	.01
ABIQ-SS	106 (12); 94–127	105 (12); 88–139	.06	.81	.01
CELF Core SS	106 (14); 82–126	112 (8); 97–130	2.49	.13	.08
PPVT SS	115 (12); 92–131	116 (11); 100–147	.03	.87	.001
SCQ SS	23.2 (6.2); 14–33	1.3 (1); 0–3	267.39	.001	.90
BRIEF WM SS	72.3 (8.5); 60–85	44.1 (7.1); 36–58	89.75	.001	.76
BRIEF Exec. Func. Composite SS	71.3 (8.5); 60–83	44.1 (7.2); 35–62	75.76	.001	.73

Notes. Data presented as Mean (*SD*); range. SS = standard score with *M(SD)* = 100(15) or *M(SD)* = 50(10; SES = Socioeconomic status (Hollingshead, 1975); possible range, 8–66); ABIQ = Stanford-Binet, 5th Ed.- Abbreviated Battery IQ (Roid, 2003); CELF = Clinical Evaluation of Language Fundamentals, 4th Ed. (Semel et al., 2003); PPVT = Peabody Picture Vocabulary Test, 3rd Ed. (Dunn & Dunn, 2007); SCQ = Social Communication Questionnaire (Rutter, Bailey, & Lord, 2003); BRIEF parent questionnaire (Gioia, Isquith, Guy, & Kenworthy, 2000) includes a Working Memory (WM) subscale and an Executive Function composite.

development (TD), ages 8–17. Individuals with Asperger Syndrome were excluded. Diagnoses were confirmed using the Autism Diagnostic Observation Schedule [ADOS; Lord, Rutter, DiLavore, & Risi, 2002], the Autism Diagnostic Interview-Revised [ADI-R; Lord, Rutter, & LeCouteur, 1994], and expert clinical judgment based on DSM-IV-TR criteria. All participants had scores of 80 or higher on full scale IQ, assessed via the Stanford-Binet, 5th Edition [Roid, 2003], and standardized language assessment, assessed via the Clinical Evaluation of Language Fundamentals, 4th Edition [CELF-4; Semel, Wiig, & Secord, 2003]. Consent and assent were obtained prior to testing, and all procedures were approved by the Institutional Review Board.

Seven participants with ASD were excluded due to failure to understand the task[1] ($n = 5$), low IQ ($n = 1$), and an anxiety disorder that prevented successful participation ($n = 1$), yielding a final sample of 13 participants with ASD. No participants with TD were excluded. Groups did not differ in chronological age, gender, IQ, or standardized language; data are shown in Table 1. TD controls had no psychiatric, neurological, or behavioral impairments or family history of ASD, and their non-ASD status was confirmed using the Social Responsiveness Scale [SRS; Constantino, 2003] and expert clinical judgment.

Procedures

Discourse task. Participants completed a cooperative discourse computer task with a trained "partner" (not previously known to the participant). The game, adapted from Hanna and Tanenhaus [2004], was presented as a pirate treasure hunt, to promote interest and engagement. Participants and partners worked at separate laptops, with an opaque barrier between them, as shown in Figure 1. Participants were told that the partner's screen displayed the final location of all shapes, and that they needed to follow the partner's instructions to move colored shapes from a resource area to specific locations on a 16-square grid using the computer mouse; the goal was to match their map to their partner's. All shapes were visible in the resource area from the start of the trial. When a shape was mentioned, it entered common ground. All trials contained "privileged" shapes whose existence was unknown to the partner; participants were told that these shapes should be kept secret to prevent the partner from stealing the treasure. Privileged (secret) shapes were highlighted only at the start of each trial, requiring participants to track these locations once the trial began. For half of these trials, the privileged shape was identical to the target shape in common ground. Participants completed eight practice trials to clarify how to move shapes with the mouse, the role of the partner, the presence of privileged shapes, and to emphasize the interactive nature of the task. During practice, participants received feedback and could ask questions. Participant eye movements were monitored using a remote EyeLink eyetracker; behavioral responses were also recorded.

