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ORIGINAL PAPER

Thinking Ahead: Incremental Language Processing is Associated with Receptive Language Abilities in Preschoolers with Autism Spectrum Disorder

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Abstract

In typical development, listeners can use semantic content of verbs to facilitate incremental language processing—a skill that is associated with existing language skills. Studies of children with ASD have not identified an association between incremental language processing in semantically-constraining contexts and language skills, perhaps because participants were adolescents and/or children with strong language skills. This study examined incremental language processing and receptive language in young children with ASD with a range of language skills. Children showed a head start when presented with semantically-constraining verbs (e.g., *Read the book*) compared to neutral verbs (e.g., *Find the book*). Children with weaker receptive language showed a smaller head start than children with stronger receptive language skills, suggesting continuity between typical development and ASD.

Keywords Individual differences · Language processing · Comprehension · Prediction · Autism · Language impairment

Spoken language unfolds quickly, but listeners do not wait until an utterance is complete to begin making sense of what they have heard. Instead, listeners process spoken language incrementally—initially activating many candidate words, but narrowing these possibilities as speech unfolds, based on cues such as the initial phonemes of a word, (Allopenna et al. 1998; Swingley et al. 1999), the gender of an article (e.g., *el* versus *la*; Lew-Williams and Fernald 2007), or the meaning of an adjective (e.g., *red* versus *blue*; Fernald et al. 2010). Incremental processing of linguistic cues allows listeners to think ahead, predicting what a speaker will say before the words are produced. The current study focused on utterances in which semantic information in verbs allows listeners to predict which noun is most likely to come next. For example, following *Read*, an object is likely to be something readable (e.g., *book* as opposed to *juice*). In typical development, experimental studies have shown that listeners can use verb semantics to think ahead (Altmann and Kamide 1999; Borovsky et al. 2012; Kamide et al. 2003). Furthermore, incremental language processing has been associated with existing language skills in both children and adults, such that individuals with stronger vocabulary skills are more able to exploit predictive contexts in language processing (Borovsky et al. 2012; Mani and Huettig 2012; Ylinen et al. 2017).

At least some children with autism spectrum disorder (ASD) can use the semantic context to facilitate incremental language processing (Bavin et al. 2016; Brock et al. 2008; Hahn et al. 2015). However, prior studies of children with ASD have not identified a significant association between incremental language processing in semantically-constraining contexts and existing language skills. It is possible that this association does not exist. Such a finding would be notable because it would indicate a qualitative difference between children with ASD and children with typical development, as has been found for other aspects of language

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development (e.g., Tek et al. 2008). However, it is also possible that previous studies have not identified the association between incremental language processing and language skills in children with ASD due to methodological factors, such as participant characteristics. For example, studies that have examined the relationship between incremental language processing and language skills in children with ASD have focused primarily on adolescents and/or children with strong language skills (Bavin et al. 2016; Brock et al. 2008). It is important to investigate this issue in a more diverse group of children with ASD because ASD can result in very different outcomes in language development. Some children with ASD acquire strong language skills, whereas others demonstrate severe impairments—particularly in the area of receptive language (Charman et al. 2003; Davidson and Ellis Weismer 2017; Kjelgaard and Tager-Flusberg 2001; Tager-Flusberg et al. 2005; Volden et al. 2011).

The current study examined the association between incremental language processing and existing language skills in children with ASD. Participants were young (4–5 years old) and showed a wide range of language skills. Our goal was to represent the variability in language skills that is likely to exist across young children with ASD, thereby maximizing our ability to detect the relationship between incremental language processing in semantically-constraining contexts and existing language skills—if such a relationship exists.

Incremental Language Processing in Individuals with Typical Development

Many experimental studies of incremental language processing have used a variant of the visual-world paradigm—a method in which participants view multiple images on a screen, and their eye movements are monitored as they listen to spoken language (Allopenna et al. 1998; Fernald et al. 2008; Huettig et al. 2011; Tanenhaus et al. 2000). These studies have consistently found that individuals with typical development can use the semantic content of verbs to direct their attention to a related object before the object itself is named (Altmann and Kamide 1999; Borovsky et al. 2012; Kamide et al. 2003). In one study, for example, 3-year-old children took part in a task that presented two images on a screen (e.g., a cookie and a glass of juice), along with utterances containing either neutral verbs (e.g., *See the cookie*) or semantically-constraining verbs that would plausibly describe only one of the images (e.g., *Eat the cookie*; Fernald et al. 2008). Because the visual context constrains the candidate upcoming nouns, this type of design has been described as a "prediction-encouraging paradigm" (Huettig and Mani 2016). Children looked more quickly and reliably to target images when presented with semantically-constraining verbs than with neutral verbs (Fernald et al. 2008), thereby demonstrating the incremental use of semantic information in unfolding speech to predict upcoming words.

This type of incremental language processing is thought to be advantageous for language development because it facilitates efficient real-time comprehension and frees cognitive resources to devote to other aspects of learning (Bar et al. 2009; Borovsky et al. 2012; Mani and Huettig 2012; Ylinen et al. 2017). It has also been hypothesized that incremental language processing is impacted by an individual's existing language skills (Mani and Huettig 2012). Regardless of directionality, these hypotheses suggest that incremental language processing and existing language skills should be correlated—and indeed, this is the case in typical development. Borovsky et al. (2012) found that typically developing children (3–10 years old) and adults who showed faster incremental language processing had higher receptive vocabulary scores. Similarly, Mani and Huettig identified a significant correlation between incremental language processing and vocabulary skills (measured by parent report) in 2-year-old children with typical development. In addition, Ylinen et al. (2017) identified a link between vocabulary scores and neural prediction error responses to novel word forms in 12-month-old infants using electroencephalography.

