



OPEN Visual statistical learning and social attention in neurotypical, minimally speaking and speaking autistic preschoolers

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Autistic children experience atypical patterns of spoken language acquisition, yet the mechanisms underlying these differences remain poorly understood. In typical development, spoken language acquisition is gated by statistical learning abilities (the ability to detect patterns) and social attention (preferential engagement with social vs. non-social stimuli). The potential role of these mechanisms in the spoken language atypicalities seen in autism are under-researched, partly due to the methodological barriers when assessing children with minimal spoken language in this population. Here we examined statistical learning and social attention in 13 autistic preschoolers who use spoken language (mean chronological age = 34.38, SD = 8.16), 15 autistic preschoolers with minimal or no spoken language (mean chronological age = 30.20, SD = 7.07), and 15 neurotypical peers (mean chronological age = 36.73, SD = 6.51) using novel eye-tracking paradigms. Participants across groups showed evidence of statistical learning (anticipation of future events based on previous events) and showed preferential attention for social over non-social stimuli, with no between-groups differences. Within-group analyses revealed no association between spoken language skills, measured via the Mullen Scales of Early Learning Expressive Language and the Vineland Adaptive Behavior Scales Expressive Communication subscales, and total fixation duration indexes of statistical learning and social attention in the eye-tracking paradigms. Our findings point to previously unknown strengths in autistic children who are minimally speaking across statistical learning and social attention, suggesting that spoken language differences in this population might be unrelated to these domains.

A growing body of literature is elucidating the processes that contribute to spoken language acquisition in typical development^{1,2}. Knowledge of those processes can provide critical insight on populations showing atypical patterns language acquisition, such as Autism Spectrum Disorder (ASD, hereafter “autism”), a condition characterized by differences in social communication³ alongside restricted and repetitive patterns of behavior.

Spoken language differences in the autistic population are heterogeneous⁴ and range from subtle atypicalities in the pragmatic domain (i.e., adapting the communication to social context and demands⁵) to delayed or absent word-learning development encompassing both the expressive and receptive domain⁶. In autistic children who develop spoken language, documented differences include atypical prosody and distinctive patterns of language use, such as idiosyncratic phrasing and echolalia (i.e., immediate or delayed repetition of others’ speech)^{7,8}. Up to 30% of autistic children are ‘minimally speaking’, i.e., they present with no spoken language, or use only a limited number of words^{9,10} or fixed sentences¹¹. While heterogeneity exists within this group, many children who are minimally speaking have higher support needs and heightened risk for lifelong disabilities^{12–14}. Nevertheless, research on this population is limited, partly because differences in information processing affecting verbally-mediated tasks preclude many standard assessment procedures¹². As a consequence, there is limited knowledge of the processes contributing to the spoken language difficulties in this population, resulting in limited guidance for services and supports.

Against this background, a critical priority in the field is the examination of plausible mechanisms that might contribute to spoken language difficulties in this population using tests that do not rely on test-taking skills such as following verbal instructions. To address this need, novel experimental paradigms should be designed to measure mechanisms known to enable language acquisition in typical development, such as statistical learning and social attention^{15,16}.

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Statistical learning

Statistical learning refers to the detection of regularities from input coming from the environment¹⁷, allowing individuals to anticipate what happens next based on what happened previously¹⁸. In the language domain, this implicit process^{19,20} allows for the extraction of phonological, syntactic and orthographic patterns from a continuous flow of speech²¹. Research shows that typical infants can segment words and identify boundaries between syllables when exposed to a stream of spoken language¹⁸. Visual statistical learning (i.e., extracting regularities from visual input to make predictions) appears to be equally relevant to spoken language acquisition. Indeed, recent research has documented that visual statistical learning at 6 months contributes to later communication skills in typical children^{22,23}. Additional studies have documented a link between implicit auditory and visual statistical learning skills and communication acquisition, in particular in relation to spoken language and syntactic abilities, in typical and atypical populations^{24,25}.

Research on autistic individuals has documented difficulties in making predictions, generalizing and extracting patterns from visual input across different types of tasks²⁶. Additionally, a recent large study documented impaired performance in visual statistical learning in autistic compared to non-autistic children, which was associated with verbal ability²⁷. However, the study also showed considerable variability in visual statistical learning skills in the autistic group, and other studies in the area reported intact visual statistical learning in the autistic population among both children²⁸ and adults²⁹. Further findings include atypical statistical learning development in autism, with autistic adults, but not autistic children, exhibiting superior visual statistical learning compared to neurotypical controls³⁰. One limitation in this body of research is its prevalent focus on autistic participants who use spoken language, thus neglecting to examine the potential role of statistical learning in those presenting with minimal use of spoken language.

Given the variability observed within the autistic population and the bias towards the more verbally able end of the spectrum, further investigation is needed to clarify whether statistical learning may be atypical and associated with spoken language use in autistic preschoolers across the range of spoken language abilities.

Social attention

Recent research suggests that social attention, i.e., engagement with socially relevant stimuli, such as faces and speech, acts as a gateway for language acquisition in typical and atypical development^{31,32}. For example, five-month-old infants show increased brain activity in response to adults engaging socially with them versus engaging with other people, with brain response to social engagement predicting later vocabulary growth³³. In autistic populations, research has shown reduced preferential attention to visual social stimuli relative to nonsocial ones, compared to neurotypical individuals³⁴. Further, a link has been reported between social attention and spoken language outcomes, with increased engagement with speech stimuli associated with more typical neural responses and stronger language skills³⁵. However, counterevidence in this area also exists. For example, a recent meta-analysis found that differences in social attention in autistic individuals emerge in response to complex (e.g., when the stimulus included more than one person) but not simple social stimuli (e.g., static pictures with side-by-side social and non-social content)³⁶. This mixed pattern of results points to the need for further research focused on minimally speaking autistic children and testing whether those who are less engaged with social stimuli experience more pronounced difficulties in language acquisition.