There were 28 total trials. In 16 critical trials, the display contained two identical shapes (e.g., two yellow squares): a target (the subject of the partner's instruction) and a competitor (the foil object). During critical trials, the partner instructed the participant to place a shape on top of the target shape (e.g., *Stack the red square on the yellow one*). This required the participant to consider what objects were known to the partner when choosing the target. In *privileged ground* trials ($n = 8$), the competitor shape was hidden from the partner; as such, instructions were unambiguous (i.e., the partner could only be referring to the yellow square in common ground). This condition was compared to

[1]These participants did not understand how to use the mouse ($n = 2$), were unable to wait for examiner instructions ($n = 1$), or did not understand that the partner was unaware of the secret shapes ($n = 2$).

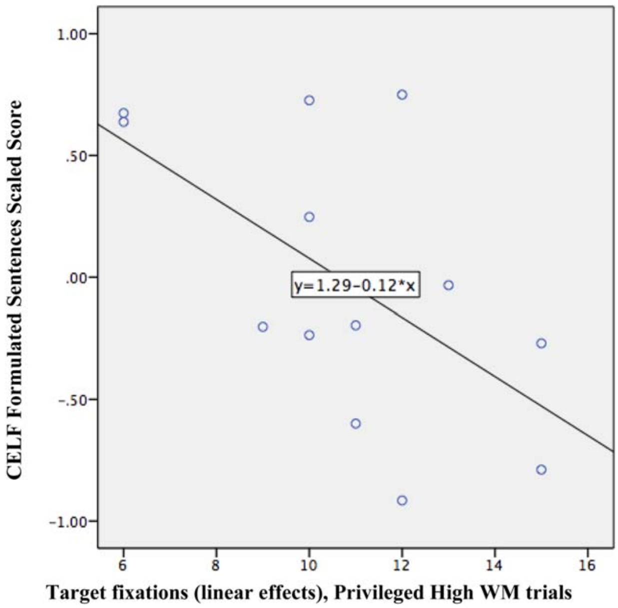


Figure 1. Association between CELF Formulated Sentences subtest score, and Target fixations (linear effects), for the ASD group.

common ground trials ($n = 8$), where the partner had already introduced the competing shape (i.e., both yellow squares—the competitor *and* target—were in common ground); as such, the instruction was ambiguous and required the participant to ask for more information. Only after the participant asked did the partner provide a scripted clarification, as in, *Stack the red square on the yellow one in space eight*. Thus, for all correctly-completed common ground trials, the participant eventually learned the explicit location of the target shape, eliminating the ambiguity. To reduce the salience of instruction ambiguities, twelve filler trials were interleaved with critical trials, with no more than two critical trials in a row. Filler trials were unambiguous and counterbalanced so that the stacking instruction: (1) was the final instruction; (2) occurred in the middle of a trial; or (3) was not present. Examples of Privileged, Common ground, and filler trials are provided in Supporting Infromation Table S1.

To manipulate WM load, the number of privileged shapes varied across trials. For both Privileged and Common ground competitor trials, four *low WM* trials contained one privileged shape and seven common shapes; four *high WM* trials contained four privileged and four common shapes. To control for trial length and number of items, the number of shapes and instructions was identical across trials.[2] The shape, color, and location of privileged and common ground shapes were counterbalanced in two orders.

Participants responded to debriefing questions about the task. They gave an average response of 4.6 (5 = "very much agree") to the statement, "*your partner did not know about the secret shapes*." The task, including debriefing, took 35 min.

WM measures. As an external assessment of verbal and nonverbal WM abilities, participants completed four tasks: (1) *Finger Windows* [Sheslow & Adam, 1990], in which the examiner placed a pencil into an increasingly-lengthy sequence of openings ("windows") in a vertical plastic card, and asked the participant to reproduce the sequence; (2) *Letter-Number Sequencing* [Wechsler, 2003], in which participants are asked to listen to an increasingly-long series of letters and numbers, and repeat back the items, reordered according to numerical and alphabetic order; (3) a *Competing Language Processing* Span task [Gaulin & Campbell, 1994], in which the participant made true/false judgments for a series of statements, and then was asked to recall the final word of each statement; and (4) *Nonword repetition* [Gathercole, Hitch, Service, & Martin, 1997], in which the participant repeated nonsense words of increasing complexity. All have good or excellent reliability and show construct validity in relation to academic achievement measures of reading, spelling, and arithmetic [Gaulin & Campbell, 1994]. Standard scores from the four WM measures were transformed into z-scores and averaged to form a WM Composite.[3] In addition, parents completed a questionnaire, the Behavior Rating Inventory of Executive Function [BRIEF; Gioia, Isquith, Kenworthy, & Barton, 2000].

