RESEARCH ARTICLE

Goal Prediction in 2-Year-Old Children with and without Autism Spectrum Disorder: An Eye-Tracking Study

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This study examined the predictive reasoning abilities of typically developing (TD) infants and 2-year-old children with autism spectrum disorder (ASD) in an eye-tracking paradigm. Participants watched a video of a goal-directed action in which a human actor reached for and grasped one of two objects. At test, the objects switched locations. Across these events, we measured: visual anticipation of the action outcome with kinematic cues (i.e., a completed reaching behavior); goal prediction of the action outcome without kinematic cues (i.e., an incomplete reach); and latencies to generate predictions across these two tasks. Results revealed similarities in action anticipation across groups when trajectory information regarding the intended goal was present; however, when predicting the goal without kinematic cues, developmental and diagnostic differences became evident. Younger TD children generated goal-based visual predictions, whereas older TD children were not systematic in their visual predictions. In contrast to both TD groups, children with ASD generated location-based predictions, suggesting that their visual predictions may reflect visuomotor perseveration. Together, these results suggest differences in early predictive reasoning abilities. *Autism Res* 2018, 0: 000–000. © 2018 International Society for Autism Research, Wiley Periodicals, Inc.

Lay Summary: The current study examines the ability to generate visual predictions regarding other people's goal-directed actions, specifically reaching and grasping an object, in infants and children with and without autism spectrum disorder. Results showed no differences in abilities when movement information about a person's goal was evident; however, differences were evident across age and clinical diagnoses when relying on previous knowledge to generate a visual prediction.

Keywords: autism spectrum disorder; eye-tracking; goal-based action predictions; prospective reasoning; goal prediction speed; infants

Introduction

Skilled social interactions require knowledge about others' intentions and the ability to implement this knowledge in real-time to generate appropriate responses to one's partner. Young typically developing (TD) infants demonstrate an understanding of other people's intentions in their first year of life [e.g., Woodward, Sommerville, Gerson, Henderson, & Buresh, 2009], for example, developing an expectation that an agent will continue to reach for and grasp an object she has previously acted upon [e.g., Woodward, 1998], and an ability to use this knowledge to predict others' future goal-directed behaviors soon after [Cannon & Woodward, 2012; Krogh-Jespersen & Woodward, 2014]. Importantly, aspects of this early intentional understanding are predictive of later social competencies [e.g., Aschersleben, Hofer, & Jovanovic, 2008; Krogh-

Jespersen, Liberman, & Woodward, 2015; Thoermer, Sodian, Vuori, Perst, & Kristen, 2012; Wellman, Lopez-Duran, LaBounty, & Hamilton, 2008], yet little is known about the emergence of this ability in children with autism spectrum disorder (ASD). The existence of social deficits in children with ASD [Dawson et al., 2004] raises questions about whether detriments in social information processing are evident earlier in development.

To engage in predictive reasoning about goal-directed actions, infants have to attend to relevant information being provided by the agent. For example, 9-month-old infants can use the kinematic cues present in a human hand to anticipate which object is the goal of the action [Ambrosini, et al., 2013; Filippi & Woodward, 2016]. Even younger infants between 6 and 8 months of age anticipate the endpoint of others' reaching actions by shifting their gaze to the goal object before

the reaching hand makes contact [Gredebäck & Melinder, 2010; Kanakogi & Itakura, 2010; Kochukhova & Gredebäck, 2010; Rohlfing, Longo, & Bertenthal, 2012; Paulus, 2011]. In fact, infants show an early sophistication in their understanding of actions such that they will shift their gaze to the appropriate side even when viewing static images of hands pointing or in a reaching position [Bertenthal, Boyer, & Harding, 2014; Daum, Ulber, & Gredebäck, 2013; Rohlfing et al., 2012] and they can implement their understanding of social contexts to anticipate the outcome of familiar movements with tools, for example, looking to the mouth when seeing a person grasp a cup or to the ear when seeing her grasp a phone [Hunnius & Bekkering, 2010]. These results, and our conceptualization of goals and intentional understanding in the current manuscript, reflect infants' developing understanding of motor intentions (i.e., what the person is doing) and are distinct from the more mentalizing act of interpreting why the person is acting in a goal-directed manner [see Bello et al., 2014 for a more detailed discussion of this distinction].

In fact, infants have a particularly sophisticated understanding of the intentional nature of actions, as they perceive the actions of an animate agent differently from those of an inanimate agent [Biro & Leslie, 2007; Guajardo & Woodward, 2004; Hofer, Hauf, & Aschersleben, 2005; Woodward, 1998]. Recently, Cannon and Woodward [2012] found that 11-month-old infants generate goal-based visual predictions when viewing the reaching and grasping actions of a human actor, whereas they do not engage in this predictive reasoning when viewing an inanimate agent. Even within the realm of actions that animate agents produce, infants are sensitive to other's goals when the actions are well-formed, yet show less responsiveness to the goal of the agent when the actions appear accidental or ambiguous [Woodward, 1999; Sommerville & Woodward, 2005]. These findings suggest that infants' response to others' actions are not driven by a general response to all human movements but instead is specific to well-formed goal-directed actions.