Incremental Language Processing in Individuals with ASD

Like typically developing children and adults, school-aged children and adolescents with ASD can use semantic information in verbs to think ahead during spoken language processing (Bavin et al. 2016; Brock et al. 2008; Hahn et al. 2015). For example, a recent study by Bavin et al. (2016) found that high-functioning children with ASD (5–9 years old) looked at target images more quickly when they heard utterances with semantically-constraining verbs (e.g., *The boy will eat the cake*) than utterances with neutral verbs (e.g., *The boy will move the cake*). Interestingly, the children with ASD in this study fixated the target as quickly as their typically developing peers in the constraining trials, despite having slower language processing than TD children in the neutral trials. These findings indicate that semantic context supports efficient language processing for at least some children with ASD.

Given the link between incremental language processing and language skills in typical development (e.g., Borovsky et al. 2012), it seems logical to hypothesize that incremental language processing is also correlated with language skills in children with ASD. Surprisingly, however, the few studies that have investigated this question have *not* identified a link between language skills and incremental language processing. Bavin et al. (2016) found no significant association between children's language skills on a standardized assessment and their processing of either semantically-constraining or neutral verbs. Similarly, Brock et al. (2008) found no significant association between participants' language skills and the effects of verb semantics in semantically-constraining contexts.[1]

What do these findings mean? One possibility is that there is truly no link between incremental language processing and existing language skills in children with ASD—potentially indicating a qualitative difference from what is observed during the course of typical language development. It is also possible that previous studies have not detected this relationship because their participant samples were restricted to older and/or high functioning children with ASD—a possibility that has also been raised by other research groups (Hahn et al. 2015). Although the participants in the study by Brock et al. (2008) demonstrated a broad range of language abilities, they were 12 to 17 years old. Thus, their experience in processing these types of utterances may have reached a threshold of performance where it was no longer associated with their standardized language scores (also see Mani and Huettig 2012). To address these issues, the current study included a group of children with ASD who have a broad range of language abilities, at a point in development where incremental lexical processing is still developing.

Although current findings suggest that incremental language processing is not associated with existing language skills in children with ASD, numerous studies have identified links between existing language skills and language processing by children with ASD in other contexts (Eberhardt and Nadig 2016; Naigles et al. 2011; Tovar et al. 2014; Venker et al. 2013). For example, a study by Venker et al. (2013) examined the association between receptive language skills (on a standardized assessment) in young children with ASD, and their processing of nouns—a factor that has been closely linked with language abilities in other groups of young children (Fernald and Marchman 2012; Fernald et al. 2006; Marchman and Fernald 2008). Children with ASD (3–6 years old) with a broad range of language abilities participated in a variation of the visual world paradigm: a looking-while-listening task (LWL; Fernald et al. 2008) that presented two images on a screen, one of which was named (e.g., *Where's the ball?*). Children who showed more accurate language processing were those with stronger receptive language skills, as indicated by their looks to named versus unnamed images. Thus, it is important to continue investigating the relationship between incremental language processing and existing language skills, as seemingly subtle differences in language processing may help us understand why some children with ASD have so much more difficulty learning language than others.

The Current Study

The current study examined the link between incremental language processing and receptive language skills in 20 preschoolers with ASD (4–5 years old). A comparison group was not included because our research questions focused solely on individual differences among children with ASD. In our view, examining individual differences is central to the study of language skills in children with ASD because variability is the norm, rather than the exception. Though many studies have focused on children with ASD who have strong cognitive and language skills (Tager-Flusberg and Kasari 2013), including children with a broad range of abilities is important for testing relationships among different linguistic and cognitive skills (Eigsti et al. 2011).

Children participated in a LWL task that included two different types of trials: trials with semantically-constraining verbs (e.g., *Ride the bike*) and trials with neutral verbs (e.g., *Find the bike*). We then tested the association between children's existing receptive language skills on a standardized assessment, and their language processing abilities in both trial types: neutral and semantically constraining.

Using an eye-gaze task of language processing in this study of children with ASD offered several advantages (also see Kylliäinen et al. 2014; Norbury 2016; Sasson and Elison 2012; Venker and Kover 2015). Eye-gaze tasks permit the measurement of language processing in real time, instead of after processing has taken place (as in pointing or demonstration tasks). In addition, eye-gaze tasks have limited behavioral response demands (e.g., no verbal or pointing response was required), which allowed us to include children with a wide range of language and cognitive abilities. Our rationale was that examining incremental language processing in children with ASD who have more limited language skills, as well as those with stronger language skills, would allow us to learn more about the processes that support language development—including areas that have been suggested to be affected in individuals with ASD. For example, there is considerable evidence that individuals with ASD organize and integrate semantic information differently than individuals without ASD (e.g., Bowler et al. 2008; Henderson et al. 2014). Differences in semantic organization and integration could impact the ability of individuals with ASD to use semantic information during language processing.