Current study

Based on the plausible, yet untested, contribution of atypicalities in statistical learning and social attention to spoken language differences in autistic preschoolers, the current study aimed to examine performance in statistical learning and social attention, two key processes in spoken language development, in minimally speaking autistic preschoolers compared to speaking autistic and neurotypical children. A novel eye-tracking paradigm designed to address limitations in the previous literature was used to test the following hypotheses; (1) statistical learning and social attention would be impaired in autistic preschoolers who are minimally speaking compared to speaking autistic preschoolers and neurotypical peers, (2) performance in both statistical learning and social attention would be associated with expressive language within each group.

Results

Statistical learning

We first examined eye-tracking metrics of attention (i.e., total fixation duration and time to first fixation; see methods section) to the events displayed in the 4 learning trials of the statistical learning experiment (Fig. 1) to determine whether their gaze indicated anticipation of future events based on previously observed events.

To this aim, we compared participants' attention towards the stream where the ball was about to fall (target area) versus the other streams (non-target area) during the bridge occlusion phase (i.e., before the ball descended a waterfall; Fig. 1b). Statistics for the total fixation duration analyses are reported in the following section, while the analyses conducted using time to first fixation (i.e., latency) are reported in the Supplementary Materials section B "Time to First Fixation—Statistical Learning".

We first conducted a proof-of-concept analysis to determine whether the experiment elicited, as intended by its design, more attention to the target compared to the non-target area across groups. Paired-samples t-test analyses revealed that participants across groups and across the 4 learning trials looked for a longer duration of time towards the target compared to the non-target area, $t(166) = 4.59$, $p < 0.001$, $g = 0.35$.

We then tested whether participants' differential attention toward the target area (operationalized as total fixation duration towards the target *minus* total fixation duration towards the non-target areas) differed across groups and increased over the 4 learning trials using a univariate general linear model (GLM) that included the 4 learning trials as a within-subject factor and diagnostic group as the between-subjects factor. Descriptive statistics for the differential attention to the target area in each learning trial and each diagnostic group are

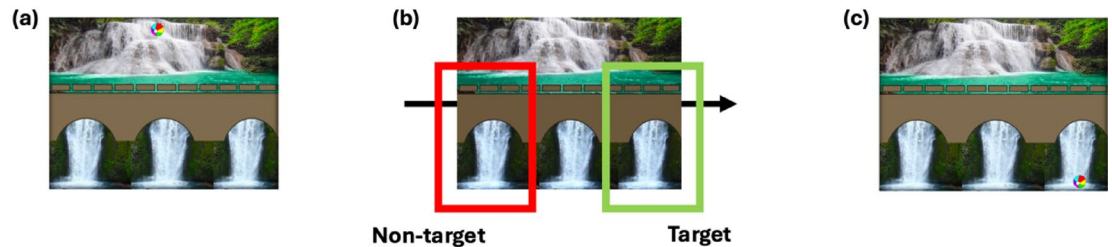
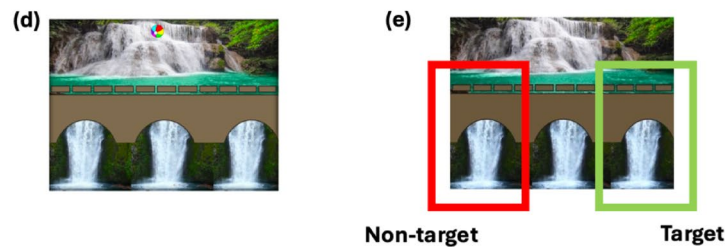
Learning Trial**Test Trial**

Fig. 1. Experimental design for assessing statistical learning through eye-tracking. This figure illustrates the sequence of events in the learning trials and test trial of the experimental paradigm designed to measure children's attention. Learning trial: (a) The ball descends a waterfall (b) the ball becomes occluded behind the bridge (c) the ball reappears in the designated stream, consistently on the same side (in this example, the right stream). Test Trial: (d) The ball descends again but (e) remains occluded behind the bridge.

reported in Supplementary Materials Table S1. The model showed no significant main effect of diagnostic group ($F(2,155) = 0.58, p = 0.56, \eta_p^2 = 0.007$), but did show a significant effect of trial ($F(3,155) = 3.11, p = 0.03, \eta_p^2 = 0.06$), indicating that the degree to which participants were looking more at the target versus non-target area varied across the 4 learning trials but not groups. Post hoc comparisons using Sidak adjustments revealed a significant increase in the differential attention towards the target area between trial 1 and trial 3 ($p = 0.04$). As illustrated in Fig. 2, this finding aligns with the hypothesis that anticipation of events increases with repeated exposure to the learning trials (i.e., the ball was increasingly expected to descend in the target vs. the non-target area), although such increase emerged in the third trial and was no longer apparent in the fourth trial (see Fig. 2).