ToM measure. To probe ToM skills, participants completed 22 verbal items from the NEPSY-II ToM subtest [Korkman, Kemp, & Kirk, 2001], which tests first-order ToM (e.g., *When your friend sees the box, what will he think is inside it?*), interpretation of non-literal statements, and inferring internal states of characters from context. While the NEPSY ToM subtest includes visual items (interpretation of facial expressions), these were not included in this analysis. The NEPSY has good reliability (.85) and has been used in studies of high-functioning children with ASD, who show deficits on the verbal items [Narzisi, Muratori, Calderoni, Fabbro, & Urgesi, 2013]. It does not provide standard scores for children over the age of 7 years; thus, raw scores were transformed to z-scores with chronological age held constant.

[2]To keep number of instructions consistent, high-WM trials included non-functional instructions (e.g., *Click on space four*).

[3]Scores among these four WM tasks were highly intercorrelated, and the composite score differed by group to a similar degree as each of the four individual measures.

Results

Children and adolescents with and without ASD completed a discourse task in which WM and common ground were manipulated. They also completed a series of task-external WM and ToM assessments. All dependent variables met the assumptions of normality and sphericity. Differences by group (ASD vs. TD), WM load (low, one shape vs. high, four shapes), and ground (common vs. privileged shape) were examined using repeated-measures ANOVAs on accuracy; eye-movement data were analyzed using growth curve analyses (GCA), which allow for sensitive detection of change over time. Regression analyses tested relationships among task performance, language ability, symptom severity, WM, and ToM.

Because sample sizes were uneven ($n = 13$ ASD, $n = 22$ TD), it was feasible to exclude participants with TD to yield samples that were more similar in standardized language scores. The analyses detailed below were repeated with the smaller TD sample; results did not differ. As such, results with the full sample are reported here.

Discourse Task

The two task orders did not differ in accuracy and did not interact with age, all P's $> .16$; they were collapsed for subsequent analyses. For critical trials, eye movement data were analyzed from the point of disambiguation (i.e., onset of the word that provided sufficient information to respond). For privileged ground trials, this was the color adjective *yellow* in *Stack the red square on the yellow one*; for common ground trials, where the participant had to ask for clarification from the partner, the point of disambiguation was the number adjective (e.g., *eight*) for the target location in the response, as in, *Stack the red square on the yellow one in space eight*.[4] Trials ended with the behavioral response (clicking a shape).

In the common ground condition, participants (incorrectly) failed to ask for clarification on 17 of 104 (16%) trials (ASD group) vs. 13 of 176 (7%) trials (TD group). These trials were excluded from further analyses.[5] This difference was significant, with a small effect size, $F(1, 27) = 5.75$, $P = .02$, $\eta^2_p = .15$, suggesting that although individuals with ASD understood the task, it may have been more difficult for them. This suggestion was supported by a chi-squared comparison of the *number* of participants who failed to ask on at least one common ground trial (ASD, $n = 11/13$ or 85%; 7 participants failed to ask on 1 trial, 2 failed to ask on 2 trials, and 2 failed to ask on 3 trials; TD, $n = 9/22$, 41%; 5 participants failed to ask on 1 trial, and 4 participants failed to ask on 2 trials) versus the number who asked on every common ground trial (ASD, $n = 2/13$ or 15%; TD, $n = 13/22$, 59%); this analysis showed a significant group difference, $\chi^2(1) = 6.37$, $P = .01$. Across 560 critical trials, one additional trial was dropped due to experimenter error. Altogether, four percent of the data was excluded.