[1] Although Brock et al. (2008) found no significant relationship between language scores and the isolated effect of verb semantics, it should be noted that in their study, "individuals with poorer language scores spent significantly more time gazing at the (contextually inappropriate) phonological competitor" (p. 899), regardless of autism diagnosis. We do not focus heavily on this finding in the present study because our task and research questions focused on looks to target in the presence of an unrelated distracter.

The current study was designed to determine whether preschoolers with ASD use semantic information in verbs to anticipate upcoming nouns. Given evidence of this ability in older and higher-functioning children with ASD, we expected that preschoolers with ASD, as a group, would show a head start in looking to the target images when presented with semantically-constraining verbs, compared to neutral verbs. However, we also expected children to vary a great deal in the size of the head start they showed when presented with semantically-constraining verbs. To make sense of this anticipated variability, we asked whether differences in incremental language processing were associated with children's existing receptive language skills. We hypothesized that children with stronger language skills would show greater use of a semantically-constraining verb for incremental language processing, and that the link between incremental language processing and language skills in semantically constrained contexts would be stronger than the link between language processing and language skills in non-constrained contexts.

Importantly, this study was not designed to determine *whether* individuals with ASD can use semantic context to think ahead during spoken language processing; several studies have shown that at least some of them can. Instead, our primary purpose was to examine the association between constrained and neutral language processing contexts, and children's receptive language skills as measured by a standardized assessment.

Table 1 Participant Information

	Mean (SD) Range
Age (in months)	56.15 (3.94) 49–62
Autism severity	8.05 (1.88) 4–10
Ratio IQ ($n = 18$)	77.06 (26.80) 38–108
Receptive language standard score ($n = 17$)	76.59 (24.45) 50–118
Receptive language age equivalent	37.47 (21.35) 9–78
Receptive language growth scale value	413.00 (86.12) 270–523
Receptive language raw score	36.35 (16.10) 49–62
Expressive language standard score ($n = 17$)	68.00 (16.18) 50–95
Expressive language age equivalent	31.00 (15.49) 5–59
Expressive language growth scale value	388.00 (74.68) 244–497
Expressive language raw score	32.06 (11.82) 9–53

Autism severity was measured by the ADOS-2 comparison scores. Ratio IQ scores were derived from the Mullen. Receptive and expressive language scores were derived from the Auditory Comprehension and Expressive Communication scales of the PLS-5

Methods

Participants in the current study were 20 children with ASD who took part in a longitudinal study of lexical processing. Children were initially seen when they were 2–3 years old. A follow-up visit took place approximately 2 years later, when children were 4–5 years old. A total of 32 children participated in the initial visit; 20 children returned for the follow-up visit. All children received a DSM-5 diagnosis of ASD at the initial visit, based on the ADI-R (Rutter et al. 2003), ADOS-2 (Lord et al. 2012), and expert clinical judgment. ASD diagnosis was confirmed at the follow-up visit based on the ADOS-2 and expert clinical judgment. For more information about the initial visit, see (Ellis Weismer et al. 2016). The follow-up visit is described in detail below.

Standardized Assessments

The research visit took place across 2 days and included a developmental evaluation with cognitive, language, and autism assessments (see Table 1 for full participant characteristics). On average, 6 days elapsed between visits ($SD = 5$, range = 1–17). The Visual Reception and Fine Motor scales of the Mullen Scales of Early Learning (MSEL; Mullen 1995) assessed nonverbal cognitive abilities. Ratio IQ scores were derived by averaging the age equivalent scores from both scales, dividing by the child's chronological age, and multiplying by 100 (Bishop et al. 2011). The Auditory Comprehension and Expressive Communication scales of the Preschool Language Scales, 5th Edition (PLS-5; Zimmerman et al. 2011), assessed receptive language and expressive language, respectively. The PLS-5 covers several different language-related domains, including vocabulary, morphology, syntax, play, gesture, and emergent literacy. Growth scale values from the Auditory Comprehension scale were used in the analyses because they provided a raw measure of children's receptive language on an equal-interval scale.[2] The ADOS-2, a standardized, play-based assessment for ASD, provided a measure of autism severity. The ADOS-2 also provided a broad indication of children's expressive language abilities, as modules were selected based in part on

[2] Because PLS-5 Auditory Comprehension growth scale values provide an absolute measure of language ability and do not control for age, we examined the correlation between receptive language and age. This correlation was non-significant, $r = -.128$, $p = .626$.

children's spoken language skills. Based on module selection for the ADOS-2, four children were not producing any spontaneous spoken language; five children were producing single words; 10 children were using phrase speech; and one child was using fluent speech. Per parent report, 18 children were receiving speech-language pathology services through their local school district. Fourteen children were receiving intensive autism services (at least 20 h/week of in-home or center-based services), and three were receiving non-intensive, autism-specific intervention (such as a social skills group or counseling services).

Experimental Task

Children participated in two looking-while-listening (LWL) tasks. A mispronunciation processing task, in which familiar words were pronounced incorrectly, was administered but will not be discussed here. The current study focused on the incremental language processing task, which included both semantically-constraining verbs and neutral verbs. The incremental language processing task used a standard LWL design (Fernald et al. 2008), presenting a sequence of trials that each consisted of two images on a screen with accompanying speech. Children were told they were going to watch a movie but were not given any other explicit instructions. Parents were asked not to direct their child's attention or talk to their child during the experiment, and they were given a pair of opaque (blacked out) sunglasses to prevent them from viewing the screen and unintentionally influencing their child's behavior. Parents were told they could stop the task at any time if their child became distressed. During the task, children sat independently on a chair or on a parent's lap in front of a 55-inch wall-mounted television screen. A video camera below the screen recorded children's faces for later offline coding of eye gaze.