We subsequently examined participants' duration of attention toward the target and the non-target area in the test trial. During this trial, presented after the 4 learning trials, the ball, after being occluded behind the bridge, is not seen descending the waterfall (see Fig. 1e). Therefore, attention toward the target area in the test trial was considered an additional index of statistical learning, as it reflected the anticipation of an event based on prior experience. Results of a repeated-measures GLM testing total fixation duration toward the target versus non-target areas with diagnostic group as a between-subjects factor revealed a significant main effect of target $F(1,40) = 15.64, p < 0.001, \eta_p^2 = 0.28$, but no effect of diagnostic group $F(2,40) = 0.34, p = 0.71, \eta_p^2 = 0.02$. This indicates that statistical learning occurred (i.e., participants expected to see the ball appearing in the area where it was seen during the learning trials), with no evidence of superior performance for any group.

Descriptive statistics for this analysis are reported in Supplementary Materials Table S2.

Finally, Kendall's tau correlation analyses testing the association between our eye-tracking index of statistical learning in the test trial and measures of expressive language (including the clinician-assessed Mullen Scales of Early Learning expressive language subscale and the parent-reported Vineland Adaptive Behavior Scales expressive communication subscale) showed no association between the variables of interest within each group or when groups were collapsed (all $ps > 0.15$). See Supplementary Materials Table S3 for correlation coefficients.

Social attention

We first investigated eye-tracking metrics of attention (i.e., total fixation duration and time to first fixation) in response to the social attention stimuli exemplified by the one illustrated in Fig. 3 to determine whether the task elicited, as per its design, more attention to the social versus the non-social areas across groups. Statistics for the total fixation duration analyses are reported in the following section, while the analyses conducted using time to first fixation (i.e., latency) are reported in Supplementary Materials section C "Time to First Fixation—Social Attention". Three stimuli were presented: one featuring two children playing and a flying balloon (Fig. 3), one featuring a girl dancing and a sunflower, and a third one featuring a group of boys playing soccer and an airplane.

A paired-samples t-test examining participants' attention (i.e., total fixation duration) allocated toward social and non-social areas of the social attention experiment (Fig. 3) revealed that overall participants allocated more attention toward the social stimuli, including when the average between the 3 stimuli was considered, $t(42) = 6.40, p < 0.001, g = 0.96$, and within each stimulus (stimulus a ($t(42) = 3.80, p < 0.001, g = 0.57$), stimulus b ($t(42) = 5.28, p < 0.001, g = 0.79$) and stimulus c ($t(42) = 3.45, p = 0.001, g = 0.52$).

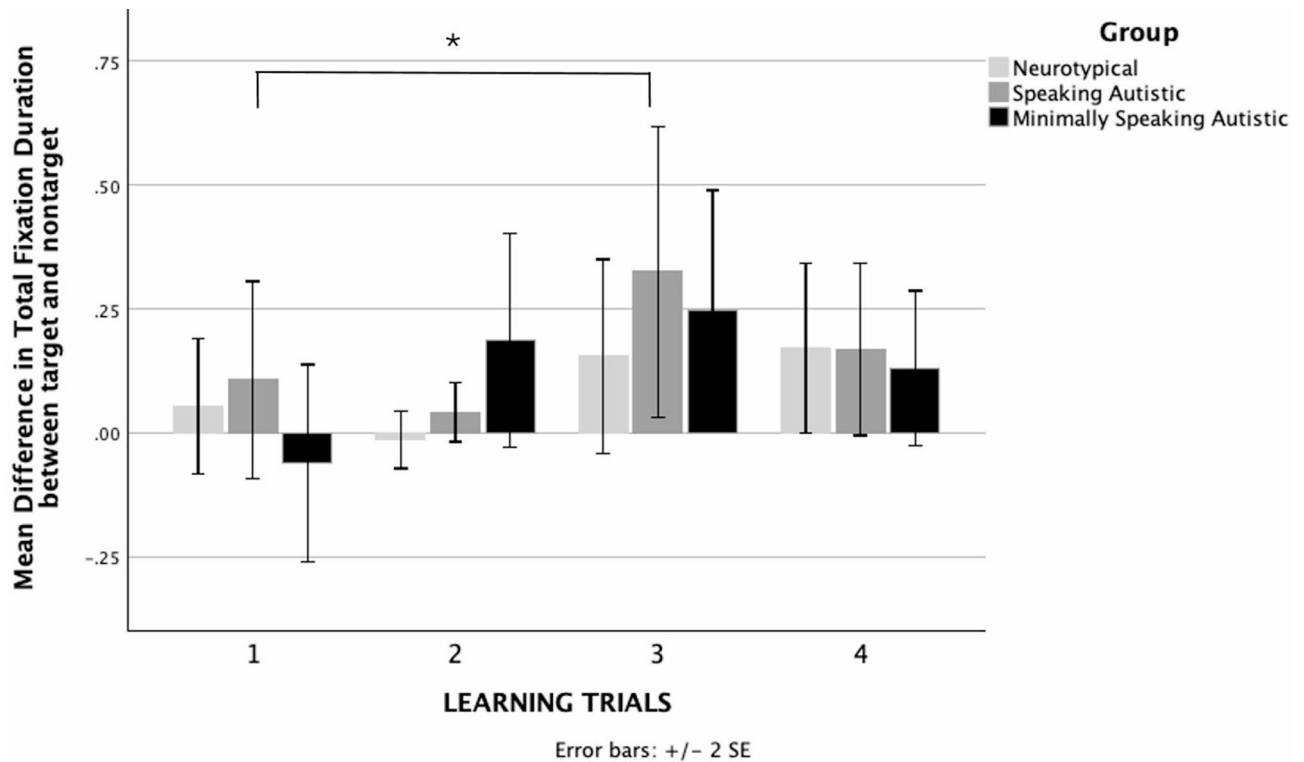


Fig. 2. Differential attention toward the target versus the nontarget area in each group and each trial.



