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RESEARCH ARTICLE

Predictive language processing in young autistic children

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Abstract
Recent theories propose that domain-general deficits in prediction (i.e., the ability to anticipate upcoming information) underlie the behavioral characteristics associated with autism spectrum disorder (ASD). If these theories are correct, autistic children might be expected to demonstrate difficulties on linguistic tasks that rely on predictive processing. Previous research has largely focused on older autistic children and adolescents with average language and cognition. The present study used an eye-gaze task to evaluate predictive language processing among 3- to 4-year-old autistic children ($n = 34$) and 1.5- to 3-year-old, language-matched neurotypical (NT) children ($n = 34$). Children viewed images (e.g., a cake and a ball) and heard sentences with informative verbs (e.g., *Eat the cake*) or neutral verbs (e.g., *Find the cake*). Analyses of children's looking behaviors indicated that young autistic children, like their language-matched NT peers, engaged in predictive language processing. Regression results revealed a significant effect of diagnostic group, when statistically controlling for age differences. The NT group displayed larger difference scores between the informative and neutral verb conditions (in looks to target nouns) compared to the ASD group. Receptive language measures were predictive of looking behavior across time for both groups, such that children with stronger language skills were more efficient in making use of informative verbs to process upcoming information. Taken together, these results suggest that young autistic children can engage in predictive processing though further research is warranted to explore the developmental trajectory relative to NT development.

Lay Summary
This study found that 3- to 4-year-old autistic children and younger, language-matched neurotypical (NT) children both used verbs to predict upcoming nouns in sentences like "Eat the cake." For both autistic and NT children, those with stronger language skills were able to predict upcoming nouns more quickly.

KEYWORDS
anticipatory language processing, autism spectrum disorder, language development, prediction, receptive language

INTRODUCTION

While children diagnosed with autism spectrum disorder (ASD) by definition demonstrate difficulty with social communication, there is considerable variability observed in structural language abilities (i.e., vocabulary/grammar) within this population (Anderson et al., 2007). An essential first step to understanding this heterogeneity across autistic individuals is to investigate potential differences in underlying learning mechanisms known to support neurotypical (NT) language skills.

Prediction, a mechanism which contributes to language processing ability in NT development (e.g., Mani & Huettig, 2012), has been proposed by several researchers in recent theoretical accounts as a domain-general impairment in ASD (e.g., Gomot & Wicker, 2012; Sinha et al., 2014; Van de Cruys et al., 2014). For example, the Prediction Impairment in

Autism (PIA) hypothesis (Sinha et al., 2014) posits that domain-general deficits in predictive ability underlie the core symptoms of ASD and its associated characteristics. While this account has been examined empirically in a number of domains including sensory processing (Baum et al., 2015; Neil et al., 2016; Stevenson et al., 2014), social cognition (Balsters et al., 2017; Chambon et al., 2017; von der Lühe et al., 2016), motor function (LeBarton & Landa, 2019) and imitation (Xavier et al., 2018), the relationship between prediction and language in ASD has not yet been extensively investigated. Given that the PIA proposes domain-general difficulties in prediction abilities, we might expect more autistic children to experience difficulties with prediction in comparison to NT children, such that autistic children perform differently from NT children on language processing tasks which rely on prediction. By examining predictive language processing in autistic preschool children and language-matched NT peers, the present study will advance our understanding of language differences in ASD in addition to informing recent theoretical frameworks of ASD (e.g., Sinha et al., 2014; van de Cruys et al., 2014).

Empirical evidence suggests prediction supports language processing and learning for NT children, including the ability to predict upcoming words in sentences (Borovsky et al., 2012; Fernald et al., 2008; Lew-Williams & Fernald, 2007; Mani & Huettig, 2012, 2014; Reuter et al., 2019; Reuter et al., 2021). For example, Mani and Huettig (2012) found 2-year-old children could use informative verbs to predict upcoming nouns in sentences like "The boy will eat the cake," as evident from anticipatory eye movements in an eye-tracking task (Altmann & Kamide, 1999). There are also notable individual differences in predictive language processing: NT children's prediction measures are positively associated with standardized measures of language ability, such as vocabulary size (Borovsky et al., 2012; Lew-Williams & Fernald, 2007; Mani & Huettig, 2012). Recent results suggest predictive language processing emerges during the early stages of typical development, as early as 18–24 months (Fernald et al., 2008; Mahr et al., 2015; Mani & Huettig, 2012).

Semantic information—especially semantic information inherent to verbs—may also enable predictive language processing for autistic children (Bavin et al., 2016; Brock et al., 2008; Hahn et al., 2015; Venker et al., 2019; Zhou et al., 2019). For example, Brock et al. (2008) found 12- to 17-year-old autistic adolescents used semantically informative verbs (e.g., "Joe stroked the hamster quietly") to look more quickly to target images (e.g., hamster vs. hammer) than when listening to sentences with neutral verbs (e.g., "Joe chose the hamster reluctantly"). Contrary to expectations, no group differences in looking behavior were found compared to NT peers matched on age, nonverbal cognition, and language (Brock et al., 2008).