Less is known about the development of predictive reasoning in individuals with ASD. ASD is a pervasive developmental disorder that is characterized by impairments in social functioning, including communicative abilities and interpretation of social cues. Impairments in social information processing in children with ASD have been found with regard to following pointing gestures [Baron-Cohen, 1989], the use of speaker's gaze cues [Baron-Cohen, Baldwin, & Crowson, 1997] and mental state language understanding [Baron-Cohen, Leslie, & Frith, 1986], among other social skills. Indeed, preschool children with ASD have difficulty using intentional state awareness to predict where the protagonist will search for an item in the typical false belief Sally-Anne task [Baron-Cohen, Leslie, & Frith, 1985]. Recently, Zalla, Labruyère, Clément, and Georgieff [2010] found that adolescents and children with ASD are less able to use action kinematics to predict the outcome of an action sequence. Surprisingly, children and adolescents with ASD in their study often made the error of choosing a temporally preceding item in an action sequence as the most likely outcome, leading the researchers to suggest that individuals with ASD may have difficulties with online processing of goal-directed actions [Zalla, Labruyère, & Georgieff, 2013]. They further posit that this deficit in the online processing of kinematic information may result in diminished Theory of Mind abilities [Zalla et al., 2013].

One account for the relation between intentional understanding and action understanding is that motor system activation facilitates a matching process between the actions we produce ourselves and those that we observe others producing [Costantini, Ambrosini, Cardellicchio, & Sinigaglia, 2013; Elsner et al., 2013; Gredebäck & Falck-Ytter, 2015] . According to this account, when we view others performing intentional actions, such as reaching and grasping, we engage our own motor plans to simulate the movements required to attain the goal of the action. Findings from electromyographic data shows that TD children ages 5–9 years show activation in the relevant muscle for an observed action (e.g., the mylohyoid muscle, which is responsible for mouth-opening, when viewing a person grasping for food) that reflects an understanding of the outcome of an intentional action, whereas this activation was not evident in same-age ASD children [Cattaneo et al., 2007]. The issue may be that children with ASD have difficulty interpreting the underlying reason or purpose that causes others to engage in intentional actions, as children with ASD show a deficit in understanding why a person engages in an intentional act but look similar to a TD comparison group when determining the actual function of an action [Boria et al., 2009]. A second account to explain deficits in the understanding of intentional actions is that ASD is associated with lowered responsivity to social cues [Vivanti, Trembath, & Dissanayake, 2014]. To test this prediction, Vivanti et al. designed an eye-tracking study in which 4-year-old children had to follow an agent's gaze cue to determine her goal (and compared it to a neutral, no-cue condition). Results revealed that an age-matched sample of children without ASD looked more at the agent's face and the target object when cues were present, whereas children with ASD did not. This study highlights the use of eye-tracking to inform our understanding of the cues that children are attending to when determining an agent's next probable action.

A growing body of research examining action anticipation has been conducted using eye-tracking. Eye-tracking paradigms allow researchers to measure online action anticipation via eye movements, yet findings from this method with individuals with ASD have been inconsistent. For example, Falck-Ytter [2010] found that 5-year-old children with ASD anticipate action outcomes similarly to age-matched TD children and Vivanti et al. [2011] found that children with ASD and TD children, ages 12–13 years, expect agents to use efficient means to achieve action goals. In contrast, Schuwerk, Sodian, and Paulus [2016] found that 10-year-old children and adults with ASD generated action predictions less frequently than age-matched controls. One primary difference between these two studies is the presence of kinematic information when predictive fixations were measured in the stimuli: the Falck-Ytter [2010] study included a human actor completing reaching action sequences in which trajectory information regarding the outcome of the action was available, whereas the Schuwerk et al. [2016] study featured an animated turtle moving underneath an occluder when visual anticipations were measured. These contrasting findings suggest that there may be specific circumstances, in which children with ASD can generate anticipatory fixations to a goal object, such as with the aid of trajectory information, and others in which they have difficulty, for example, when the goal prediction must rely on an analysis of the agent's goal. In the latter case, accurate goal predictions are only evident when an individual considers the actor's intentions, as there is no helpful perceptual information regarding the outcome of the action to rely upon.

A necessary step to examining this proposal is to test participants' action understanding under both circumstances. Recently, Krogh-Jespersen and Woodward [2014] developed the Goal Prediction Speed paradigm to examine whether 15-month-old TD infants can differentiate between grasping and back of hand actions, using the goal-directed nature of the former to anticipate a person's future action-goal. In this study, infants' eyes were tracked as they watched a person either grasp or brush the back of her hand against one of two objects presented side-by-side. Here, the actor provided kinetic cues regarding her goal (e.g., her arm moved in a straight path toward the toy, with her hand in a natural reaching and grasping posture directed toward the goal object). Across two test trials, infants were shown events in which the objects' positions had been reversed and the person began to reach, pausing with her hand midway between the two objects. In this instance, no movement or trajectory information was presented and infants' ability to generate goal-based predictions was measured. After viewing the purposeful grasping action, infants reliably generated goal-based predictions, looking to the object that was the person's prior goal rather than object in the location to which she had previously reached. When the action was more ambiguous, as in the back of hand gesture, infants generated less consistent predictive gaze behavior. Across both conditions, infants required more time to recruit their knowledge of others' goals and then deploy that knowledge to accurately predict the most likely future behavior of their social partner than when they generated inaccurate visual predictions. Thus, goal-based visual predictions took longer to generate than simpler, movement-based location predictions, suggesting that deploying one's understanding of intentions bears a cognitive cost.

The current set of experiments aims to examine whether predictive reasoning in children with ASD varies depending on the type of analysis required to succeed at the task. First, we aim to extend this paradigm to examine whether there are impairments in the goal prediction abilities of young, 2-year-old children with ASD compared with a sample of chronologically age-matched TD children. We also aim to replicate the findings from Krogh-Jespersen and Woodward [2014] using the Goal Prediction Speed paradigm with a TD sample consisting of infants aged 14–19 months, which is slightly more variable than the original study, in a different research setting. Additionally, this sample serves as a mental age-match for our sample of children with ASD. It is important to point out that we studied children at the time that they were first diagnosed. Apart from prospective studies with high-risk infants, this approach offers the best opportunity to reveal the cognitive phenotype of ASD at the youngest possible age, before they may participate in clinical interventions and develop potential compensation strategies.