Task Accuracy

Accuracy (placing the correct shape in the correct location) was high for both ASD [M (SD) = .89 (.15)] and TD [$M(SD)$ = .93 (.08)] groups, and they did not differ, $F(1,33) = .92$, $P = .35$, $\eta^2_p = .03$. There was a significant main effect of WM load, with all participants more accurate in low WM load trials, $F(1, 33) = 10.45$, $P = .003$, $\eta^2_p = .24$. There was a trend for a main effect of ground, with greater accuracy across groups in the common ground condition, $F(1, 33) = 3.96$, $P = .06$, $\eta^2_p = .11$. There was no WM by ground interaction, $F(1, 33) = 2.33$, $P = .14$, $\eta^2_p = .07$, and no group by WM by ground interaction, all F's $(1, 33) < .59$, P's $> .45$, η^2_p's $< .02$. Analysis of explicit behavioral responses alone would thus indicate that all participants performed more accurately in low WM load and common ground conditions, with no group differences.[6]

Eye Movement Analyses

Eyetracking time course data were analyzed using Growth Curve Analysis (GCA). This multilevel modeling framework is sensitive to subtle patterns of change over time [Mirman, 2014; Mirman, Dixon, & Magnuson, 2008; Mirman, Yee, Blumstein, & Magnuson, 2011]. The time course of target fixation proportions was modeled using third-order orthogonal polynomials with: (1) fixed effects of ground (privileged vs. common), WM load (low vs. high), and group (ASD vs. TD) on all time terms; and (2) participant-by-condition random effects, which characterize effects for an *individual* participant in a *particular* condition, and can quantify individual differences along continuous dimensions such as WM capacity or ASD symptom severity.

Eyetracking analyses focused on the proportion of looks, and patterns of looks, toward the target shape and toward the competitor shape (that is, the same shape, of the same color, contrasted with all other possible locations/objects, including the target shape). Full

[4]Note that while analyses are time-aligned to different spoken words, they are aligned to the same moment in the discourse: when the participant was able to respond. Aligning the analyses on the initial color-word for the common ground trials yielded too much variability in eye movement patterns to detect the final looks to the target; these results are available from the authors by request.

[5]Participants also asked for more information on 66 of 280 trials (24%) in the privileged ground condition, although these trials were unambiguous (i.e., the clarification was unnecessary). There were no group differences in asking, $F(1, 33) = .06$, $P = .81$. Analyses began when the partner responded (e.g., *That is all the information I have*).

[6]Analyses of reaction time followed the same pattern.

fixed effect parameter estimates are presented in Supporting Information 2, available online.

Target Fixations

There were fewer overall target fixations in privileged ground trials (*Ground* effect on intercept term, Estimate = −.128, *SE* = .051, *P* = .01); that is, participants tended to fixate multiple locations. Rise time (where slope represents the over-time likelihood of fixating the target) was slower in privileged trials (*Ground* effect on quadratic term, Estimate = .282, *SE* = .118, *P* = .02). Rise time was also slower in high-WM trials (*WM* effect on quadratic term: Estimate = −.270, *SE* = .118, *P* = .02). Finally, rise times were slower, with a larger quadratic term, in high WM-privileged ground trials (as compared to all high WM trials; Linear: Estimate = −.622, *SE* = .235, *P* = .01; Quadratic: Estimate = .324, *SE* = .168, *P* = .05). These findings indicate that *both* WM load and perspective-taking impacted the degree to which participants fixated on the target.

Competitor Fixations

There was a trend for a three-way interaction of group, ground, and WM load (Linear: Estimate = −.243, *SE* = .137, *P* = .08), indicating an interaction between the effect of group on competitor fixations, with increased competitor fixations in high WM-privileged ground trials; see Figure 2. This three-way interaction reflected a significant interaction of group by ground (Linear: Estimate = .229, *SE* = .096, *P* = .02), such that the ASD group had significantly prolonged fixations to the competitor shape for privileged trials; and a significant interaction of ground by WM (Intercept: Estimate = .057, *SE* = .012, *P* = .03), such that fixations in the common ground trials were minimally affected by WM load, but competitor fixations in the privileged ground trials were strongly affected. Finally, there were significant main effects of group (Intercept: Estimate = .053, *SE* = .023, *P* = .02), indicating that the ASD group had significantly prolonged fixations to the competitor shape across conditions. These results indicated that the ASD group was significantly more affected by both WM and common ground manipulations.