Fig. 3. Visual stimulus used to assess social attention through a preferential looking paradigm. This figure presents one of the stimuli used in the social attention experiment. White rectangles indicate the predefined social and non-social areas of interest. The total duration of attention, quantifying how long participants focused their gaze on each predefined area of interest, was measured.

We then conducted a repeated-measures GLM with attention toward the social versus non-social areas as the within-subject factor and diagnostic group as the between-subjects factor. There was a main effect of condition (attention toward social vs. non-social area), $F(2,40) = 23.82$, $p < 0.001$, $\eta_p^2 = 0.37$, and no significant diagnostic group effect, $F(2,42) = 3.00$, $p = 0.06$, $\eta_p^2 = 0.13$ or group by condition interaction, $F(2,42) = 0.05$, $p = 0.95$, $\eta_p^2 = 0.003$, indicating an attentional preference for social stimuli that did not differ between the 3 groups (see Supplementary Materials Table S4 for the descriptive statistics for this analysis).

Finally, Kendall's tau correlation analyses testing the association between our eye-tracking index of social attention (total fixation duration toward social vs. non-social areas) and measures of expressive language (including the clinician-assessed Mullen Scales of Early Learning expressive language subscale and the parent-reported Vineland Adaptive Behavior Scales expressive communication subscale) showed no association between

the variables of interest within each group or when groups were collapsed (all $ps > 0.14$). See Supplementary Materials Table S5 for correlation coefficients.

Discussion

The aim of this study was to examine the performance of minimally speaking autistic children, speaking autistic children, and neurotypical children in experimental paradigms designed to test statistical learning and social attention—two processes known to contribute to spoken language acquisition^{27,35}. There was evidence for increased attention toward areas where future events were anticipated to occur based on previous events (i.e., statistical learning) and for preferential allocation toward social versus non-social stimuli across each group, including minimally speaking autistic preschoolers. Results of the analyses focused on latency of attention (Section B and C in the Supplementary Materials) were substantially aligned with this pattern. Additionally, within-group analyses did not support a link between performance in the experimental tasks and expressive language, suggesting that these processes, at least in the way they were operationalized in our eye-tracking experiments, were not contributing to variations in spoken language in our sample.

To our knowledge, this was the first study testing statistical learning and social attention using eye-tracking paradigms designed to be independent from spoken language and social engagement skills (e.g., following verbal instructions, engaging socially with an experimenter). As such, confounding factors that may have influenced findings in previous research (e.g., the ability to follow complex verbal instruction or “decoding” complex social interactions) were minimized in the current study, which may have contributed to our results. Indeed, although the experiments were successful in eliciting the processes under examination (anticipation of future events based on previous events, and preferential attention toward social vs. non-social stimuli) we found no evidence for impairments in these processes in autistic children, including minimally speaking preschoolers.

These findings challenge previous research documenting statistical learning impairments and reduced social attention in autism—although they do align with some studies indicating normative performance in this population^{28,36,37}.

Importantly, to our knowledge, our study was the first in this area of research to include a group of minimally speaking children, a population often overlooked in research due to barriers with traditional testing requirements. The rationale for including this group was the hypothesized contribution of statistical learning difficulties to the lack of spoken language. Contrary to our predictions, visual statistical learning did not appear to contribute to their presentation in the language domain—although our results do not rule out potential difficulties in other aspects of statistical learning, including impairments specific to the auditory domain.

With regards to our social attention experiment, our findings suggest typical patterns of social attention in response to static images in autistic preschoolers, including minimally speaking and speaking autistic children. These results contrast with a previous study that used the same paradigm on an older sample of autistic children (mean age = 46 months)³⁴, raising the possibility that age-related factors may modulate social-attentional patterns in this population. Age-related differences might be attributable to increased learning experiences during social interactions, which, in some cases, may involve repeated experiences of social difficulty that reduce motivation to engage. Additionally, age-related changes in neural circuitry supporting social cognition could modulate the salience of social stimuli over time. Moreover, there is an abundant literature documenting atypical visual social engagement in autistic individuals, including a preference for non-social stimuli such as background objects³⁸ and geometric patterns over social images³⁹. Our findings of a typical preference for social versus non-social images might reflect the influence of stimulus characteristics, such as their simple, static, and passive viewing nature—a notion aligned with previous research documenting normative social attention in response to static images in autism³⁷. Further, social attention seems to be more impacted in relation to the social content of the image, with autistic individuals showing greater difficulties with images representing more than one person³⁶, and the inclusion of stimuli related to circumscribed interest, i.e. geometric objects, that might lead to greater attention toward non-social aspects⁴⁰.

Despite these contributions, the study has some limitations, including the significant difference in chronological age between the neurotypical children and the minimally speaking autistic children, with the latter group being older. However, the inclusion of chronological age as a covariate in our analyses mitigates the potential impact of this difference.

The sample size, although comparable to that of similar eye-tracking research in autism³⁴, limits the statistical power to detect subtle group differences or interactions. Additionally, the use of static stimuli in the assessment of social attention may have resulted in an underestimation of social attention differences. Evaluating multiple components of social attention and pairing eye-tracking tasks with ecologically valid tasks (e.g., live interaction, dynamic scenes) could provide a more comprehensive examination of these processes among autistic preschoolers with various spoken language presentations. Relatedly, it is possible that performance of the specific tasks used in the study plateaued, limiting sensitivity to detect differences across groups and associations between eye-tracking and spoken language variables.