The Goal Prediction Speed paradigm allows for examination of the following three questions: (a) When trajectory information is present, can children use this information online to anticipate the outcome of an agent's goal-directed action?; (b) In the absence of this kinematic information, can children recruit their understanding of intentions to generate a goal-based visual prediction in a novel situation?; and (c) If children are successful at generating goal-based predictions, do they show the same latency detriment as young infants in the prior study [Krogh-Jespersen & Woodward, 2014], suggesting that predicting goals based on intentions is cognitively challenging? We addressed these questions with three relevant samples: 2-year-old children with ASD, a chronologically age-matched sample of 2-year-old children without ASD, and a mental age-matched younger sample of 17-month-old children without ASD. Based on the results from Falck-Ytter [2010], we expect that all groups will be able to predict the outcome of an agent's action when trajectory information is

Table 1. Summary of Participants' Demographic Information and Scores on Standardized Assessments. Mullen Scores Are Presented as Raw Scores with the Exception of the ELC, Which Is Age Normed

	17-month-old TD infants		2-year-old children diagnosed with ASD		2-year-old TD children
N	20		36		19
# Females	9		4		12
Mean age:	16;27	***	27;27	ns	26;23
Age range:	14;13–19;5		16;1–36;15		20;25–34;16
Ethnicity:	# of children		# of children		# of children
Hispanic or Latino	4		19		6
Not Hispanic or Latino	15		15		12
Race:	# of children		# of children		# of children
Asian	0		2		1
Black/African American	3		13		3
White	13		12		13
Other/multiple/no response	3		9		3
Mullen Scales:	mean ± SD		mean ± SD		mean ± SD
Visual Reception (VR)	24.47 ± 3.44	ns	23.03 ± 3.71	***	31.43 ± 6.22
Fine Motor (FM)	21.47 ± 2.36	ns	21.75 ± 4.63	*	24.93 ± 4.08
Receptive Language (RL)	21.33 ± 5.78	***	14.25 ± 5.52	***	26.93 ± 4.29
Expressive Language (EL)	17.60 ± 4.55	ns	16.06 ± 4.41	***	24.93 ± 7.19
Early Learning Composite (ELC) - age normed	107.5 ± 17.6	***	64.9 ± 12.6	***	102.2 ± 15.4
ADOS-2:			mean ± SD		
Social Affect (SA)			15.1 ± 3.7		
Restricted and Repetitive Behavior (RRB)			5.3 ± 1.9		
Overall Total			20.4 ± 4.0		
Calculated Severity Score (CSS)			8.5 ± 1.5		

* indicates $P < .05$
** indicates $P < .01$
*** indicates $P < .001$

present. However, without the aid of trajectory information, we hypothesized that differences may emerge in the predictive reasoning abilities of our samples. Consistent with Krogh-Jespersen and Woodward [2014], both the older and younger TD children should generate goal predictions and show the latency difference. Predictions regarding the children with ASD are less clear, although the findings of Schuwerk et al. [2016] suggest that older children with ASD have difficulty generating goal-based visual predictions without the aid of trajectory information.

Method
Participants

We compared the performance of 2-year-old children with ASD to a chronological age-matched group of TD children. We also tested a group of younger TD children (17-month-olds). We had two rationales for including this group. First, these children have overall absolute cognitive functioning levels that were approximately the same as the 2-year-old children with ASD (as demonstrated by the highly similar raw scores in all subscales on the MSEL, except for Receptive Language, where the children with ASD had significantly lower scores; see Table 1). Thus, this group represents a mental age-matched group. Second, these children were similar in age to those tested in Krogh-Jespersen and Woodward [2014], who were successful in predicting goals in the same paradigm.

Therefore, three sample groups were examined in the current study with sample size determined based on effect sizes measured in our previous research [Krogh-Jespersen & Woodward, 2014]: two groups consisted of TD infants and children, all of whom were considered full term (minimum 37 weeks gestation), and one group consisted of children with ASD.

TD participants were recruited from an urban population in the U.S. based on birth records via mailings. Two age groups were sampled for the TD group: The younger age group consisted of 17-month-old infants ($N = 20$; $M = 16$; 27 months, range: 14;13–19;5 months; 9 females) and the older group consisted of 2- to 3-year-old children ($N = 19$; $M = 26;23$ months, range: 20;25–34; 16 months; 12 females). For all children in the TD sample, following the experimental protocol, their overall cognitive functioning was assessed with the Mullen Scales of Early Learning [Mullen, 1995], and based on the results, all infants and children in the final sample were in the normative range (for detailed participant characteristics, including Mullen scores, see Table 1). An additional 12 infants were tested and

excluded from further analysis due to overall insufficient data (data collection rate was below 50%) from the Tobii eye-tracker (1 from the younger group; 4 from the older group), distress/fussiness during eye-tracking or parent interference (1 from the older group), Mullen Early Learning Composite scores below the typical (<70) range (2 from the younger group), failure to attend to the action during the familiarization trial (2 from the younger group), failure to generate a predictive fixation on either test trial (1 from the younger group), or for later receiving an ASD diagnosis from an external clinic (1 from the TD group). We verified that no TD participant had a history of neurological disorders, developmental issues, ASD behaviors, or siblings with developmental disorders at the time of testing. Parents of all participants received a small toy and compensation for their travel expenses.