Auditory stimuli were recorded in child-directed speech by a female native English speaker and were presented at a level of 70 dB from a central speaker located below the screen. Visual stimuli were pictures of prototypical objects obtained through online image searches. Each trial displayed two images, one on each side of the screen. To enhance visibility, each image was placed on a grey box and presented on a black background (see Fig. 1). In both Neutral and Constraining trials, verbs began 1800 ms into the trial and nouns began 2790 ms into the trial. Onsets of the verbs and nouns were time-locked across trials and across trial types to allow direct comparison. A reinforcing phrase (e.g., *That's great!*) followed each noun to maximize engagement. Each trial lasted 6 s.

The incremental language processing task included two trial types: Neutral and Constraining. On Neutral trials, verbs contained no disambiguating semantic information that would allow children to predict which of the two objects would be named (e.g., *Find the bike*). On Constraining trials, verbs provided semantic information that would plausibly describe only one of the two objects (e.g., *Ride the bike*), thereby allowing children to predict which object would be named. The task included two neutral verbs (*find, look at*), six constraining verbs (*eat, ride, throw, drink, read, open*) and six nouns (*cake, bike, ball, juice, book, door*). It should be noted that although the constraining verbs named actions that were not feasible to carry out during the testing situation (e.g., children could not actually eat the cake pictured on the screen), we did not encounter any situations in which children attempted to carry these actions out. It should also be noted that only the neutral verbs provided instructions that encouraged children to do the task (*find, look at*). Though these instructional verbs could theoretically have increased children's attention to the task, such a result would work against our hypothesis that children would show a head start in Constraining trials relative to Neutral trials.

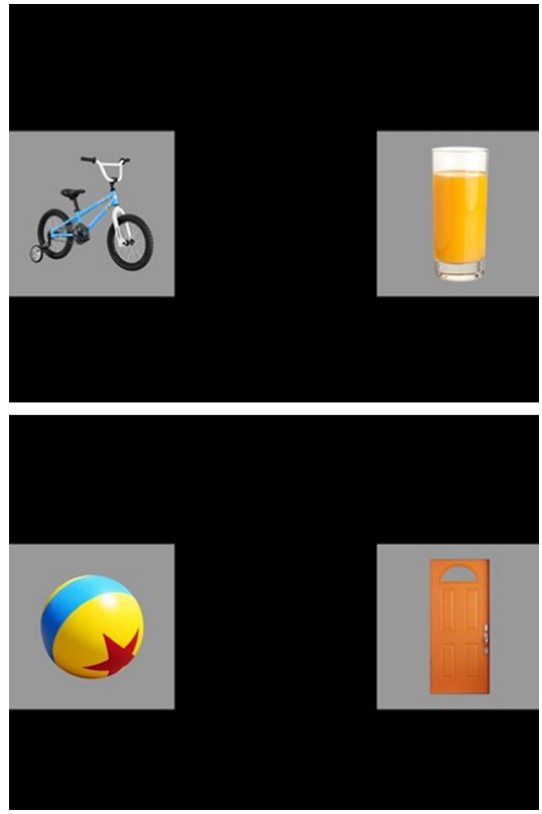

Fig. 1 Sample visual stimuli from the experimental task

The utterances included in the Constraining trials were: *Eat the cake, Ride the bike, Throw the ball, Drink the juice, Read the book*, and *Open the door*. The experimental words we selected were actions and object nouns likely to be known by young children with ASD, based on preliminary data from one of the author's labs. In addition, the verbs selected in this study overlapped almost entirely with those used in a previous study of 2-year-olds with typical development (Mani and Huettig 2012). Each noun served as the target and the distracter in both trial types. The task was presented on both days of the visit. Children viewed 12 Constraining and 12 Neutral trials on each day, for a maximum of 24 trials per trial type. Stimuli were counterbalanced and two different versions of the task were created to ensure that children's performance was not driven by specific aspects of the experimental design.

Eye-Gaze Coding and Processing

For each 33 ms time segment, trained coders determined from video whether children's gaze was directed toward the target image, distracter image, or neither image (e.g., looks between the images or away from the screen). Following procedures from previous published studies (Fernald et al. 2010; Naigles et al. 2011), inter-coder agreement was calculated by comparing videos from two independent coders for a subset of the full participant sample. Agreement was conducted for four randomly-selected participants (20% of the full sample). Overall agreement across all time segments was 98%, and agreement for time segments with a shift in gaze was 96%.[3] Based on Barr (2008), we selected an analysis window that incorporated the point where looks to target began to consistently increase in Constraining trials and captured the approximate peak of looking to target for both trial types (i.e., where the two curves crossed). The analysis window began at average verb offset (460 ms before the onset of the noun) and ended 900 ms after noun onset, lasting a total of 1360 ms. Because the onsets of verbs and nouns were time-locked across trials, the same analysis window was used regardless of target word or trial type. (Though there was some variability in looks to the target before verb onset across both trial types, this variability was unlikely to reflect meaningful looking behavior since children did not yet have any auditory information regarding which object would be named.) Trials were excluded if a child had looked at the images less than half of the time during the analysis window. On average, children contributed 17.0 trials in Constraining trials ($SD = 4.7$, range = 8–24) and 16.1 trials in Neutral trials ($SD = 4.6$, range = 6–24), of the maximum of 24 trials per trial type. During the analysis window, children looked away from the images 10.7% of the time in Constraining trials ($SD = 4.0\%$, range = 5.9–21.9%) and 11.0% of the time in Neutral trials ($SD = 3.6\%$, range = 5.3–20.7%).