Further, longitudinal designs are needed to better understand how these early emerging mechanisms contribute to the emergence and development of spoken language during preschool years. In particular, the need for longitudinal studies is underscored by our finding of no significant differences among the three groups of preschoolers. This is in contrast with literature suggesting that older autistic individuals may exhibit enhanced statistical learning compared to neurotypical peers^{28–30}. Longitudinal studies would provide a unique opportunity to track the developmental trajectories of these abilities over time, while accounting for potential covariates, ultimately helping to identify distinct trajectories and their underlying mechanisms.

Additionally, the three groups in our study were not matched in all variables that could potentially contribute to the processes under examination, such as clinical and adaptive measures. While this is partially inevitable given the group composition (e.g., to be included in the minimally speaking group, children had to have below-

	TD ³ n = 15	ASD-S ⁴ n = 13	ASD-MS ⁵ n = 15	<i>T</i> test <i>p</i> value TD vs ASD-S	<i>T</i> test <i>p</i> value TD vs ASD-MS	<i>T</i> test <i>p</i> value ASD-S vs ASD-MS
	Mean (SD)	Mean (SD)	Mean (SD)			
Sex						
Males n (%)	8 (53.33%)	8 (61.54%)	13 (86.67%)			
Females n (%)	7 (46.67%)	5 (38.46%)	2 (13.33%)			
Chronological Age	36.73 (6.51)	34.38 (8.16)	30.20 (7.07)	0.41	0.01	0.16
MSEL ¹ Early Learning Composite Score	103.93 (26.42)	70.46 (21.21)	51.07 (3.52)	.001	<0.001	0.006
MSEL Visual Reception T score	53.07 (16.07)	36.23 (17.58)	21.67 (3.56)	0.01	<0.001	0.01
MSEL Fine Motor T score	49.73 (16.18)	31.38 (13.51)	23.73 (6.10)	0.003	<0.001	0.08
MSEL Receptive Language T score	51.67 (14.94)	34.23 (12.35)	19.53 (1.81)	0.003	<0.001	0.001
MSEL Expressive Language T score	51.93 (13.86)	31.31 (10.66)	20.80 (4.00)	<0.001	<0.001	0.004
VABS-3 ² Adaptive Behavior Standard Score	101.60 (10.08)	75.23 (18.07)	55.36 (10.49)	<0.001	<0.001	0.002
VABS-3 Communication Standard Score	105.20 (14.21)	79.38 (16.74)	44.14 (17.96)	<0.001	<0.001	<0.001
VABS-3 Daily Living Skills Standard Score	94.60 (8.63)	73.46 (26.36)	58.50 (11.06)	0.02	<0.001	0.08
VABS-3 Socialization Standard Score	105.27 (11.32)	74.00 (15.86)	61.50 (10.63)	<0.001	<0.001	0.03
VABS-3 Motor Skills Standard Score	95.93 (13.71)	81.23 (17.39)	80.71 (9.38)	0.02	0.002	0.93

Table 1. Participant information. ¹MSEL = Mullen Scales of Early Learning. ²VABS-3 = Vineland Adaptive Behaviour Scales-3. ³TD = Neurotypical. ⁴ASD-S = Autistic-Speaking. ⁵ASD-MS = Autistic-Minimally Speaking.

average scores in the expressive language subscales of the adaptive and cognitive measures), future research should include groups that are closely matched. Finally, statistical learning and social attention could be examined using tasks with progressively increasing complexity. Modifications could include varying the objects involved, incorporating both static and dynamic stimuli, using animations as well as real-life videos, and increasing scene complexity (e.g. the number of waterfalls in the statistical learning experiment) and social demands. Such an approach may help to better identify potential differences across groups.

In conclusion, our results did not support the hypothesized differences in statistical learning and social attention in autistic preschoolers, or a contribution of differences in these areas to spoken language difficulties. Rather, our findings point to previously unknown strengths in minimally speaking autistic children across statistical learning and social attention, suggesting that these processes can be leveraged to support their learning and wellbeing, and that spoken language differences in this population might be unrelated to these domains.

Further, our study attested the feasibility of eye-tracking paradigms to examine statistical learning and social attention in minimally speaking autistic preschoolers and revealed unexpected strengths across both domains in this under-researched population.

Methods

The current study was conducted as part of two larger projects by the Drexel University Institutional Review Board (approval IDs 1512004088 and 2103008436) and was conducted in accordance with the relevant guidelines and regulations. Informed consent was obtained from the caregivers of study participants.

Participants and clinical characterization

Forty six children aged 21–41 months participated in the study, including 15 who were neurotypical and 31 who were diagnosed with autism.

Neurotypical children were assessed by experienced clinicians using the Mullen Scale of Early Learning (MSEL)⁴¹, and Vineland Adaptive Behavior Scale Third Edition (VABS-3)⁴². Only children with no history of developmental concerns reported by parents and for whom no developmental concerns were identified based on these assessments were included in the neurotypical group. Formal autism assessment tools were not administered to the neurotypical sample.

Exclusion criteria across groups included the presence of uncorrected hearing or vision impairment, and the presence of major medical problems. Autism diagnoses were established according to DSM-5 criteria⁴³ by community providers and the Autism Diagnostic Observation Schedule - Second Edition (ADOS-2)⁴⁴ was administered for diagnostic confirmation. Additionally, all participants were administered the MSEL by a clinician and VABS-3 were completed by parents, to characterize the sample in terms of cognitive and adaptive functioning, respectively.