We recruited children with ASD through a local early intervention site participating in a separate ASD multi-stage screening study. The final sample included 36 children with ASD ($M = 27;27$ months, range: 16;1–36;15 months; 4 females). An additional 8 children were tested and excluded from further analysis due to insufficient data (data acquisition rate was below 50%) from the Tobii eye-tracker (2), distress/fussiness during eye-tracking or parent interference (3), failure to attend to the action during the familiarization trial (1), or failure to generate a predictive fixation on either test trial (2). For detailed participant characteristics of the final sample, please see Table 1. ASD diagnoses were assigned to children referred from early intervention agencies based on evidencing scores in the Mild to Moderate or Moderate to Severe concern range on the Autism Diagnostic Observation Schedule-2 [ADOS-2; Lord, Luyster, Gotham, & Guthrie, 2012; Lord et al., 2012] and a clinical psychologist's (Alice S. Carter) appraisal that the children met DSM-5 criteria for ASD following a clinical review of the child's behaviors during the evaluation and an interview with the parent(s). Children recruited from the early intervention provider who did not meet ASD criteria were excluded from the study (9 children). An ANOVA with group (17-month-old TD infants, 2-year-old TD children, 2-year-old children with ASD) revealed a significant difference in Mullen ELC scores ($F(2,64) = 62.1$, $P < .01$). Post hoc LSD comparisons revealed that the two TD groups did not differ from each other ($P = .34$); however, both groups had higher ELC scores when compared to scores for the children with ASD (17-month-old TD infant: $P < .01$; 2-year-old TD children: $P < .01$).

Procedure

All procedures performed in studies involving human participants were in accordance with the ethical standards of the Institutional Review Board and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. Participants viewed videos presented on a 17-inch monitor of a Tobii T120 corneal reflection eye-tracking system (accuracy approx. 1°, used at a sampling rate of 60 Hz). Participants were seated in their caregivers' laps at an approximate distance of 60 cm from the monitor. Calibration was performed with a 5-point procedure using the default animation for infant calibration provided by Tobii Studio (Tobii Technology, Sweden) software. When necessary, the calibration process was repeated until all 5 points were properly calibrated. The stimuli were presented using Tobii Studio. Some of the actions presented in the videos were accompanied by sound effects: a bell sound at the start of the trial, and a squeaking sound when the actor completed the reaching and grasping behavior.

All participants saw two pre-familiarization trials, one familiarization trial, and two test trials. The pre-familiarization videos started with an actor demonstrating that she could reach for a single object on either side of a table (both objects were likely to be unfamiliar to the participant: a blue plastic dog toy and an orange plastic dog toy). Next, in a single familiarization trial, she reached for and grasped one of two objects (a stuffed giraffe or bear; see Fig. 1, panel a). The target object (giraffe vs. bear), the hand the actor used (right vs. left), and the side (right vs. left) on which the target sat were counterbalanced. Half of infants observed a single ipsilateral action during the familiarization trial and the other half observed a single contralateral action. The timing of the actions was as follows: the actor looked at the camera (1 sec), looked down at her hand (.5 sec), raised her hand (1 sec), performed the reaching and grasping action (2.5 sec), and held the final resting position (2.5 sec). To control for the presence of facial cues during the familiarization trial, the actor looked straight ahead (1 sec), looked down to her hand (.5 sec), watched her hand perform the reaching and grasping action (2.5 sec), and upon contact with the toy, looked to the contact point where her hand and the toy were conjoined (2.5 sec). During this familiarization trial, participants could rely on trajectory cues from the actor's hand to anticipate the outcome of her action following the 2.5-sec time-point.

During two identical test trials, the objects were shown in reversed locations from their positions in the familiarization trial, and the actor raised her hand and then paused with her hand centered in mid-air between the two objects (see Fig. 1, panel b). The actor never made contact with either object during the test trials. The timing of the actions in the test trials was as follows: the actor looked at the camera (1 sec.), looked down at her hand (.5 sec.), raised her hand (1 sec.), and

Figure 1. Still images from the final positions of the experimental stimuli for the a) Familiarization trial, which presented trajectory information, and the b) Test trial, which did not. Each infant saw one Familiarization trial followed by two identical Test trials. Areas of interest (AOIs) are shown on the test trial image.

held her hand centered between the two objects (5 sec.). During the test trials, the actor looked straight ahead (1 sec.), shifted her gaze down to her hand as she lifted her hand (.5 sec.), and then looked at her hand for the remainder of the test trial. Her hand remained centered between the two objects (5 sec.), and she did not look at either object during the test trials. During these trials, participants were not provided with trajectory information; therefore, their predictive eye movements reflect their ability to recruit and deploy their knowledge of her previous goal-directed action.

Data Analysis

Our dependent variables were total fixation durations and the latency of fixations to the relevant Areas Of Interest (AOIs; see details below). The AOIs were generated for the actor based on the location of the social information she provided, for example, one AOI encompassed her face and one encompassed the space in which her hand moved during the test trials. A total of five AOIs were defined to encompass the female actor's Face and Hand, the Prior Goal and Prior Location objects and the entire viewing screen (see Fig. 1, panel b) for all video recordings. The Prior Goal and Prior Location AOIs were identical in shape and size, and were equidistant to the Hand AOI. The Tobii default fixation filter was used to define fixations: a fixation was defined as a stable gaze (within .75 visual degrees) for a minimum of 200 ms.[1]

There were three main measurements for action anticipation, as follows:

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[1]We used this value to match the parameters of Krogh-Jespersen and Woodward (2014). Applying a shorter fixation duration threshold (100 ms) did not affect our results.