[3] To simplify internal algorithms, the software used to calculate inter-coder agreement excluded trials that differed in the number of gaze shifts. On average, 77% of trials were retained.

Analysis Plan

We used growth curve analysis (Mirman 2014) to model the probability of looking at the target image during each 33 ms time frame. Time was the independent variable and log odds of looking to the target (versus looking to the distracter) was the dependent variable. Following standard practice in LWL studies (Fernald et al. 2008), looks away from the images were not included in the calculation of the dependent variable. Models included participant and participant by trial type random effects. Orthogonal time terms (linear and quadratic time) were used to allow independent interpretation of each term. The model containing linear and quadratic time was selected as the baseline model because it provided a significantly better fit to the data than the model containing linear time alone ($\chi^2_8 = 1025.81$, $p < .001$). Although the model including cubic time provided a significantly better fit to the data than the model with linear and quadratic time alone ($\chi^2_{10} = 598.96$, $p < .001$), this model was not selected for two reasons. First, individual coefficients revealed no significant contribution of cubic time in either trial type (*p*s > .18). Second, examination of the weighted orthogonal time terms in each trial type revealed that cubic time contributed minimally to the shapes of the curves.

The Neutral trial type was the reference category. The z distribution was used to evaluate the significance of the t-values for individual coefficients (i.e., $t \geq \pm 1.96$ was considered significant at the 0.05 level). When child characteristics (e.g., receptive language) were entered into the models, we tested the association between the child variable and random effects in each of the time terms: intercept (which can be interpreted as overall accuracy, or area under the curve), linear time, and quadratic time. Child variables (e.g., receptive language, age) were mean-centered to facilitate interpretation.

Results

As expected, children's gaze to the target image increased over the course of the trial for both trial types. This general pattern of results is consistent with previous findings in studies using eye-gaze methods to examine comprehension/language processing (Bavin et al. 2014; Marchman and Fernald 2008; Venker et al. 2013). However, it is also clear that the trial type—Neutral versus Constraining—determined how quickly children began increasing their looks to the target.

Our first research question was: Do preschoolers with ASD use semantic information in verbs to predict upcoming nouns? As illustrated in Fig. 2, children showed a head start when presented with semantically-constraining verbs, with a reliable increase in their looks to the target earlier in Constraining trials (approximately 500 ms after verb onset)

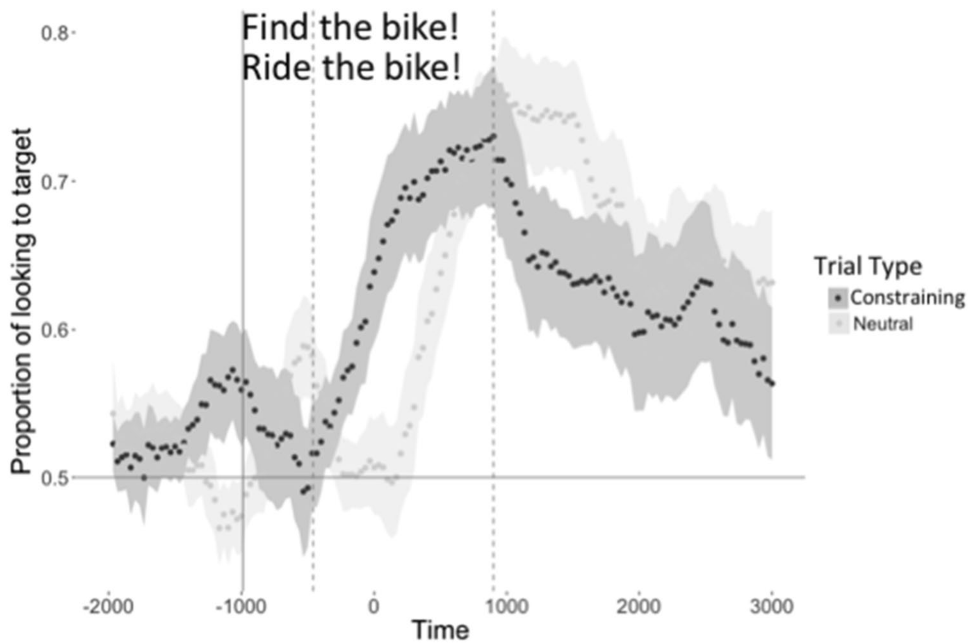

Fig. 2 Mean looks to target in each trial type during the full trial. Time represents the time course of the trial, with 0 at the onset of the target noun. The proportion of looking to target was the amount of time looking at the target, divided by the amount of time looking at either image. The solid grey line indicates verb onset. The first dotted line indicates the start of the analysis window, and the second dotted line indicates the end of the analysis window. Shading represents plus or minus one standard error of the mean