Prior findings further suggest 5- to 9-year-old autistic children with language and cognitive abilities in the average range can also use verb meanings to rapidly and accurately direct attention to target images, demonstrating task performance on par with same-age NT children with similar (but not statistically matched) language and nonverbal cognition (Bavin et al., 2016). However, there were notable differences in looking behavior in this study; the ASD group looked later to targets when listening to sentences with neutral verbs and looked away from targets more quickly than NT children when listening to sentences with informative verbs. The authors attributed this tendency to a preference for visual information among autistic children (Bavin et al., 2016). Another study demonstrated a similar ability to use the semantic context of a sentence to resolve lexical ambiguity between targets and homophones in 6- to 9-year-old autistic children and gender-, age-, language-, and nonverbal cognition-matched NT peers (Hahn et al., 2015).

More recent eye-gaze studies have likewise found that 4- and 5-year-old autistic children looked more quickly to target images when sentences included a semantically informative verb as compared to sentences with a neutral verb (Venker et al., 2019; Zhou et al., 2019). Autistic 5-year-old looked as quickly to target nouns following informative verbs as younger, language-matched NT children and age-matched NT children, but looked less to targets overall compared to age-matched NT children (Zhou et al., 2019).

Language ability has also been examined in two existing studies in relation to predictive language processing among autistic children. Both studies found a positive association between language ability and predictive language processing, such that 4- to 5-year-old and 12- to 17-year-old autistic children with higher scores on standardized language assessments showed greater sensitivity to semantically informative verbs (Brock et al., 2008; Venker et al., 2019). Similar results have emerged in studies of NT children (e.g., Borovsky et al., 2012) suggesting language ability and prediction ability may be positively associated regardless of children's diagnostic status. This pattern of findings is not unexpected—for any child, making predictions based on the semantic content of a verb requires some degree of extant knowledge about that verb.

It is worth noting that most studies to date have included only autistic children with language and nonverbal cognition abilities within the average range, sometimes referred to in the literature as "high-functioning" (Bavin et al., 2014; Bavin et al., 2016; Hahn et al., 2015; Zhou et al., 2019). These studies exclude a significant portion of individuals on the autism spectrum and are thus not representative of this population as a whole. By excluding children with co-occurring cognitive and structural language difficulties, the generalizability of these prior findings is limited.

The developmental emergence of predictive language processing in ASD also remains underspecified in the current literature. To date, the youngest autistic participants studied have been 4–5 years old (Venker et al., 2019; Zhou et al., 2019). Evidence from one of these studies suggests there may be some developmental differences in this ability for autistic children: Using an eye-gaze task, Zhou et al. (2019) observed that while autistic 5-year-olds used semantically informative verbs to predict the target image, they showed a smaller proportion of looks to target nouns following informative verbs compared to neutral verbs relative to age-matched NT peers. Establishing whether such differences in predictive language processing emerge during earlier stages of development is critical for understanding the mechanisms underlying early language processing and learning in ASD.

In order to address these limitations in the existing literature, the present study examined predictive language processing in 3- to 4-year-old autistic children and 1.5- to 3-year-old, language-matched NT peers. We aimed to evaluate (1) whether young (3- to 4-year-old) autistic children with a broader range of abilities predict upcoming words as they process incoming, familiar words and (2) to what extent their prediction abilities are on par with those of younger, language-matched NT children. We carefully considered our options for matching, as there is no clear consensus on ideal matching variables in the ASD language processing literature (Bavin et al., 2016; Hahn et al., 2015; Zhou et al., 2019). Given the highly verbal nature of the task, and prior findings indicating a strong positive link between autistic children's language ability and prediction ability in the task (Venker et al., 2019), we wanted to ensure that any group differences would not be readily explained by a simple difference in language ability between diagnostic groups. We used an experimental eye-gaze task to measure predictive language processing and standardized assessments to measure language, cognition, and autism severity. Unlike previous studies (e.g., Bavin et al., 2016; Zhou et al., 2019), we included autistic children with below-average language and cognitive assessment scores (Table 1). The eye-gaze task was based on prior work by our research team with somewhat older autistic children (Venker et al., 2019) and included two types of trials with pre-recorded sentences: Informative sentences included semantically informative verbs enabling the prediction of upcoming target nouns (e.g., *Ride the bike*) and Neutral sentences included uninformative verbs (e.g., *Find the bike*). If 3- to 4-year-old autistic children use informative verbs to make predictions, we expected them to look more quickly to the target image (e.g., bike) during Informative trials than Neutral trials, as observed for older autistic children (e.g., Venker et al., 2019). Moreover, if 3- to 4-year-old autistic children show differences in looking behavior compared to younger, language-matched NT children, these results may suggest developmental differences in predictive language processing for young autistic children.