Participants diagnosed with autism were then classified as ‘speaking’ or ‘minimally speaking’. Following previous literature⁴⁵, ‘minimally speaking’ status was based on an age equivalent score equal or lower than 14 months in the expressive communication subscale of the Vineland Adaptive Behavior Scales -3 (VABS-3) or the Mullen expressive language subscales for participants who were not administered the VABS-3 (n = 1). Based on this criterion, 15 autistic participants were classified as ‘speaking’ and 16 as ‘minimally speaking’.

3 children (2 speaking, 1 minimally speaking) were excluded as they did not complete the Statistical Learning experiment due to inattentiveness to the task. This resulted in a final sample of 43 participants, whose characteristics are reported in Table 1. Speaking autistic children presented higher scores compared to minimally speaking autistic children across most developmental and adaptive scales and subscales. The minimally speaking

autistic children were significantly younger than the neurotypical children (see Table 1; for additional information see Table S9 in Supplementary Materials). This difference in chronological age was statistically accounted for by including age as a covariate in the relevant models. Both speaking and minimally speaking autistic children presented significantly lower development and adaptive behavior scores compared to the neurotypical children. However, clinical variables were not included as covariates in the statistical models fitted due to their potential overlap with the constructs under investigation.

Eye tracking experiments

Overall procedure and apparatus

Testing took place in a quiet room at the A.J. Drexel Autism institute by study personnel blind to study hypotheses. Measures of statistical learning and social attention relevant to the study hypotheses were gathered using eye-tracking, a non-invasive infra-red technology that generates indices of attentional engagement in response to passively viewed stimuli presented on a screen. Participants were encouraged to sit in a comfortable chair, 60 cm from a Tobii Pro Spectrum eye-tracking system featuring a pre-mounted monitor (60.40 cm), and their attention in response to video-stimuli presented via the monitor was recorded and analyzed using frame-by-frame defined areas of interest using Tobii Studio analysis software. Fixation criteria were set to Tobii Studio defaults of a 30-pixel dispersion threshold for 100 ms. Stimuli presentation was controlled through Tobii Pro lab software via a connected laptop. Before presentation of the experimental stimuli, a 5-point calibration and validation procedure was administered, with calibrations being signaled as “valid” by the software when all 5 points showed good fit in the computed mapping for both eyes. The procedure was repeated until the 5 points were properly calibrated for each eye. Across experimental paradigms, stimuli were interspersed by ‘filler’ stimuli (child-friendly videos) to maintain attention. The presentation of the video-stimuli was arranged in two fixed random orders, with left and right presentation counterbalanced across participants.

Statistical learning experiment

Participants were shown 5 video stimuli, which included a learning phase (4 videos, each 5 s long) and a test trial (1 video, 10 s long). Each video was preceded by an attention-getting stimulus, such as cartoon characters, presented for 2 s in the center of the screen.

Each of the 4 videos comprising the learning trials (Fig. 1) included the following sequence: (a) a ball descended a waterfall, (b) the ball became occluded behind a bridge for 2 s, and (c) the ball reappeared, continuing its descent down a stream of the waterfall (see Fig. 1). The ball in phase (c) always descended into either the left or right stream, with each participant exposed to only one of the two sides. For the test trial (Fig. 1), participants were presented the following sequence: (d) a ball descended a waterfall, (e) the ball became occluded behind a bridge. Two areas of interest were created, identifying the “target” area, i.e. the waterfall where the ball was descending or expected to descend, and the “non-target” area, i.e. the opposite waterfall, in the phase where the ball was occluded by the bridge (Fig. 1b for Learning Trials; Fig. 1e for Test Trial). The AOIs for target and non-target regions each measured 444×602 pixels (width $\times$ height), equivalent to $267,288$ pixels² each.

For both the learning trials and test trial, participants’ attention was operationalized using total fixation duration and time to first fixation. The total duration of the attention allocated toward the target versus non-target waterfall during the phase where the ball was occluded by the bridge (Fig. 1b and e) was used as an index of statistical learning, as indexed by the increase in the attention toward the target area over the four learning trials, and greater attention towards the target area in the test trial. The difference in the total fixation duration toward the target versus non-target areas was computed to determine whether participants looked longer to target or non-target, with positive index indicating greater attention toward target.

Time to first fixation toward the target and non-target areas during the phase in which the ball was occluded by the bridge (Fig. 1b and e) was used as a secondary indicator of participants’ expectations based on statistical learning (i.e., how quickly participants look towards an area where they anticipate a future event based on previous events).

Each learning trial was considered valid if the child looked at the different areas of interest for at least 100 ms during the presentation of the stimulus. This duration corresponds to a fixation as operationalized by the Tobii Pro Spectrum eye-tracking system and is considered standard in eye-tracking research. Further, outliers for specific learning trials were identified for each trial by graphically examining the data distribution through scatter plots. Data points falling outside the expected range, defined as values exceeding ± 4 standard deviations from the mean, were considered outliers and were removed. Based on these criteria 1 minimally speaking autistic participant was removed in the first learning trial, 4 participants (1 speaking autistic participant, 3 minimally speaking autistic participants) were removed in the second learning trial, 2 participants (1 speaking autistic participant, 1 minimally speaking autistic participant) were removed in the third learning trial. The test trial was considered valid if the child had at least two valid learning trials. All 43 participants had valid data for the test trial analysis.