Table 2 Baseline model

	Estimate	*SE*	*t* value	*p* value
(Intercept)	0.375	0.139	2.706	.007
Linear time	2.156	0.482	4.476	< .001
Quadratic time	1.198	0.399	2.998	.003
Constraining trials	0.371	0.136	2.736	.006
Linear time: constraining trials	−0.259	0.606	−0.428	.669
Quadratic time: constraining trials	−1.964	0.565	−3.477	< .001

Effects were significant at $p < .05$. Neutral was the reference trial type. The independent variable was time and the dependent variable was the log odds of looking to the target image

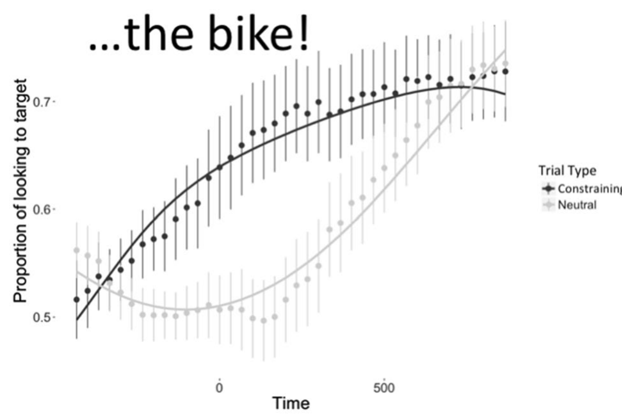

Fig. 3 Raw data and model fits (from the baseline model) in each trial type during the analysis window. Time represents the time course of the trial, with 0 at the onset of the target noun. The proportion of looking to target was the amount of time looking at the target, divided by the amount of time looking at either image. Error bars represent plus or minus one standard error of the mean

than in Neutral trials. In fact, children's looks to target on Constraining trials began to increase, on average, approximately 500 ms before the onset of the noun. The primary analysis window began at average verb offset (460 ms before the onset of the noun) and ended 900 ms after noun onset. In the baseline model, overall accuracy (i.e., orthogonal intercept) was significantly higher in Constraining trials (68%) than in Neutral trials (60%; $p = .006$), demonstrating that children looked significantly more overall at the target in Constraining trials (see Table 2). There was no significant effect of trial type for linear time ($p = .669$), but the interaction between quadratic time and trial type was significant ($p < .001$), indicating a difference in the shapes of the curves for Neutral versus Constraining trials. As shown in Fig. 3, the mean curve for Neutral trials bowed downward; starting at noun onset (Time = 0), the proportion of looking to target showed an increasing rate of change over time. In contrast, the mean curve for Constraining trials bowed upward, indicating a decreasing rate of change over time as looking to target reached a plateau.

To determine whether the effect of semantically-constraining verbs was also evident in later processing, we constructed a model of looks to target during the latter part of the trial (900–3000 ms after noun onset). There were no significant differences between trial types for any time terms at the end of the trial (all $ps > .27$); thus, the effects of verb semantics were reflected only in the initial head start.

Next, we asked whether incremental language processing in a semantically constrained context (i.e., performance in Constraining trials) was associated with children's

Table 3 Model containing receptive language

	Estimate	*SE*	*t* value	*p* value
(Intercept)	0.408	0.110	3.710	< .001
Linear time	2.204	0.404	5.454	< .001
Quadratic time	1.390	0.403	3.452	< .001
Constraining trials	0.425	0.132	3.210	0.001
Receptive language	0.003	0.001	2.598	0.009
Linear time: constraining trials	0.009	0.571	0.015	0.988
Quadratic time: constraining trials	− 2.245	0.560	− 4.012	< .001
Linear time: receptive language	0.022	0.005	4.556	< .001
Quadratic time: receptive language	0.004	0.005	0.925	.355
Constraining trials: receptive language	0.003	0.002	2.112	.035
Linear time: constraining trials: receptive language	− 0.012	0.007	− 1.828	.068
Quadratic time: constraining trials: receptive language	− 0.018	0.007	− 2.729	.006

The Neutral trial type was the reference category. The independent variable was time and the dependent variable was the log odds of looking to the target image. Receptive language was represented by growth scale values from Auditory Comprehension scale of the PLS-5

concurrent receptive language skills on a standardized assessment, and—if so—how the strength of this association compared to the strength of the association between receptive language skills and incremental language processing in a non-constrained context (i.e., Neutral trials). To address these questions, we added receptive language (Auditory Comprehension growth scale values from the PLS-5) to the baseline model. Three children were excluded from these analyses because they failed to complete the PLS-5, leaving 17 children. The model with receptive language provided a significantly better fit to the data than the baseline model ($\chi^2_6 = 32.60$, $p < .001$), indicating that receptive language helped to explain children's performance in the experimental task.[4] As in the baseline model, overall accuracy was significantly higher ($p = .001$) in Constraining trials than in Neutral trials, demonstrating that children looked more reliably at the target image in Constraining trials, as a result of looking to the target earlier. The shapes of the curves again differed between the two trial types ($p < .001$), but the linear time term did not significantly differ ($p = .998$).