METHODS

Participants

Participants were 34 autistic children (24 male) and 34 neurotypical children (13 male) who took part in a larger investigation of language processing that included an initial visit when autistic participants were 2- to 3-year-old and a follow-up visit approximately 1 year later. Prior publications have reported other experimental eye-gaze tasks that were administered to the children in the broader project (Ellis Wesimer et al., 2016; Pomper et al., 2021; Venker et al., 2019). Participants in the ASD group received DSM-5 ASD diagnoses from an experienced clinical psychologist on our research team based on the ADI-R (Rutter et al., 2003), ADOS-2 (Lord et al., 2012) and their best estimate clinical diagnosis. In the NT group, children were excluded if they received elevated scores on the Modified Checklist for Autism in Toddlers (M-CHAT; Robins et al., 2014) or if the team psychologist and speech language pathologist observed any behaviors consistent with atypical development and/or ASD. At the time of the eye-tracking task reported in the present study (visit 2), autistic children were 37–50 months old ($M =$ 44 months, SD = 4 months) and NT children were 18–36 months old ($M =$ 26 months, SD = 5 months). The NT group was significantly younger than the ASD group ($p < 0.001$) by design, because we included autistic children with concomitant language and/or cognitive delay. Table 1 details group comparisons.

We tested but excluded 18 additional children from all analyses due to: previously diagnosed vision impairment (1), failing to complete the PLS-5 (3), evidence of atypical development in assessment scores or behavior observed by the team psychologist and speech-language pathologist (12), the child refusing to participate (1), or inattention such that the child completed less than half of both task orders (1). Additionally, 7 children provided data for only one of the two task orders due to: computer error (3), experimenter error (1), ambient noise (1), or the child refusing to participate (2).

Families were recruited from communities across Wisconsin and Illinois. Children lived in monolingual, English-speaking households, and had no known hearing or vision impairments. Self-reported maternal education ranged from 12 to 24 years ($M =$ 16 years, SD = 3 years). According to parent report, the racial composition of the sample was White ($n = 61$), Multiracial ($n = 5$), Black/African-American ($n = 1$), and American Indian/Alaska Native ($n = 1$). Sixty-four children were reported not to be Hispanic or Latino and 4 children were Hispanic or Latino. The Education and Social

TABLE 1 Participant characteristics

	ASD group Mean (SD) range	NT group Mean (SD) range	Group comparisons
Age (months)	44 (4) 37–50	26 (5) 18–36	Cohen's $d = 4.04$ variance ratio = 0.48 $p < 0.001$
Auditory comprehension			
Raw score	32 (9) 18–50	32 (8) 19–48	Cohen's $d = 0.06$ variance ratio = 1.54 $p = 0.79$
Standard score	75 (18) 50–108	110 (14) 81–137	Cohen's $d = 2.17$ variance ratio = 1.72 $p < 0.001$
Expressive communication			
Raw score	32 (7) 14–46	33 (6) 25–43	Cohen's $d = 0.10$ variance ratio = 1.46 $p = 0.787$
Standard score	79 (12) 50–108	111 (9) 95–130	Cohen's $d = 2.99$ variance ratio = 1.65 $p < 0.001$
Nonverbal ratio IQ	75 (20) 48–116	112 (14) 94–152	Cohen's $d = 2.16$ variance ratio = 1.90 $p < 0.001$
ASD symptom severity	8 (2) 4–10	—	—

Note: Descriptive statistics for the ASD group ($n = 34$) and NT group ($n = 34$). Auditory comprehension and expressive communication were measured by the Preschool Language Scales, 5th edition. Nonverbal Ratio IQ was measured by the Mullen Scales of Early Learning. ASD symptom severity was measured by the ADOS-2 comparison score.

Sciences Institutional Review Board at the University of Wisconsin-Madison approved this research protocol. Experimenters obtained written informed consent from a legal guardian for each participant. Families received payment at each longitudinal visit as compensation for their time and children received a book or small toy.

Standardized measures

During each longitudinal visit, participants received a comprehensive developmental evaluation including cognitive, language, and autism assessments, a subset of which were included in the present study. To confirm ASD diagnoses, a clinical psychologist administered the ADOS-2 (Lord et al., 2012), a standardized assessment considered part of the "gold-standard" evaluation for ASD diagnosis (Kamp-Becker et al., 2018). The ADOS-2 also provided derived comparison scores—a measure of the severity of autism symptoms compared to others with ASD diagnoses of the same age and language ability on a scale of 1–10, with greater scores indicating greater severity (Weitlauf et al., 2014). The team psychologist also administered the Mullen Scales of Early Learning (MSEL; Mullen, 1995) in order to evaluate participants' nonverbal cognition and to calculate nonverbal ratio IQ scores for each participant (Bishop et al., 2011). A certified speech-language pathologist administered the Preschool Language Scales 5th Edition (PLS-5, Zimmerman et al., 2011) to assess receptive and expressive language. The PLS-5 is a standardized language assessment consisting of two subscales, Auditory Comprehension (AC) and Expressive Communication (EC), measuring receptive and expressive language respectively. Table 1 provides descriptive statistics for ASD and NT groups, including age, autism symptom severity, nonverbal IQ, and language ability.