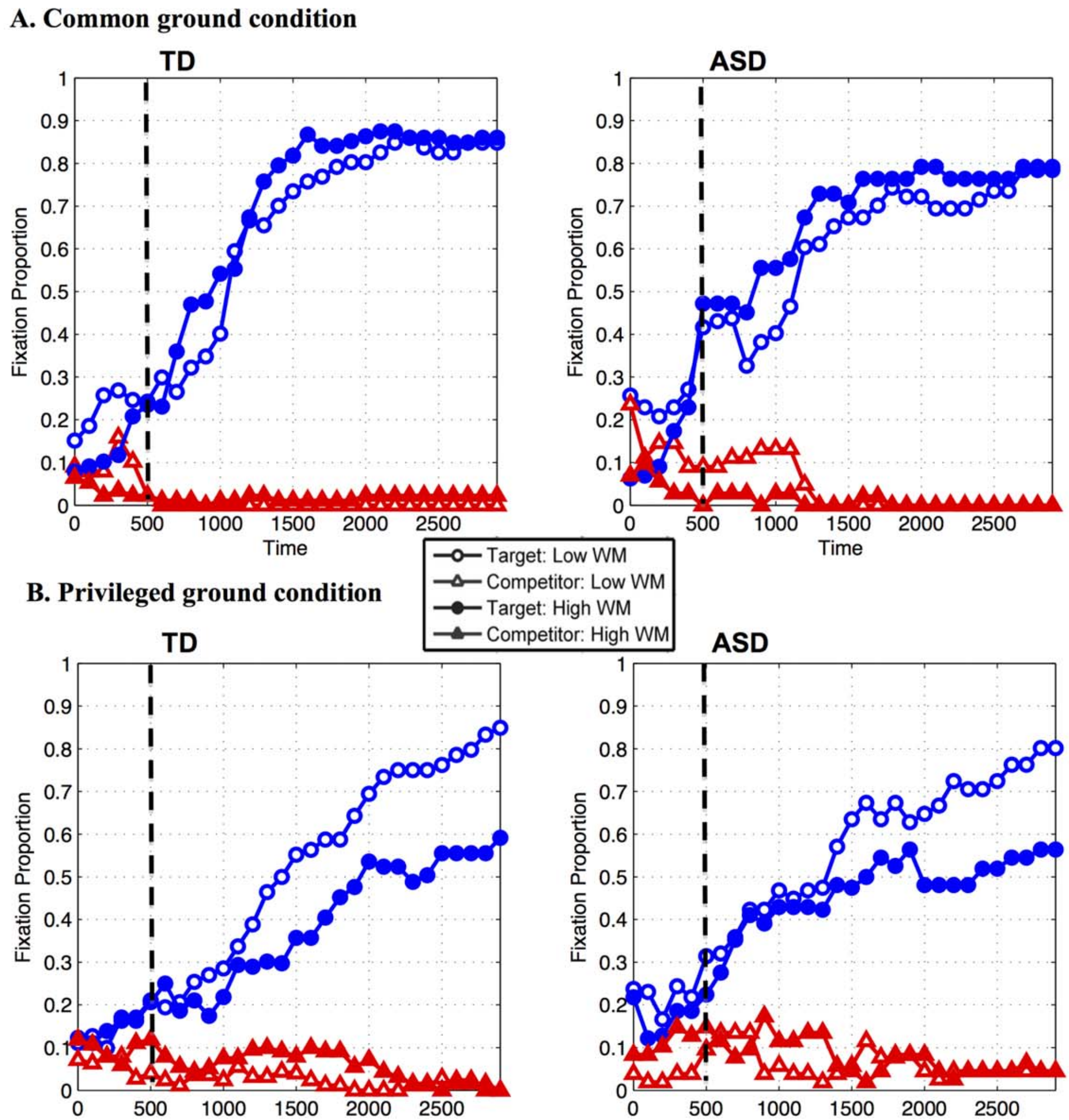
Working Memory and ToM Assessments

Performance on standardized measures of WM provided an index of individual differences in WM capacity. There were significant group differences on three of four measures (group differences in letter-number sequencing reached trend level, *P* = .10), with lower scores for the ASD group in each case, and with the largest effect size for the visuospatial WM measure, Finger Windows. The composite WM score differed by group as well, with a very large effect size. Data and statistics are shown in Table 2. Although groups had similar IQ and standardized language scores, the ASD group showed significant WM impairments [as reported previously, Schuh & Eigsti, 2012]. Caregivers in the ASD group endorsed significantly more symptoms on the BRIEF composite measure of executive functioning, as well as the specific WM subscale, both *P*'s < .001 (see Table 1). These data suggest greater WM challenges in the daily lives of children with ASD, and indicate that these challenges are of clinical significance, with T-scores above 65. As for ToM performance, controlling for age, there was no group difference, $F(1,31) = 1.44$, $P = .24$, $\acute{\eta}^2 = .04$ (scores in Table 2). WM composite scores and ToM scores were significantly correlated within each group: ASD, $r(12) = .71$, $P = .01$; TD, $r(22) = .49$, $P = .02$.