We next examined model results to determine the role of receptive language skills more precisely (see Table 3). There was a significant association between receptive language and overall accuracy in Neutral trials ($p = .009$), such that children looked more at the target as receptive language scores increased. The association between receptive language and accuracy was significantly stronger in Constraining trials than in Neutral trials ($p = .035$), indicating that the increase in accuracy associated with an increase in receptive language was larger when children heard a semantically-constraining verb than when they heard a neutral verb. In fact, the effect of receptive language was twice as strong for Constraining trials than Neutral trials. This effect is illustrated in Fig. 4: Children with stronger receptive language skills showed a considerable head start in looking to target in Constraining

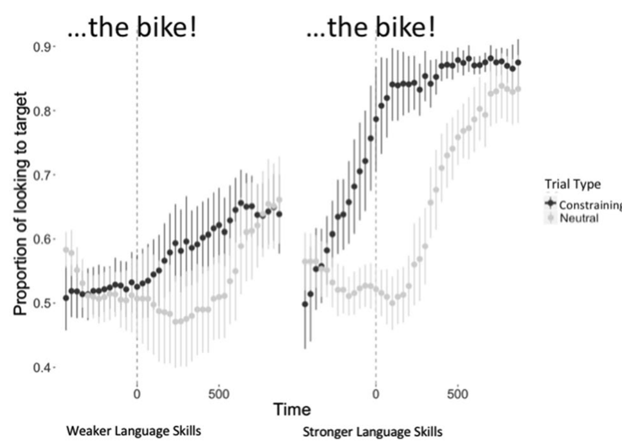

Fig. 4 Mean looks to target in each trial type during the analysis window. For purposes of illustration, patterns for children with weaker receptive language skills (below the median) are shown in the left panel and patterns for children stronger receptive language skills (above the median) are shown in the right panel. Receptive language was measured by growth scale values from the Auditory Comprehension scale of the PLS-5. Children with weaker language skills showed an attenuated head start relative to the children with stronger language skills. Time represents the time course of the trial, with 0 at the onset of the target noun. The proportion of looking to target was the amount of time looking at the target, divided by the amount of time looking at either image. Error bars represent plus or minus one standard error of the mean

[4] Following Borovsky et al. (2012) we also tested whether age was associated with children's performance in the experimental task. The model containing age did not provide a significantly better fit to the data than the baseline model ($\chi^2_6 = 7.851$, $p = .249$), and age yielded no significant main effects or interactions ($ps > .176$).

trials, whereas children with weaker receptive language skills showed an attenuated head start.

There was a significant association between receptive language and linear slope in Neutral trials ($p < .001$), indicating that children with stronger receptive language skills were faster to increase their looks to the target. The association between receptive language and linear slope was marginally weaker in Constraining trials than in Neutral trials, but this difference was not significant ($p = .068$). Receptive language was not significantly associated with quadratic time in Neutral trials ($p = .355$). However, the strength of the association between receptive language and the quadratic term was significantly stronger in Constraining trials than in Neutral trials ($p = .006$).

In summary, children with weaker receptive language abilities showed a smaller head start than children with stronger receptive language abilities. Receptive language was associated with more looking to target in both trial types, but the effect of receptive language was significantly stronger when children heard semantically-constraining verbs than when they heard neutral verbs. Receptive language was associated with faster processing speed (linear slope) in both trial types.

Discussion

This study provided the first evidence that incremental language processing in a semantically constraining context is associated with existing receptive language skills in children with ASD. When presented with semantically-constraining verbs, children with ASD (ages 4–5) showed an overall head start in lexical access, indicating that they were capable of using semantic cues in unfolding speech to predict upcoming nouns (also see Bavin et al. 2016; Brock et al. 2008; Hahn et al. 2015). However, the size of the head start shown by individual children varied as a function of their receptive language skills. Children with stronger receptive language skills (as measured by the Auditory Comprehension scale of the PLS-5) began increasing their looks to the target images immediately after hearing a semantically-constraining verb, showing a head start of approximately 600 ms relative to trials with neutral verbs (see Fig. 4). Children with weaker receptive language skills showed a much smaller head start. Thus, although children with ASD are capable of incremental language processing as a group, performance was considerably less robust in children with ASD with weaker receptive language skills.

What does it mean that incremental language processing was closely linked with receptive language skills in children with ASD? First and foremost, these findings demonstrate continuity between patterns of language development in typical development and in ASD. In the current study, variability in incremental language processing was associated with children's existing receptive language skills—a finding that aligns with evidence of previous associations in children and adults with typical development. The results of the current study add to growing evidence that some aspects of language development in children ASD are qualitatively similar (though delayed) to those in typical developing children (Arunachalam and Luyster 2016; Ellis Weismer et al. 2011) and supports the benefit of providing semantically rich language input to children with ASD—including those with considerable language delays. It is not entirely clear why the current study identified an association where previous studies of children with ASD did not. It may relate to our inclusion of children with a diverse range of language skills, as well as the fact that we used an absolute measure of children's receptive language skills (growth scale values), as opposed to a standard score that accounted for children's age.

Why did some children show greater incremental language processing than others? Additional research is needed to answer this question, but some insights may be gained by considering the skills that were required for successful incremental language processing in our experimental task. First, children would have needed to know the meanings of the constraining verbs (*eat, ride, throw, drink, read, open*). Though we did not have access to an independent measure of word knowledge outside the experimental context, children's performance in the task itself provided an indication that they understood the verbs. As illustrated in Fig. 4, even the children with weaker receptive language skills showed a head start in the Constraining trials, relative to the Neutral trials. This boost in performance makes sense because even though many of the children demonstrated considerable delays in language development, they were between 4 and 5 years old and had no doubt heard verbs like *read* and *eat* many thousands of times at this point in development. These specific verbs and nouns were selected because they were those most likely to be known by children with ASD as young as 2 years old (as well as children with typical development). In addition, the visual context of the LWL task constrained candidate words to only two choices, thereby maximizing the likelihood that children would activate and use their existing verb knowledge.