Anticipation of the outcome of the reach during the familiarization trial. During the familiarization trial, the actor's hand began reaching to the goal object at the 2.5-sec time point and completed the reaching behavior at 5 sec (see Fig. 1, panel a). Prior to the 2.5-sec time point, participants had no information from the agent to predict her goal; therefore anticipation based on movement and trajectory information could only occur after the 2.5-sec time point. To determine whether infants' fixations to the object were anticipatory vs. reactionary when movement and trajectory information was present, we computed a difference score from the time that infants' fixated to the goal object minus the time at which the actor's hand overlapped with the object (with a time window from 2.5-sec to the point that the hand overlapped, ranging in time from 3.6- to 3.88-sec in the video presentation). A positive value reflects a reactionary fixation to the goal object, whereas a negative value reflects an anticipatory fixation.

Goal-based predictions during the test trials. During the test trials, the actor paused with her hand centered between the two objects, which had switched positions from the familiarization trial, at the 2.5-sec. mark and remained in that position for a total of 5 sec (see Fig. 1, panel b). Participants could generate a visual prediction at any time point from the start of the video during these trials, yet the eye movements did have to meet the following criterion: a predictive fixation was defined as a fixation to the actor's Hand AOI followed by a fixation to either the Prior Goal AOI (e.g., the object that the actor acted upon during the familiarization trial) or the Prior Location AOI (e.g., the previously unreferenced object). For each trial, infants' visual predictions were coded as either to the Prior Goal
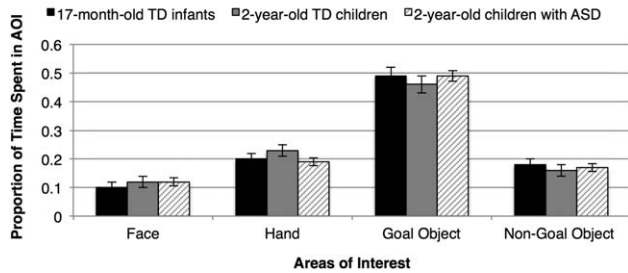
Figure 2. Means and standard errors for participants' proportion of time spent in each area of interest as a function of their total looking time during the Familiarization trial.
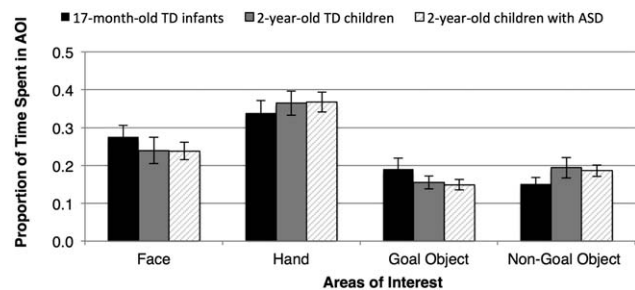

Figure 3. Means and standard errors for participants' proportion of time spent in each area of interest as a function of their total looking time averaged across the two test trials.

object, the Prior Location object, or as No Prediction. The AOIs for the objects were located equally distant from the Hand AOI during the test trials. During these trials, apart from the actor raising her hand, movement or trajectory information was not present. Gaze responses were averaged across the two trials to determine participants' proportion of goal-based predictions.

Goal prediction speed. The latency (in seconds) for participants to initiate a prediction during each test trial to either the Prior Goal object or the Prior Location was measured from the start of the test trial to the time that a predictive fixation occurred. This latency is referred to as Goal Prediction Speed [GPS; Krogh-Jespersen et al., 2015] and this measure may reflect the amount of time participants required to recruit information about the actor's goal, relate this information to changes in the context, and then generate a prediction about the actor's future behavior. For each trial, infants' latency to generate a prediction was coded with regard to whether it was toward the Prior Goal object or the Prior Location object.

In addition, with the ASD group, we examined whether variations in the accuracy and latency measures from the eye-tracking task related to severity of autism diagnosis or children's cognitive functioning.

Results
Preliminary Analyses

Across all recordings, the average percentage of useable gaze data (excluding blinks and fixations out of the boundaries of the screen) that was correctly identified by the Tobii eye-tracking system was 88.15% ($SD = 14.15$) for the younger TD group, 80.16% ($SD = 15.74$) for the older TD children, and 84.11% ($SD = 14.12$) for the children with ASD. The difference between groups was not significant: $F(2, 75) = 1.47$, $p = .24$, $n.s.$

In our Goal Prediction Speed data, 6 of the 105 data points (5.7%) were identified as outliers (i.e., more than $+/-$ 2SD away from the group mean) and were excluded from further analyses. The remaining data for each group and condition passed the Shapiro-Wilk tests of normality (all p's > 0.1).

One possible explanation for any divergence in predictive reasoning abilities may be that participants encoded information in a different way during the familiarization trial in which the agent provides the necessary information to succeed at the subsequent prediction task. Previous research has found that children with ASD generally spend less time looking at faces [see Falck-Ytter, Bölte, & Gredebäck, 2013, for a review]. Our paradigm featured a female agent who maintained a forward gaze during the first 1 sec of the familiarization trial, then she directed her gaze to her hand and to the object that served as her goal. We contrasted the distribution of fixations across all groups during the familiarization trial. Participants' proportions of attention to the Face, Hand, the object that served as the Goal Object, and the object that served as the Non-Goal Object. AOIs were calculated by dividing their amount of time they spent in each AOI by their total time spent looking at the screen. For the single familiarization trial, a repeated measures ANOVA with Group (17-month-old TD infants, 2-year-old TD children, 2-year-old children with ASD) as the between-subjects factor revealed that participants' distribution of fixations to the AOIs did not differ across groups ($F(2,72) = .38$, $P = .69$; see Fig. 2 for means and standard errors). That is, differential looking during familiarization cannot explain any differences in our primary dependent measures.