Associations of Discourse with Independent WM and ToM Assessments

Linear regression tested the contribution of WM and ToM to discourse processes. Analyses utilized individual participant WM effect sizes for target fixations in privileged ground trials (i.e., the high vs. low WM fixation proportion curves from privileged ground trials). The individual participant effect sizes were quantified using GCA random effect estimates, which estimate how the fixation proportion curves of each participant in each condition differs from the overall sample pattern for all participants captured by the fixed effects. That is, a linear term random effect estimate for participant A in the high WM, privileged ground condition quantifies the overall slope of the fixation curve for participant A in that condition, relative to the fixation curves for the entire group of participants in that condition. With this analysis, we quantify the effect of high WM and privileged ground on the overall slope of the fixation proportion curve for each participant relative to the entire sample. An analogous calculation for the quadratic term quantifies the effect of high WM and privileged ground on the curvature of fixation proportion curves for each participant relative to the entire sample. (Analysis details are available in Mirman, 2014; Mirman et al., 2008). The linear and quadratic terms capture the rate of using privileged ground information to correctly interpret the partner's instruction, so these terms were tested.

Predictors were entered in a single step for the entire sample and included: chronological age; SCQ symptom severity measure score, to account for diagnostic status; CELF Core Language and PPVT vocabulary scores; WM composite score; BRIEF WM subscale score; and ToM age-adjusted score. The regression was not conducted separately by group, because predictor variables showed distribution over a continuum; instead, ASD symptomatology



Graphs depict fixations over time. Target fixations (correct shape) are circles; competitor fixations are triangles. For *Common Ground trials* (**A, top panels**), both participant and partner know of the competitor shape; for *Privileged Ground trials* (**B, lower panels**), only the participant knows. Open shapes = low WM load; filled shapes = high WM load. The early timecourse of eye movements (e.g., through 500 ms, marked by the dotted line) is particularly informative about the degree of interference; note in particular the extent of interference from competitor shapes for the ASD group in the Privileged-High WM conditions.

Figure 2. Eye-tracking responses in common and privileged ground conditions for low and high working memory loads.

(SCQ scores, which were available for all participants) was included as an independent predictor.

When examining effect sizes for target fixations in high WM, privileged ground trials, for the linear term (which captures slope of the fixation curve), the overall model was not significant, F (7, 20) = .24, P = .97, nor were the individual predictors, all P's > .50. For the quadratic term (which captures the curvature of the fixation curve), the overall model was significant, F (7, 20) = 6.47, P < .001. In this model, multiple predictors accounted for *significant independent variance*: SCQ symptom severity, $\beta = -1.165$, P < .001; CELF language, $\beta = -.580$, P = .002; PPVT, $\beta = .567$, P = .002; BRIEF WM, $\beta = .918$, P = .001; WM composite, $\beta = -.601$, P = .02; and ToM, $\beta = .662$, P = .001. Age missed significance, $\beta = .282$, P = .06. A table presenting the entire

Table 2. **Performance on Working Memory (WM) and Theory of Mind (ToM) measures**

	ASD	TD	*F*	*P*	η^2_p
WM Composite	−.559 (.750)	.330 (.474)	18.60	<.001	.36
Finger Windows SS	9 (3); 5–14	12 (2); 9–15	19.29	< .001	.37
Letter-Number Seq SS	10 (4); 3–19	12(3); 8–17	2.87	.10	.08
Span Task RS (max = 72)	34 (17); 10–63	45 (14); 16–63	4.76	.04	.13
Non-Wd rep RS (max = 20)	16 (2); 14–20	18 (1); 15–20	10.94	.002	.25
ToM Verbal RS	19.5 (2.0)	22.3 (1.8)	1.44	.24	.04