Group matching

We matched diagnostic groups based on receptive language, as measured by PLS-5 AC raw scores (Table 1). We used a bootstrap procedure to match groups, with a caliper of five points for scores. For details on this approach, refer to Pomper et al. (2019). We quantified group differences with Cohen's d, variance ratio (ASD divided by NT), and p values (Kover & Atwood, 2013).

We used a two-sample, two-tailed t test to obtain p values, unless either group's distribution failed the Shapiro–Wilk normality test (Shapiro & Wilk, 1965), in which case we used a non-parametric Wilcoxon rank sum test (Wilcoxon, 1945).

Eye-tracking task

Procedure

The task took place in a sound-attenuated booth at Waisman Center. Children sat on their caregiver's lap, approximately 60 cm from the display screen. The experimenter told children that they would see a 'movie' and that they should watch and listen. The experimenter instructed caregivers to avoid talking to their child or directing their child's attention during the task, and caregivers wore opaque glasses to further prevent them from influencing their child's looking behaviors. The experimenter monitored children's attention via a camera below the display screen. During the task, children viewed visual stimuli on the 55-inch display screen and heard auditory stimuli at 65 dB from a central speaker. A video camera below the screen recorded children's eye movements with a frame-rate of 30 Hz. The experimenter controlled the task from a PC host computer, using E-Prime software (Version 2.0, Schneider et al., 2002). The total duration of the eye-tracking task was approximately 3 min.

Stimuli

Auditory stimuli consisted of two types of pre-recorded sentences from a prior study (Venker et al., 2019). Informative sentences included semantically informative verbs that children could use to predict an upcoming target noun (e.g., *Ride the bike*). Neutral sentences, in contrast, did not include any words that would facilitate accurate predictions (e.g., *Find the bike* or *Look at the bike*). A female, native speaker of English recorded auditory stimuli, using child-directed intonation. The total duration of sentences was 3818 ms. The onset of the verb (e.g., *ride/find*) occurred 1800 ms after trial onset, and the onset of the target noun (e.g., *bike*) occurred 2790 ms after trial onset, such that verb onset was 990 ms before noun onset. To help maintain children's engagement, a reinforcing sentence (e.g., *That's great!*) followed each target noun.

Visual stimuli were also identical to a prior study (Venker et al., 2019) and included prototypical images of the six target nouns: *ball*, *bike*, *book*, *cake*, *door*, and *juice*. Each image appeared within a 600 × 600 pixel gray box on a black background to enhance visibility (Figure 1). Each item appeared eight total times during the eye-tracking task (four times per condition; four times as the target image and four times as the distractor image). As each item appeared on multiple trials, we used four exemplars for each item to help maintain children's attention.

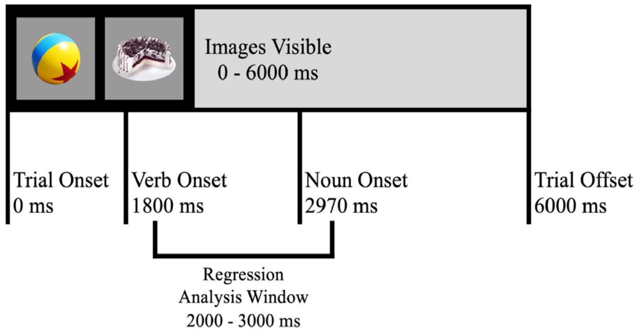

FIGURE 1 Trial schematic. The total duration of each trial was 6000 ms. The cue sentence duration was 3818 ms. The onset of the verb (e.g., *eat/find*) occurred 1800 ms after trial onset, and the onset of the target noun (e.g., *cake*) occurred 2790 ms after trial onset, such that verb onset was 990 ms before noun onset. The regression analysis window began at 200 ms after verb onset and ended 200 ms after noun onset (1000 ms total duration) from 2000 ms to 3000 ms from trial onset. Following the cue sentence, in order to help maintain children's attention to the task, a reward sentence (e.g., *That's great!*) followed each target noun

During each trial, visual stimuli appeared for 1800 ms before the onset of auditory stimuli and remained visible throughout the remainder of the trial. Total trial duration was 6 s, and there was a 500 ms inter-trial interval. Trials appeared in one of two quasi-randomized task orders, which counterbalanced target side (right or left). Orders also ensured that condition (neutral or informative) and target side (right or left) did not repeat for more than two trials sequentially, and that visual stimuli did not appear in the same locations (e.g., *ball* on the left and *door* on the right) for sequential trials. Filler trials occurred every six trials, and consisted of 5-s musical videos. In total, each order of the eye-gaze task included 12 informative trials, 12 neutral trials, and 4 filler trials.