Successful incremental language processing also required knowledge about the semantic links between the verbs and the upcoming target nouns—for example, that a book is readable, but juice is not. This is an interesting point to consider because individuals with ASD appear to organize and integrate semantic information differently than individuals without ASD, even during the toddler and preschool years (Bowler et al. 2008; Dunn et al. 1996; Gastgeb et al. 2012; Henderson et al. 2014; McGregor and Bean 2012; Naigles and Tek 2017; Potrzeba et al. 2015). It is possible, then, that differences in semantic organization—specifically, the degree to which children's lexical representations of verbs and nouns were semantically linked—contributed to children's varying levels of success. This will also be an important issue to investigate in children with language impairments in the absence of ASD, as previous studies have identified similar patterns of language processing in children with impaired language (regardless of ASD diagnosis; Brock et al. 2008; Norbury 2005).

In addition to knowing the semantic link between verbs and nouns, children had to use this information to predict what word would come next, as indicated by their increased attention to the object that would subsequently be named. The role of incremental abilities is important to investigate because deficits in prediction have been proposed to underlie numerous aspects of the ASD phenotype (Gomot and Wicker 2012; Pellicano and Burr 2012; Van de Cruys et al. 2014), including language (Sinha et al. 2014). For example, some children may give an inflexibly strong weight to instances in which they have made incorrect predictions—likely to happen quite often in a noisy domain such as language—which deters them from making strong predictions in the future (Sinha et al. 2014). Another possibility is that some children's language processing is driven more by lower-level sensory aspects of the environment (e.g., perceptual salience) than by top-down, integrative systems, which leads to difficulties in making flexible predictions (Amso et al. 2014; Gomot and Wicker 2012). One challenge for future research is to make these broad proposals more specific, testable, and linked with theory and clinical practice.

Because the results of this study linking incremental language processing and existing receptive language are correlational, our results cannot speak to the directionality of this relationship. Like Borovsky et al. (2012), the current study identified a correlation between incremental language processing and receptive language, but not between incremental language processing and age, which could be viewed as suggesting that incremental language processing may exert some influence on vocabulary development (also see mediation analyses by Weisleder and Fernald 2013, which begin to address directionality in typical development). Using semantic cues to think ahead increases the efficiency of language processing. A limited ability to use such cues would likely lead to delayed language comprehension and lost learning opportunities. Although differences of a few hundred milliseconds may seem small in isolation, such differences would quickly accumulate, producing cascading negative effects on language development over time (also see Bavin et al. 2016). In addition, impairments in incremental language processing may make it more difficult for children to rapidly identify novel word forms or to realize when there is an inconsistency between their mental representations and the linguistic input (i.e., when a prediction does not match the subsequent input). Given the variable performance across children, it is important to determine what can be done to support the development of strong incremental language processing abilities in children with ASD. Although we are not aware of behavioral interventions that directly target incremental language processing, it is not difficult to imagine techniques that could facilitate this ability—for example, providing strong semantic contexts that encourage prediction or reinforcing successful incremental language processing when it occurs.

One strength of the current study was that we examined the link between children's receptive language skills and their processing of utterances with semantically-constraining verbs (e.g., *Eat*) and utterances with neutral verbs (e.g., *Find*). This allowed us to examine differences not only in children's ability to process spoken nouns after they were presented, but also in their ability to use semantic cues to think ahead, directing their attention to the object consistent with the action described. Although children with weaker receptive language skills showed poorer language processing overall, the association between language skills and incremental language processing was significantly stronger than the association between language skills and non-incremental language processing. Although we are not aware of any other published studies in typical development or in ASD that have tested the association between language skills and incremental as well as non-incremental language processing, this approach may be valuable for gaining insight into the relative contributions of language processing in different linguistic contexts.

Though children in the current study showed evidence of thinking ahead, we fully acknowledge that our results cannot speak to the extent to which prediction occurs during language processing in everyday life. As discussed by Huettig and Mani (2016), there is little empirical evidence that prediction is *necessary* for language processing. Instead, there may simply be some processing contexts—such as the constraining trials in the current study—in which prediction can provide a "helping hand." It is also important for future studies to determine how incremental processing in children with ASD is affected not only by bottom-up cues, such as semantic information, but also by top-down cues, such as plausibility. Previous work with typically developing children has shown that although adults consider top-down information during incremental processing, children rely more heavily on bottom-up information (Kidd et al. 2011).

In conclusion, the findings of this study underscore the value of examining the link between incremental language processing and language skills in children with ASD who demonstrate a wide range of receptive language skills. Although structural language skills are no longer part of the diagnostic criteria for ASD (American Psychiatric Association 2013), language remains a critical area of concern for many of these individuals with ASD and thus should receive thorough attention in both research and clinical settings (Eberhardt and Nadig 2016). In addition to advancing our understanding of variability in language skills across ASD, longitudinal and experimental work including a comparison group will clarify the role of incremental language processing in both typical and atypical language development. For example, factors such as attention, memory, socio-economic status, and autism severity may also play a role.

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Compliance with Ethical Standards

Conflict of interest All authors declare that they have no conflict of interest.

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