Notes. Data are presented as Mean (*SD*); Range. SS = Standard scores with *M(SD)* = 10 (2); RS = Raw Score. WM (working memory) Composite was calculated from z-scores averaged across all WM tasks (Finger Windows, Letter-Number Sequencing, Span Task, and Non-Word Repetition. ToM = NEPSY Theory of Mind subtest raw scores; note that analyses used TOM Verbal Raw Scores, transformed to z-scores with chronological age held constant.

model can be found in Supporting Information Table 3. Visual inspection of data patterns suggested that individuals with higher WM had curves with sharp slopes that more rapidly reached ceiling levels for the target, suggesting an association between greater WM capacity and efficient discourse communication. Interestingly, with effect size during low WM, privileged ground trials as the dependent variable, the model was not significant, nor were the individual predictors, all *P*'s > .13, suggesting that when WM demands are low, perspective-taking may require fewer executive, linguistic, and pragmatic resources, such that individual differences in these abilities have little impact.

Taken together, these findings suggest that, when maximally burdened by high WM load and the need to distinguish between privileged and common ground information, participants with better WM abilities as assessed by parent report and direct assessment display more efficient performance (they more rapidly fixate the target). Autism symptom severity, language ability, WM capacity, and ToM abilities *each* contributed *independently* to task performance in these conditions. The ASD group did not appear to differ in ToM, but had more limited WM capacity, and they had a disproportionately larger difference in performance during high WM, privileged conditions; the significant predictors in the regression analysis suggest that individual differences in these dimensions contributed to the group differences in performance.

Discussion

This study assessed the ability of individuals with ASD to represent common ground information during discourse; and the contributions of WM and ToM to such representations. Previous studies exploring the relationship between WM and pragmatic deficits in ASD have been correlational in nature, or have focused on utterance production. In this study, we directly assessed the influence of WM and ToM on listener comprehension during discourse by manipulating the number of objects in privileged ground (WM), and manipulating whether or not a competitor object was known to the communicative partner (ToM).

Performance inefficiency was exacerbated under high WM load. Differences for low versus high WM trials suggest that WM capacity modulates the ability to incorporate common ground information, and that the ASD group (with significantly lower WM capacity) was particularly susceptible to WM demands. Other studies have reported on the importance of WM in perspective-taking in discourse [Horton & Gerrig, 2005b; Mutter, Alcorn, & Welsh, 2006]. Perspective-taking in ASD has been found to relate to WM skills [Reed, 2002], symptom severity [Dawson & Fernald, 1987], general cognition [Dahlgren & Sandberg, 2008], and language ability [Bodner, Minshew, & Williams, 2009; Nadig et al., 2009].

Eye-movement and accuracy data indicated that *all* participants were slower when required to integrate privileged information (i.e., when perspective-taking demands increased). Differences between common and privileged ground trials indicated that the need to access knowledge about a conversational partner's representations (that is, to use ToM) leads to decreases in performance efficiency (fewer target fixations overall and slower rise-time to fixate the target). When the competitor was privileged, participants used common ground knowledge; this knowledge clearly involves ToM [e.g., Farrant et al., 2006]. Previous research on perspective-taking in ASD suggests that individuals with ASD do not lack perspective-taking abilities as a whole, but rather have greater difficulty incorporating common ground information in comparison to controls [Geller, 1991; Nadig & Sedivy, 2002; Volden et al., 1997]. Others have reported that ToM correlates with the number of features described during referential communication [Dahlgren & Sandberg, 2008].

While the results reported here suggest that ToM is important for perspective-taking, because ToM scores contributed independent variance to discourse performance, they do not conclusively indicate that ToM limitations lead directly to perspective-taking difficulties. For one thing, participants with ASD did not score lower on a standardized assessment of ToM; however, they had less efficient responding during the eyetracking task. Future studies must explore this relationship in individuals with greater ToM impairments, and with ToM measures that are more sensitive to deficits in adolescents and high-functioning individuals; but the current results suggest that simple assessments of TOM, using standard tasks, in high-functioning individuals with ASD do not reveal clear impairments.