Data analysis

Data processing

Following established procedures for eye-gaze paradigms (see Fernald et al., 2008), researchers coded videos of children's looking behaviors, indicating whether the child was looking to the right image, left image, shifting, or looking away from the screen for each video frame. To prevent potential biases, coders were unaware of the visual and auditory stimuli and diagnostic group assignment. A second researcher independently re-coded 44 randomly selected videos (65% of the total sample, prior to group matching) to attain two standard measures of inter-coder reliability: Frame agreement (the mean proportion of frames on which coders agreed) and shift agreement (the mean proportion of shift frames on which coders agreed) were 98% and 92% respectively for the ASD group. For the NT group, frame agreement was 99% and shift agreement was 94%, indicating robust inter-coder reliability for both groups.

If children used informative verbs (e.g., *ride*) to anticipate upcoming nouns (e.g., *bike*), then we expected to observe anticipatory eye movements to the target image (Altmann & Kamide, 1999; Kamide, 2008; Kamide et al., 2003). We therefore focused on a time window which began 200 ms after verb onset and ended 200 ms after noun onset (1 s total duration), taking into account the estimated time needed to generate an eye movement based on phonological information (Canfield et al., 1997; Matin et al., 1993). As in prior studies (Pomper et al., 2019; Venker et al., 2019) we excluded trials in which children looked to the visual stimuli for less than 50% of the analysis window and trials in which the child's caregiver interfered (i.e., pointing to the screen). Instances of interference were extremely rare (six total trials). Children in the ASD group contributed an average of 17/24 trials in the Informative condition (SD = 5, range = 5–24) and 17/24 trials in the Neutral condition (SD = 5, range = 5–24). Children in the NT group contributed an average of 20/24 trials in the Informative condition (SD = 3, range = 12–24) and 20/24 trials in the Neutral condition (SD = 4, range = 11–24). Per participant, the ASD group contributed fewer trials for analysis than the NT group for Informative trials ($t[57] = -2.91$, $p = 0.005$) and for Neutral trials ($t[57] = -2.93$, $p = 0.005$). Two participants in the ASD group were outliers, meaning their total trials contributed fell more than 2.5 SDs below the mean for the entire sample. Post-hoc analyses did not indicate a significant effect of trials contributed and are included in Supporting information. We used R software (Version 4.0, R Core Team, 2020) and RStudio software (Version 1.3, RStudio Team, 2020) for analyses. Analyses and R code are available on the *Open Science Framework*.

Analytical approach

To evaluate children's language processing abilities, we used cluster-based permutation analyses and a mixed-effects logistic regression model, detailed below. Cluster-based permutation methods are typically used for neurophysiological data analyses (Maris & Oostenveld, 2007), but this non-parametric approach is valuable for visualizing temporal effects from eye-gaze data as well (Borovsky, 2017; Chan et al., 2018; Dautriche et al., 2015; Hahn et al., 2015; Reuter et al., 2021; Wittenberg et al., 2017). Mixed-effects models are commonly used for eye-gaze analyses (Barr, 2008; Barr et al., 2013; Huettig et al., 2011). Together, these analyses aid in evaluating whether there may be differences in predictive language processing between ASD and NT groups.

RESULTS

Cluster-based permutation analyses

To compare and visualize results for ASD and NT groups (Figure 2), we analyzed children's mean proportion of looks to the target image during informative and neutral sentences with cluster-based permutation analyses, following procedures from prior eye-gaze studies (e.g., Hahn et al., 2015). We analyzed target looks from 1 s before to 1 s after target noun onset, identified clusters