We also contrasted the distribution of fixations in all groups across the test trials to determine whether differences in participants' attention to the objects or the actor could have contributed to our findings. Participants' proportions of attention to the Face, Hand, the
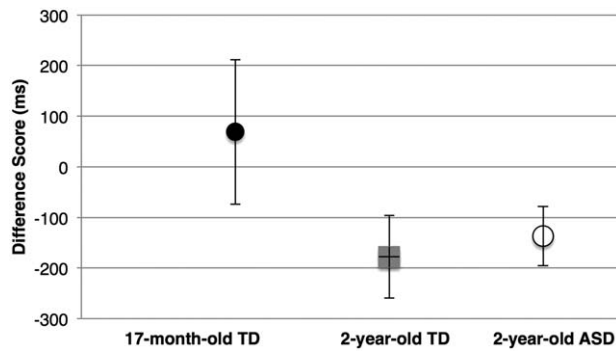
Figure 4. The average difference scores and standard errors by age group. The vertical axis depicts the timing of the gaze arrival at the goal object during the familiarization trial, in which trajectory information was present, relative to the time at which the actor's hand overlapped with the goal object. The time of overlap is represented by the horizontal line at 0ms. A positive value reflects a reactionary fixation to the goal object, whereas a negative value reflects an anticipatory fixation.

object that served as the Goal Object, and the object that served as the Non-Goal Object AOIs were calculated by dividing their amount of time they spent in each AOI by their total time spent looking at the screen for each test trial and then averaging the data across the two test trials. A repeated measures ANOVA with Group (17-month-old TD infants, 2-year-old TD children, 2-year-old children with ASD) as the between-subjects factor revealed that participants' distribution of fixations to the AOIs did not differ across groups ($F(2,72) = .36$, $P = .70$; see Fig. 3 for means and standard errors). That is, differential looking to the objects or the actor's face at test cannot explain the following visual prediction results.

Anticipation of the Outcome of the Reach during the Familiarization Trial

First, we evaluated participants' ability to visually anticipate the outcome of an agent's reach as her hand was moving toward the object in the familiarization trial, as much of the prior literature has focused on infants' action anticipations in such a manner [Gredebäck & Melinder, 2010; Kanakogi & Itakura, 2010; Kochukhova & Gredebäck, 2010; Rohlfing et al., 2012; Paulus, 2011]. The average difference score was calculated as the latency to fixate the goal object subtracted from the time point at which the actor's hand overlapped with the goal object (see Fig. 4 for means and standard errors). We found no differences between the groups in their latency to anticipate the outcome of a goal-directed action, $F(2, 75) = 1.83$, $P = .16$, *n.s.* Although there was no overall difference in latency, one-sample t-tests revealed that both the 2-year-old TD sample ($t(18) = 2.18$, $P = .043$) and the 2-year-old children with ASD ($t(35) = 2.32$, $P = .03$) anticipated the goal of the
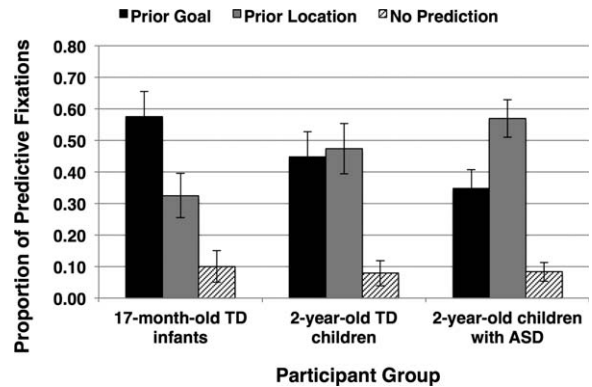

Figure 5. Proportion of predictive fixations to either the prior goal or prior location object, or no prediction across the two test trials.

reaching and grasping action, whereas 17-month-old TD children demonstrated more reactionary looking behavior ($t(19) = .48$, $P = .63$). Using the Benjamini-Hochberg procedure for correcting for multiple comparisons [McDonald, 2014], both older groups' results remained significant, at a false discovery rate of 7%.

Goal-Based Predictions during the Test Trials

Next we asked whether, having attended and responded to the actor's action, participants could go on to use this information to generate goal-based predictions. We analyzed participants' visual predictions during the two test trials when the actor did not provide trajectory information regarding the outcome of her actions. Younger TD infants generated predictive fixations, looking first to the actor's hand and then to one of the two objects, on 90% of trials (four trials were excluded from this analysis due to no predictive fixation occurring), older TD children generated predictive fixations on 92% of trials (three trials excluded from this analysis) and 92% of trials for the children with ASD (six trials were excluded from this analysis). A chi-square test showed that the three groups (17-month-old TD, 2-year-old TD children, 2-year-old ASD children) differed in their generation of these types of visual predictions, $\chi(2) = 6.344$, $P = .042$, effect size: Cramer's $V = 0.542$. To explore this difference, we examined each groups' pattern of generating goal-based visual predictions in more detail. An exact binomial test showed that 17-month-old TD infants tended to generate more goal- than location-based predictions (23 of 36 trials, $P = .0662$, one-tailed). An exact binomial test showed that 2-year-old TD children did not systematically generate goal predictions by trial, with TD children generating goal-based visual responses on 17 of 35 trials, $P = .50$, one-tailed. An exact binomial test revealed that unlike the aged-matched TD children, 2-year-old children with ASD showed a trend toward systematically generating
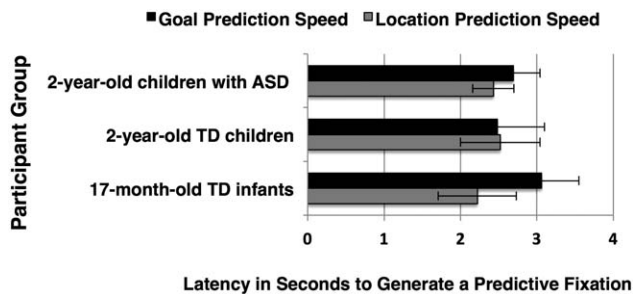
Figure 6. Latency in seconds to generate a predictive fixation to either the prior goal or prior location object.