One consideration is that participants with ASD could perform the task using an alternative strategy, ignoring privileged shapes altogether and treating the task as a simple memory task of old versus new information. If this were the case, we might expect similar fixation patterns in both the common and privileged ground conditions, where participants would fixate quickly to the target, with little to no interference from the competitor shape. However, participants in both groups showed greater competitor influence during privileged than common ground trials, suggesting they were incorporating common ground representations over time.

Regression analyses using growth curve models, which may be more sensitive to subtle individual differences, indicated that performance in the discourse task was associated with both ToM and WM, and was correlated with symptom severity. We propose that WM deficits in ASD could lead to a cascade of effects whereby a) difficulties updating common ground knowledge b) lead to perspective-taking difficulties, which in turn c) impacts pragmatic language, including topic maintenance, reciprocal communication, and descriptive language. Certainly, this proposal invokes a model of causality which requires further research, including longitudinal studies following children with ASD, but it is consistent with related research in typical development [Benson, Sabbagh, Carlson, & Zelazo, 2013; Carlson, White, & Davis-Unger, 2014]. There is extensive evidence linking ToM to WM, in TD individuals and in patient populations involving significant WM impairments [e.g., traumatic brain injury, Levy & Milgram, 2014]. Further, longitudinal work suggests that the relationship is directional, with WM constraining ToM abilities over time [Austin, Groppe, & Elsner, 2014]. While there are few studies of this phenomenon vis a vis pragmatic language in ASD, previous research has found that perspective-taking is related to symptom severity [Dawson & Fernald, 1987], consistent with the current findings that common ground use was related to symptom severity; it is possible that WM could have played an (often unmeasured) role in many such studies.

The current study has several limitations. Children in this study were high functioning, and well matched on age, gender, and standardized measures of IQ and receptive vocabulary, to better establish the relationship between WM and discourse; future work must examine the relationship between WM and perspective-taking in lower functioning participants, where cognitive or language deficits play a larger role. In addition, participants with ASD did had marginally lower scores on a measure of language structure (the CELF); note that results did not differ when analyses were limited to TD participants who were specifically matched on language. Further, WM may differentially affect discourse for speakers as opposed to listeners. A study incorporating both roles during discourse would illuminate how these abilities relate to one another. A further limitation is that because the partner gave ambiguous instructions, participants may have become less reliant on discourse information, instead adopting some other strategy and decreasing the ecological validity of the current results. That said, everyday communication involves failures of speaker informativeness, and these data provide some window into how listeners respond to communicative failure. One final limitation of this work is the small sample size; it is not clear that the present results will generalize to a larger group of individuals with ASD, given the heterogeneity that characterizes this disorder.

These results have clinical implications. Explicit training in perspective taking has been found to benefit children with TD [Marsh, Serafica, & Barenboim, 1980] and with emotional difficulties [e.g., antisocial or chronic adjustment difficulties; Chandler, Greenspan, & Barenboim, 1974]. TD children ages three to five improved referential communication when they received online immediate feedback from listeners that they did not have enough information [Matthews, Lieven, & Tomasello, 2007]. Children and young adults with ASD ages 9 to 23 who received direct training in referential communication produced more informative and precise utterances than their ASD counterparts who did not receive training [Olivar-Parra, De-La-Iglesia-Gutierrez, & Forns, 2011]. WM may also be a useful target for intervention. Implementing WM demands into training, and adapting them for older children, may be helpful. In addition to strengthening WM abilities, interventions that take WM limitations into account (e.g., breaking information into smaller portions) may enhance task performance, enabling children to experience successful communication.

Results of this eyetracking study of discourse processing indicate that social impairments in ASD are strongly associated with WM capacity. WM, in addition to ToM, influences perspective-taking in children and adolescents with ASD. Greater WM demands may result in individuals appearing more egocentric, with a greater difficulty incorporating common ground representations. Deficits in low-level, nonsocial processes such as WM cascade up and exert influences on complex, high-level, discourse performance.

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Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's web-site:

Table S1. Examples of Common and Preivileged Ground trials, and Filler trials.

Table S2. Fixed effect parameter estimates and significant tests for growth curve analyses of target fixations (left columns) and competitor fixations (right columns).

Table S3. Summary of hierarchical regression analysis of competitor fixations for linear (top panel) and quadratic terms (bottom panel).