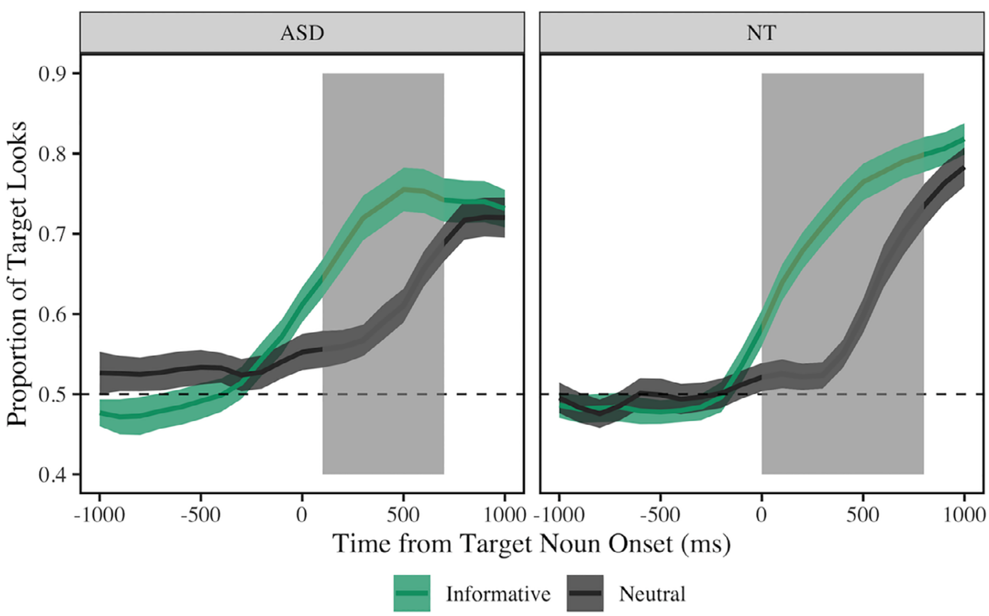

FIGURE 2 Cluster permutation analysis results. Proportion of target looks for children with autism spectrum disorder (ASD, $n = 34$) and neurotypical (NT) children ($n = 34$) during Informative sentences (green) and Neutral sentences (gray). The onset of the target noun (e.g., *cake*) is at 0 ms. Line shading represents one standard error from the mean, averaged by subjects. Horizontal dashed line indicates chance performance. The full analysis window for the cluster permutation analysis (1000 ms before noun onset to 1000 ms after noun onset) is depicted. Area shading indicates significant clusters from permutation analyses ($ps < 0.001$)

of adjacent 100-ms time-bins in which logistic regression models indicated significant condition effects, and summed t values within each observed cluster. We then created a null distribution by randomly permuting condition labels 1000 times and replicated the cluster-finding procedure with permuted data. The resulting cluster p value conveys the proportion of permuted cluster t values that were greater than the observed cluster t value. Findings revealed significant clusters for the ASD group (100–700 ms after target noun onset, cluster $t = 24.70$, $p < 0.001$) and for the NT group (0–800 ms after target noun onset, cluster $t = 36.60$, $p < 0.001$), suggesting both ASD and NT groups used informative verbs to predict the upcoming target noun (Figure 2).

Regression analysis

We next analyzed children's proportion of looks to the target image during sentences with a mixed-effects regression model, using the lme4 package (Version 1.1-26, Bates et al., 2015) and the lmerTest package (Version 3.1-3, Kuznetsova et al., 2017). The model included interacting fixed effects for diagnostic group (contrasts: NT = −1, ASD = 1), linear time (33-ms frames, from 200 ms after verb onset to 200 ms after noun onset, centered and scaled), and receptive language (PLS-5 Auditory Comprehension raw scores, centered and scaled), with child age (centered and scaled) included as a covariate. The random-effects structure included a by-subject random intercept and by-subject slope for linear time, a by-item (target noun) random intercept, and by-item random slopes for linear time, diagnostic group, and receptive language. This was the maximal model that successfully converged (Barr et al., 2013). Our analysis window (200 ms after verb onset to 200 ms after noun onset, total duration 1000 ms) captured the rise and peak of changes in target looks as a function of the verb (Informative minus Neutral). Our dependent variable was the mean difference in proportion of looks to the target noun between the Informative and Neutral conditions (Informative minus Neutral), calculated for each 33-ms frame within the analysis window. Positive target look difference scores indicated that children used informative verbs (e.g., *ride*) to predict upcoming nouns (e.g., *bike*).

Accounting for the effect of age, findings revealed a significant main effect of diagnostic group ($\beta = -0.13$, $t = -2.53$, $p = 0.014$), which indicated a smaller mean difference between Informative and Neutral conditions across the analysis window in the ASD group compared to the NT group. There was also a significant effect of time ($\beta = 0.03$, $t = 2.34$, $p = 0.030$), indicating that the difference in children's looks to target images during Informative trials compared to Neutral trials increased over time throughout the analysis window. The effect of age was also significant, ($\beta = 0.14$, $t = 2.59$, $p = 0.012$) such that the difference in looks to target between Informative and Neutral conditions (difference scores) increased with child age. Results further revealed a significant interaction for time and receptive language ($\beta = 0.03$, $t = 2.87$, $p = 0.006$), such that children with stronger receptive language ability had more robust time-bound condition differences in their looking behaviors. That is, children with stronger receptive language ability were able to look more to target (e.g., *bike*) following informative verbs (e.g., *ride*) compared to neutral verbs (e.g., *find*) sooner in the trial compared to children with weaker receptive language abilities. We observed no significant interaction effect for diagnostic group with time ($p = 0.363$), indicating that there were no group differences in time-bound change in target look difference scores. To visualize results, we divided children into two PLS groups based on a median split of PLS-5 auditory comprehension raw scores (Figure 3).

To further explore the effect of age for each group, we conducted a post-hoc analysis allowing age and diagnostic group to interact in the regression model, which can be found in Supporting information. The interaction of age and diagnostic group was not significant ($\beta = 0.03$, $t = 0.82$, $p = 0.416$).