predictions by trial, however their predictions were towards the prior location, not the prior goal, with children with ASD generating location-based visual responses on 41 of 66 trials, $P = .064$, two-tailed. Using the Benjamini-Hochberg procedure for correcting for multiple comparisons, both the 17-month-olds' and the 2-year of ASD group's results remained significant, at a false discovery rate of 10%. Figure 5 presents the data regarding predictive fixations.

Goal Prediction Speed

Finally, we examined participants' Goal Prediction Speed to determine whether participants exhibited a latency difference when generating goal- vs. location-based predictions. The younger TD children generated goal-based predictions on average in 3.06 sec ($SD = 1.97$) and location-based predictions on average in 2.22 sec ($SD = 1.70$), two-tailed t-test: $t(25) = 1.15$, $P = .26$, $d = .46$. Although this difference was not statistically significant, the effect size is in the medium range and it is consistent with the pattern found in Krogh-Jespersen and Woodward [2014], where 15-month-old infants' latencies to generate goal-based predictions were 3.12 sec ($SD = 1.40$) vs. 1.93 sec ($SD = 1.27$) for location-based predictions. In contrast to the younger TD children, older TD children generated goal-based predictions on average in 2.48 sec ($SD = 2.31$) and location-based predictions on average in 2.52 sec ($SD = 2.00$), $t(27) = .57$, $P = .96$, $n.s.$ Children with ASD generated goal-based predictions on average in 2.69 sec ($SD = 1.65$) and location-based predictions on average in 2.43 sec ($SD = 1.49$), $t(51) = .59$, $P = .56$, $n.s.$ Figure 6 presents the latency data for all groups.

To examine whether variations in the accuracy and latency measures from the eye-tracking task related to severity of autism diagnosis, a series of regressions were conducted. The first regression predicted children's ADOS-Total Comparison Scores using their speed to generate a prediction and the type of prediction (goal-based vs. location-based) from the eye-tracking task as factors. There were no significant main effects and no significant interactions (all $ps > .28$). A similar

regression examining children's Mullen ELC scores also resulted in no significant findings (all $ps > .34$). Finally, children's latency to generate an anticipatory eye movement to the goal object following the start of the actor's reaching action during the familiarization trial did not correlate with autism severity or cognitive functioning.

Discussion

The first aim of our study was to establish the reliability of the Goal Prediction Speed paradigm with young infants. Results are consistent with those of Krogh-Jespersen and Woodward [2014] in that the 17-month-old TD infants tended to generate goal-based visual predictions based on the actor's intentions in the absence of trajectory information. Taken together with previous findings, the current results suggest that young infants recruit their analysis of an actor's intentions to determine her next action even when she is not providing kinematic cues about her likely next action. Moreover, our latency results point in the same direction as the pattern found by Krogh-Jespersen and Woodward [2014], such that longer latencies were evident when generating accurate goal-based visual predictions than simpler, location-based visual predictions. This finding is consistent with the proposal that goal-based predictions that rely on intentional analysis may be more cognitively burdensome to infants. Surprisingly, these young infants showed difficulty with the quick implementation of their understanding of goal-directed actions in the moment to predict future outcomes as an action unfolded, as revealed by their reactive latency during the familiarization trial. Together, these findings suggest that this paradigm is appropriate for investigating action anticipation and goal-based predictions in TD infants.

Our next aim was to extend the Goal Prediction Speed paradigm to examine whether there are differences in predictive reasoning abilities of young TD children and children with ASD. Results highlight similarities in action anticipation abilities in 2-year-old TD children and children with ASD as both groups were able to predict the most likely outcome of a goal-directed action when trajectory information was present. This type of predictive reasoning occurs during online processing of an event and may rely on tracking and perceptual abilities more so than on analytic reasoning regarding intentional actions. These results are consistent with the findings from Falck-Ytter [2010] with 5-year-old TD children and children with ASD who showed no differences in anticipating the outcome of an action. Thus, regarding in the moment processing of events, we found no differences in the speed with

which the older TD children and children with ASD process an action event and predict the most likely future outcome.

However, a different pattern of results is evident for goal-based visual predictions in the absence of trajectory information. Inconsistent with our hypotheses, older TD children did not systematically generate goal-based visual predictions. While surprising, the finding that visual anticipation rates reduce across time when actions are not completed is consistent with research conducted by Krogh-Jespersen et al. [2015], who utilized the Goal Prediction Speed paradigm with 20- to 22-month-old infants (note: the older TD age range starts at 20 months). They found a decrement in the generation of goal-based visual predictions across trials, yet still found that the likelihood of generating a goal-based visual prediction predicted behavioral competence in a perspective-taking task. It is currently unclear from our current data why older children would be less likely to generate these types of visual predictions, yet the Krogh-Jespersen et al. (2015) suggest that, when they do generate goal-based responses, it is predictive of social competence. Future research should examine the conditions under which children are motivated to generate anticipatory visual responses.