Social attention experiment

Social attention was assessed using a preferential looking paradigm previously validated by Vivanti and colleagues³⁴.

The stimuli consisted of naturalistic scenes featuring people and objects with similar visual salience (e.g., color contrast) displayed for 5 s each (see Fig. 3). The presentation order of the stimuli was counterbalanced across two sequences to control for order effects. Social and non-social areas of interest were defined as illustrated in Fig. 3 and their size was identical. Three stimuli were presented (described in the Results—Social Attention section). In the first one the AOIs encompassed the boys (social area) and the balloon (non-social area) regions, each measuring 168×148 pixels (width $\times$ height), equivalent to $24,864$ pixels² each. In the second stimulus the AOIs

encompassed the girl (social area) and sunflower (non-social area) regions, each measuring 150×190 pixels, equivalent to 28,500 pixels² each. In the third one, the AOIs encompassed the group of boys (social area) and the airplane (non-social area) regions, each measuring 270×170 pixels, equivalent to 45,900 pixels² each.

Total fixation duration and time to first fixation were extracted from Tobii eye-tracking and used as measures of attentional preference, with longer attention allocated toward the stimulus and faster fixations toward it indicating a preference for the specific stimulus, either social or non-social.

In the analysis the differences in the total duration of attention toward social versus non-social areas were computed, with positive index indicating greater attention toward social stimuli compared to non-social.

Participants' data were considered valid if the child looked for at least 100 ms at a minimum of two out of the three presented stimuli. Outliers were assessed on a stimulus-by-stimulus basis through visual inspection of the data distribution using scatter plots. Data points falling outside the expected range, defined as values exceeding ± 4 standard deviations from the mean, were considered outliers and removed. This process did not lead to the exclusion of any participant.

Data availability

The datasets generated during and/or analyzed during the current study will be made available from the corresponding author on reasonable request.

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References

- Guasti, M. T. *Language Acquisition* 2nd edn: *The Growth of Grammar*. (MIT Press, 2017).
- Quinn, S., Donnelly, S. & Kidd, E. The relationship between symbolic play and language acquisition: A meta-analytic review. *Dev. Rev.* **49**, 121–135 (2018).
- American Psychiatric Association. *Diagnostic and Statistical Manual of Mental Disorders* 5th edn Text Rev. (2022).
- Vogindroukas, I., Stankova, M., Chelas, E.-N. & Proedrou, A. Language and speech characteristics in autism. *Neuropsychiatr. Dis. Treat.* **18**, 2367–2377 (2022).
- Volden, J., Coolican, J., Garon, N., White, J. & Bryson, S. Brief report: Pragmatic language in autism spectrum disorder: Relationships to measures of ability and disability. *J. Autism Dev. Disord.* **39**, 388–393 (2009).
- Saldaña, D. Atypical vocabulary acquisition in autism: Where is it coming from? *J. Cult. Cogn. Sci.* **7**, 1–7 (2023).
- Williams, D., Botting, N. & Boucher, J. Language in autism and specific language impairment: Where are the links? *Psychol. Bull.* **134**, 944–963 (2008).
- Roberts, J. M. A. Echolalia and comprehension in autistic children. *J. Autism Dev. Disord.* **19**, 271–281 (1989).
- Schaeffer, J. et al. Language in autism: Domains, profiles and co-occurring conditions. *J. Neural Transm. Vienna Austria* **1996**(130), 433–457 (2023).
- Rose, V., Trembath, D., Keen, D. & Paynter, J. The proportion of minimally verbal children with autism spectrum disorder in a community-based early intervention programme. *J. Intellect. Disabil. Res.* **60**, 464–477 (2016).
- Kasari, C., Brady, N., Lord, C. & Tager-Flusberg, H. Assessing the minimally verbal school-aged child with autism spectrum disorder. *Autism Res.* **6**, 479–493 (2013).
- Tager-Flusberg, H. & Kasari, C. Minimally verbal school-aged children with Autism spectrum disorder: The neglected end of the spectrum. *Autism Res.* **6**, 468–478 (2013).
- Posar, A. & Visconti, P. Update about “minimally verbal” children with autism spectrum disorder. *Rev. Paul. Pediatr.* **40**, e2020158 (2021).
- Clarke, E. B. et al. Understanding profound autism: implications for stigma and supports. *Front. Psychiatry* **15**, (2024).
- Isbilen, E. S. & Christiansen, M. H. Statistical learning of language: A meta-analysis into 25 years of research. *Cogn. Sci.* **46**, e13198 (2022).
- Congiu, S., Doneddu, G. & Fadda, R. Attention toward social and non-social stimuli in preschool children with Autism spectrum disorder: A paired preference eye-tracking Study. *Int. J. Environ. Res. Public Health* **21**, 421 (2024).
- Saffran, J. R. & Kirkham, N. Z. Infant statistical learning. *Annu. Rev. Psychol.* **69**, 181–203 (2018).
- Sherman, B. E., Graves, K. N. & Turk-Browne, N. B. The prevalence and importance of statistical learning in human cognition and behavior. *Curr. Opin. Behav. Sci.* **32**, 15–20 (2020).
- Schapiro, A. & Turk-Browne, N. Statistical Learning. In *Brain Mapping* 501–506 (Elsevier, 2015). <https://doi.org/10.1016/B978-0-12-397025-1.00276-1>.
- Saffran, J. R. Statistical learning as a window into developmental disabilities. *J. Neurodev. Disord.* **10**, 35 (2018).
- Romberg, A. R. & Saffran, J. R. Statistical learning and language acquisition. *WIREs Cogn. Sci.* **1**, 906–914 (2010).
- Bettoni, R. et al. Visual statistical learning in preverbal infants at a higher likelihood of autism and its association with later social communication skills. *PLoS ONE* **19**, e0300274 (2024).
- Ellis, E. M., Gonzalez, M. R. & Deák, G. O. Visual Prediction in Infancy: What is the Association with Later Vocabulary? *Lang. Learn. Dev.* **10**, 36–50 (2014).
- Mok, X. T. J., Goh, S. L., Saddy, J. D., Varley, R. & Zimmerer, V. Language production and implicit statistical learning in typical development and children with acquired language disorders: an exploratory study. *Speech Lang. Hear.* **25**, 349–363 (2022).
- Kidd, E. Implicit statistical learning is directly associated with the acquisition of syntax. *Dev. Psychol.* **48**, 171–184 (2012).
- Parsons, O. & Baron-Cohen, S. Extraction and generalisation of category-level information during visual statistical learning in autistic people. *PLoS ONE* **18**, e0286018 (2023).
- Jones, R. M. et al. Statistical learning is associated with Autism symptoms and verbal abilities in young children with Autism. *J. Autism Dev. Disord.* **48**, 3551–3561 (2018).
- Haebig, E., Saffran, J. R. & Ellis Weismer, S. Statistical word learning in children with autism spectrum disorder and specific language impairment. *J. Child Psychol. Psychiatry* **58**, 1251–1263 (2017).
- Pesthy, O. et al. Intact predictive processing in autistic adults: evidence from statistical learning. *Sci. Rep.* **13**, 11873 (2023).
- Roser, M. E., Aslin, R. N., McKenzie, R., Zahra, D. & Fiser, J. Enhanced visual statistical learning in adults with autism. *Neuropsychology* **29**, 163–172 (2015).
- Swensen, L. D., Kelley, E., Fein, D. & Naigles, L. R. Processes of language acquisition in children with Autism: Evidence from preferential looking. *Child Dev.* **78**, 542–557 (2007).
- Lytle, S. R. & Kuhl, P. K. Social interaction and language acquisition. In *The Handbook of Psycholinguistics* 615–634 (John Wiley & Sons, Ltd, 2017). <https://doi.org/10.1002/9781118829516.ch27>.