DISCUSSION

The present study aimed to evaluate predictive language processing among preschool (3- to 4-year-old) autistic children across a broader range of language and cognitive ability than prior research and to assess the extent to which their skills are on par with younger, language-matched NT children. In light of current theoretical frameworks positing a domain-general deficit in prediction skills in ASD (e.g., Sinha et al., 2014), we anticipated that diagnostic groups may demonstrate differences on language tasks relying on predictive ability. Our results indicated that both ASD and younger NT groups made use of semantically informative verbs to predict upcoming nouns, as evidenced by anticipatory eye movements during an eye-gaze task. Regression results revealed the ASD group (when controlling for age) demonstrated a weaker condition effect (Informative verbs relative to Neutral verbs) than the NT group, similar to previous studies (Brock et al., 2008; Zhou et al., 2019). This finding may suggest that autistic children may not make as much use of the semantic content of verbs when predicting upcoming nouns as NT children with similar language ability. Alternatively, group differences may be indicative of weaker links in autistic children's semantic networks (Arias-Trejo & Plunkett, 2013; Borovsky et al., 2016; Willits et al., 2013). Our research group is currently investigating these two possible interpretations in ongoing studies. However, according to regression results, those group differences were not time-bound. The ASD group predicted upcoming target nouns as efficiently as younger, language-matched NT peers. In

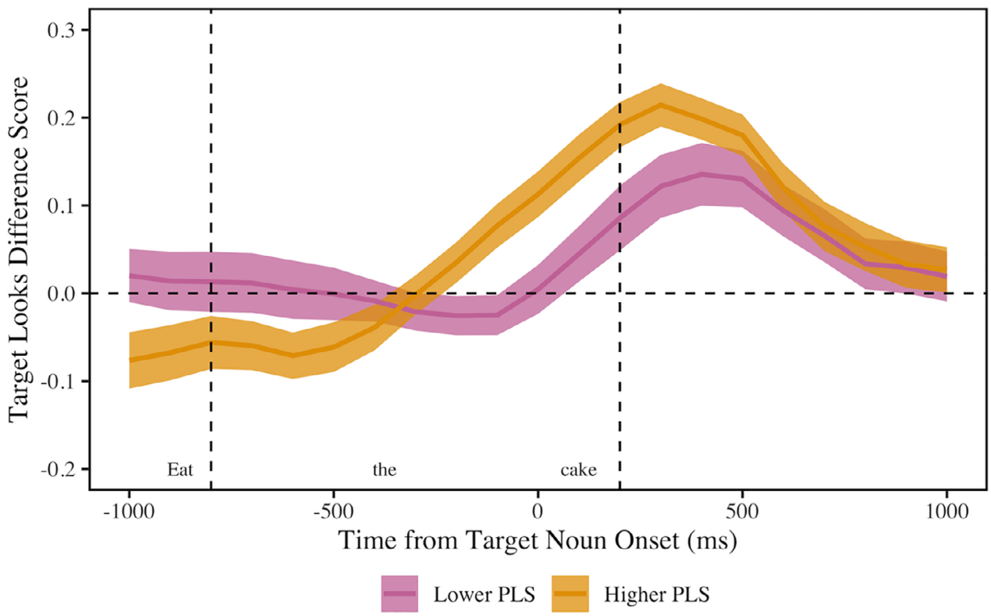

FIGURE 3 Regression analysis results. Children's proportion of looks to the target image (e.g., cake) during Informative sentences (e.g., *Eat the cake*) minus their proportion of looks to the target image during Neutral sentences (e.g., *Find the cake*) for neurotypical (NT) children ($n = 34$) and children with ASD ($n = 34$). To aid in visualizing regression results, we collapsed across groups and divided children into a Lower PLS group (pink) and a Higher PLS group (orange) based on a median split of PLS-5 Auditory Comprehension raw scores. Target noun onset is at 0 ms. Vertical dashed lines indicate the analysis time window (200 ms after verb onset to 200 ms after noun onset). Horizontal dashed lines indicate equivalent target looks for Informative and Neutral conditions. Line shading indicates one standard error from the mean, averaged by subjects

contrast to some accounts (e.g., Naigles & Tek, 2017) but in line with other findings (Haebig et al., 2015), this evidence suggests similarities in the organization of autistic children's semantic networks to language-matched NT peers. While the interaction between diagnostic status and time was not significant, we did find evidence for a time-bound relationship between receptive language and predictive processing, such that children across groups with stronger receptive language skills were able to more efficiently use informative verbs to predict upcoming nouns.