Although the 2-year-old TD children were not above chance in their goal-based visual predictions as a group, the findings for the 2-year-old children with ASD revealed a different pattern with regard to the ability to recruit and implement information regarding an actor's goal. Children with ASD showed a trend toward systematically generating location-based predictions, suggesting that their visual predictions may reflect visuomotor perseveration. Gaze analyses showed no differences in time spent on different parts of the scene during the familiarization event that could account for this finding. Across both studies, infants and children attended to the areas of interest similarly during the familiarization event. Southwick et al. [2011] proposed that individuals with ASD have difficulty encoding and organizing information, rather than with storage and retrieval. If this is the case, one possibility is that the children with ASD in the current study attended to the familiarization event, but they may have had difficulty recruiting and implementing their intentional understanding to predict future behaviors. Instead, they relied on low-level features, like kinematic information, to predict likely outcomes: this strategy is successful when adequate trajectory information is present, as in the familiarization trial, but results in inaccurate predictions in more ambiguous situations, such as the test trials. Consistent with this proposal is research with adults with ASD suggesting that they more likely to focus on low-level features than intentionality when anticipating outcomes of actions [Hudson, Burnett, & Jellema, 2012].

A second possibility is that children with ASD have deficits that are evident during tasks that require implicit mentalizing, even when controlling for their explicit mentalizing abilities. Support for this possibility comes from a recent study by Schuwerk, Jarvers, Vuori, and Sodian [2016] in which 8-year-old children with and without ASD completed an implicit false belief task on an eye-tracker and an explicit false belief task based on Wellman and Liu [2004]. Although children in both groups performed similarly on the explicit task, differences in their visual behaviors were evident during the implicit task, as children with ASD did not correctly predict the likely outcome of an actor's actions based on her false belief. These findings are consistent with the current results that young children with ASD show visual patterns of behavior that differ from TD children during tasks that require utilizing intention understanding.

Finally, results for the Goal Prediction Speed measure also suggested that recruitment of predictive reasoning abilities may change across early development. The current results for the younger, 17-month-old TD children are consistent with those found with 15-month-olds in Krogh-Jespersen and Woodward [2014], but differs from the pattern in the mentally age-matched ASD children, who did not show a latency difference. Yet, in light of the current results that older TD children also do not show a latency difference, the current findings do not provide a clear picture of whether this task is cognitively demanding for older children. This lack of a latency differential in older children was also evident in a study by Krogh-Jespersen et al. [2015] using this paradigm, which found that 20-month-old infants' latencies to generate goal-based predictions were 2.71 sec (SD =1.73) and 2.51 sec (SD =1.56) for location-based predictions. Some insight may be gained from younger infants with regard to these latency results, as Krogh-Jespersen and Woodward (2018) have found that 8-month-old infants do not evidence a latency difference in this task (goal-based visual predictions $M = 2.64$-sec; $SD = 1.21$ vs. location-based visual predictions $M = 2.58$ sec ($SD = 1.48$) unless they are given active experience reaching for and grasping the objects presented in the videos (goal-based visual predictions $M = 3.44$-sec; $SD = 1.60$ vs. location-based visual predictions $M = 2.18$-sec; $SD = 1.45$). This suggests that older children may require a context for engaging in predictive reasoning about an agent's goal in our task and future research should address this possibility.

The current research highlights the need to understand further the similarities and differences in predictive reasoning abilities in young children who are TD and those with ASD. Given that 2-year-old children,

regardless of developmental diagnosis, successfully used trajectory information from a social agent to predict her future behavior, we have empirical support for a common action anticipation ability early in development. Yet, when situations are more ambiguous, when it is not obvious via perceptual cues what a person aims to do, here is where both developmental and diagnostic differences were evident. Open questions remain regarding whether children with ASD are encoding the event using different strategies or whether there are deficits in the retrieval of intentionality information that limit prediction abilities. Importantly, eye-tracking paradigms aimed to detect differences early in children with ASD, particularly with 2-year-olds, may help researchers and clinicians to disentangle differences in infants' knowledge about others' intentions as the action unfolds from their difficulties with implementing prior knowledge in more complex social situations.

Limitations

Gender of the sample. Consistent with the presentation of ASD in the population, our sample of 2-year-olds with ASD were predominantly male (32 out of 36). We found no gender differences within our TD sample in performance (Accuracy: Females: 20/27; Males: 20/34 trials with goal-based predictions, P = n.s.; Latency to predict: Females: M = 2.671 (1.86), Males: M = 2.59 (1.37), P = n.s.), which makes it unlikely that gender differences among children with ASD account for our findings. However, gender differences cannot be excluded.

Manipulation of cues. Our study design relied on two changes from the familiarization stimuli to the test stimuli: (a) the objects switched locations; and (b) the actor did not provide information regarding her goal. We utilized this measure and the lack of cues in the test phase as a manipulation of whether participants can engage in predictive reasoning when the context of the situation has changed. Our current study does leave open the possibility that TD children and children with ASD would perform similarly if, during the test trials, the location of the objects did not change, but there was an absence of cues. This is an interesting future direction for the current research. Evidence from previous research and from our action anticipation measure would suggest that both ASD and TD children may succeed on this type of task.

Acknowledgments

Conflict of interest

Sheila Krogh-Jespersen declares that she has no conflict of interest. Zsuzsa Kaldy declares that she has no conflict of interest. Alice S. Carter declares that she has no conflict of interest. Annalisa Groth Valadez declares that she has no conflict of interest. Amanda L. Woodward declares that she has no conflict of interest.

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