33. Bosseler, A. N. et al. Infants' brain responses to social interaction predict future language growth. *Curr. Biol.* **34**, 1731–1738.e3 (2024).
34. Vivanti, G., Fanning, P. A. J., Hocking, D. R., Sievers, S. & Dissanayake, C. Social Attention, Joint Attention and Sustained Attention in Autism Spectrum Disorder and Williams Syndrome: Convergences and Divergences. *J. Autism Dev. Disord.* **47**, 1866–1877 (2017).
35. Kuhl, P. K., Coffey-Corina, S., Padden, D. & Dawson, G. Links between social and linguistic processing of speech in preschool children with autism: behavioral and electrophysiological measures. *Dev. Sci.* **8**, F1–F12 (2005).
36. Chita-Tegmark, M. Social attention in ASD: A review and meta-analysis of eye-tracking studies. *Res. Dev. Disabil.* **48**, 79–93 (2016).
37. Trembath, D., Vivanti, G., Iacono, T. & Dissanayake, C. Accurate or Assumed: Visual Learning in Children with ASD. *J. Autism Dev. Disord.* **45**, 3276–3287 (2015).
38. Shic, F., Bradshaw, J., Klin, A., Scassellati, B. & Chawarska, K. Limited activity monitoring in toddlers with autism spectrum disorder. *Brain Res.* **1380**, 246–254 (2011).
39. Pierce, K., Conant, D., Hazin, R., Stoner, R. & Desmond, J. Preference for geometric patterns early in life as a risk factor for autism. *Arch. Gen. Psychiatry* **68**, 101–109 (2011).
40. Hinz, J. R., Eikeseth, F. F., Chawarska, K. & Eikeseth, S. A systematic review and meta-analysis of atypical visual attention towards non-social stimuli in preschoolers with autism spectrum disorder. *Autism Res.* **17**, 2628–2644 (2024).
41. Mullen, E. M. *Mullen Scales of Early Learning*. (AGS, Circle Pines, MN, 1995).
42. Sparrow, S. S., Cicchetti, D. V. & Saulnier, C. A. *Vineland Adaptive Behavior Scales: Third Edition (Vineland-3)*. (NCS Pearson, Bloomington, MN, 2016).
43. American Psychiatric Association. *Diagnostic and Statistical Manual of Mental Disorders* 5th edn. (American Psychiatric Publishing, 2022).
44. Lord, C. et al. Autism diagnostic observation schedule, second edition (ADOS-2). <https://doi.org/10.1037/t54175-000> (2012).
45. Tager-Flusberg, H. et al. Defining spoken language benchmarks and selecting measures of expressive language development for young children with autism spectrum disorders. *J. Speech Lang. Hear. Res. JSLHR* **52**, 643–652 (2009).

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EP: Methodology, investigation, formal analysis, data curation, writing—original draft, review and editing. GC: Writing—original draft, review and editing. NRL: Conceptualization, review and editing, funding acquisition. GV: Conceptualization, methodology, investigation, formal analysis, data curation, writing—original draft, review and editing, project administration, supervision, funding acquisition.

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Declarations

Competing interests

The authors declare no competing interests.

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