The present findings add to a growing body of developmental literature investigating predictive language processing in ASD. Results are consistent with existing evidence from older children and adolescents that language-matched diagnostic groups are similarly efficient in predicting upcoming nouns (e.g., Brock et al., 2008; Zhou et al., 2019). This was the case even though our sample included autistic children with language and cognitive deficits as well as children with average abilities in these areas. Moreover, the observed relationship between receptive language and predictive language processing in the present study aligns with previous evidence in older autistic children (Brock et al., 2008; Venker et al., 2019). For example, using a similar eye-gaze task, Venker et al. (2019) found a positive link between these measures for 4- and 5-year-old autistic children. Similar findings indicating a positive correlation between prediction measures and standardized measures of language ability have also been reported in the NT literature (Borovsky et al., 2012; Lew-Williams & Fernald, 2007; Mani & Huettig, 2012; Ylinen et al., 2017).

In addition to expanding upon prior empirical evidence, the present findings provide important information for refining theoretical frameworks of ASD proposing prediction deficits (Gomot & Wicker, 2012; Sinha et al., 2014; van Boxtel & Lu, 2013; van de Cruys et al., 2014). Our results do not support a strong form of prediction deficit accounts of ASD—at least not in the realm of language. Young autistic children were indeed able to engage in predictive language processing. Further, language abilities, rather than diagnostic status per se, appeared to play a greater role in the ability to anticipate upcoming target nouns. That said, our findings may be viewed as suggesting that predictive language processing is typically utilized by autistic children at a later point in development than for NT children. Recall that the NT group in this study was intentionally younger than the ASD group to allow us to match on absolute language skills (raw scores) but yet enroll a representative sample of young children on the autism spectrum. Although ASD diagnostic criteria do not include structural language delay or cognitive delay, these concomitant conditions are relevant to the social-communication challenges in ASD. Language and cognitive delays are more prevalent in autism cohorts than a similarly defined neurotypical cohort and are predictive of functional outcomes (Goodwin et al., 2017; Kover et al., 2016; Wiggins et al., 2015). Thus, the similar performance of the ASD and NT groups, reflected by the lack of a significant group by time interaction, should be viewed within the larger context of group characteristics. The ASD group was significantly older, had significantly poorer receptive and expressive language abilities relative to age-level expectations (lower standard scores), and had significantly lower cognitive abilities than the NT group (Table 1). Although suggestive, this study cannot confirm development delays in predictive processing because we did not have an age-matched comparison group (as a group, autistic children in the age range of the NT group could not perform this task).

There are certain limitations of this study that should be acknowledged. While we included children with a broader range of cognitive and language ability compared to previous work, it is still worth noting that this sample does not represent the full range of language ability that exists within the ASD population. In the process of matching groups on receptive language, autistic children whose PLS-5 scores could not be matched with those within the NT group were excluded. Matching groups therefore reduced variance within the ASD group to some extent, but it also allowed for greater interpretability of results. By matching groups on receptive language measures, any observed group differences would be more likely to reflect diagnostic status as opposed to differences in language ability. Another limitation of the study is that our groups were not matched on sex and we had relatively few girls in the ASD group. This overrepresentation of boys in the ASD group is in line with the disproportionate sex distribution found in the population at large. However, recent research has reported sex-based differences in ASD, including in linguistic features (Boorse et al., 2019; Ratto et al., 2018; Song et al., 2021). It will be important for future studies to examine possible sex differences in predictive language processing across groups matched on this variable. As noted above, groups also differed in terms of nonverbal cognitive abilities which is another variable that should be further examined in subsequent research. A post-hoc analysis including the effect of nonverbal cognition yielded the same pattern of results as reported above and can be found in Supporting information. The present study also lacks demographic variance in that families were predominantly white and reported high levels of educational attainment; it is important to consider how children's social context might shape the course of their development (Nielsen et al., 2017). In addition, although sample sizes for the present study were on par with existing research (Hahn et al., 2015; Zhou et al., 2019), small samples reduce statistical power and can lead to erroneous conclusions (Oakes, 2017). Further work is needed to build upon the present results, ideally including a greater diversity of participants and larger sample sizes.

Finally, it should be noted that these data cannot speak to claims about directionality in the relationship between prediction and language ability. While receptive language scores and predictive language processing measures were positively linked, the present results do not establish the developmental time course or causality between these constructs (Rabagliati et al., 2016). Our research group aims to address this limitation in ongoing longitudinal work.

CONCLUSIONS

Findings indicate that autistic 3- to 4-year-olds are able to use verbs' semantic information to predict upcoming nouns and do so in a manner that is generally as efficient as toddlers who were on average 18 months younger but had equivalent language skills. While this study included a younger and more ability-inclusive ASD sample than previous work, the relationship between prediction and language in ASD requires further examination in order to determine directionality, stability over development, and associations with language learning. The present findings also provide a fruitful pathway for developing future language interventions. For autistic children, semantically informative sentence contexts facilitate more efficient processing of target nouns, but the emergence of this skill may be delayed compared to NT children. It is advised that clinicians targeting the specific needs of young autistic children should consider the role of semantic contexts when designing language interventions.

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