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Do Children and Adults with Autism Spectrum Condition Anticipate Others' Actions as Goal-Directed? A Predictive Coding Perspective

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Abstract

An action's end state can be anticipated by considering the agent's goal, or simply by projecting the movement trajectory. Theories suggest that individuals with autism spectrum condition (ASC) have difficulties anticipating other's goal-directed actions, caused by an impairment using prior information. We examined whether children, adolescents and adults with and without ASC visually anticipate another's action based on its goal or movement trajectory by presenting participants an agent repeatedly taking different paths to reach the same of two targets. The ASC group anticipated the goal and not just the movement pattern, but needed more time to perform goal-directed anticipations. Results are in line with predictive coding accounts, claiming that the use of prior information is impaired in ASC.

Keywords Autism spectrum condition · Goal anticipation · Cognitive processes · Social cognition · Predictive coding · Eye-tracking

When we interact with others, we spontaneously respond to their actions. For example, we anticipate who is next to speak in a conversation, or we predict where people are heading when crossing a busy street and move out of their way to avoid a collision. Similarly, we efficiently infer another's action goal. If our counterpart reaches for her cup, we anticipate that she is going to take a sip. A fair amount of research posits that people with autism spectrum condition (ASC) have difficulties making action anticipations and representing goal-directed behaviors (e.g. Chambon et al. 2017; Zalla et al. 2006; for an overview see Schuwerk and Paulus 2018). These difficulties are often linked to core ASC symptoms; some suggested that altered action anticipation is the cause of social interaction and communication deficits in ASC (Sinha et al. 2014). Here, we investigated these difficulties in action anticipation more profoundly. In particular, we examined whether—and if so, how—individuals with ASC are impaired in their ability to anticipate actions as goal-directed. More specifically, we explored what information they base their anticipations on: Do they learn the specific action goal or do they anticipate the mere spatiotemporal movement trajectories after frequent observation?

Theories regarding anticipatory abilities in ASC follow two different theoretical directions. On the one hand, domain-specific conceptual theories see impairment specifically in the social domain. They argue that an inability to attribute intentional states and goals to others lies at the core of ASC (e.g. Frith et al. 1991). It is claimed that individuals with ASC are impaired in anticipating other's actions, as they have difficulties inferring other people's intentions and goals. However, empirical evidence so far is not fully compatible with this hypothesis (Hamilton 2009; see also Schuwerk and Paulus 2018), as individuals with ASC perform equally well as typically developed persons on some goal-anticipation tasks (e.g. Falck-Ytter 2010), but have problems in others (e.g. Zalla et al. 2006). For example, Zalla et al. (2006) showed that adolescents with ASC have difficulties sequencing goal-directed actions in a picture-story task. This implies that domain-specific theories cannot explain ASC-symptomatology sufficiently and suggests that subtler domain-general accounts, that imply a general cognitive deficit in predictive abilities, whether social or not, are needed to explain social cognitive characteristics in ASC.

It was recently proposed that individuals with ASC have difficulties with action predictions because they have

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problems estimating conditional probabilities (e.g., calculating the probability of event B following event A) in their environment (Sinha et al. 2014). This hypothesis is confirmed by findings demonstrating reduced motor anticipations in ASC (Brisson et al. 2012; Hughes 1996; Schmitz et al. 2003). For example, infants (which were later diagnosed with ASC) did not open their mouth as regularly as comparison participants in anticipation of being spoon-fed (Brisson et al. 2012). However, the picture becomes less clear considering the perception of motion. Empirical findings on whether action anticipation abilities differ between people with and without ASC over various age groups are mixed (Braukmann et al. 2018; Cusack et al. 2015; Murphy et al. 2009; Schuwerk et al. 2016; von Hofsten et al. 2009).

Complementary to this account, Ruffman (2014) suggested that individuals with ASC have problems with statistical learning. He argues from a developmental perspective and claims, similar to Sinha et al. (2014), that statistical regularities help us to make sense of the world and that they are essential for developing a Theory of Mind; early spontaneous or implicit understanding of others' actions precedes later explicit intention understanding (see also Paulus 2012). If we see someone performing an action in a certain way, we use this information to anticipate that action in the future. Studies on non-social implicit learning tasks draw an incoherent picture though; some report no difference between people with and without ASC (Barnes et al. 2008; Roser et al. 2015), whereas others found weaker implicit learning skills (Kourkoulou et al. 2012; Mostofsky et al. 2000).

In an action-anticipation study by Schuwerk et al. (2016), individuals with ASC could not make use of the repeated presentation of an agent's behavior when making action anticipations as effectively as typically developed participants. In their study, children and adults were presented with videos of an agent aiming for one of two paths to reach a goal. One path was shorter, the other was longer. At the crossroad, where the path divided into the two possibilities (short vs. long path), an occluder was overlaid to trigger anticipatory eye movements and measure this visual anticipation of the agent's reappearance. Participants saw four repetitions of the agent who always took the short path. Children and adults without ASC increased their correct action anticipations during the repeated presentation of this action. In contrast, children and adults with ASC did not increase their correct anticipations as much, which suggests that the ability to use prior information to anticipate other's actions is attenuated in ASC. However, it remains unclear whether individuals with ASC are generally impaired in statistical learning or whether they just need more repetitions to learn from past experience.

Similarly, predictive coding theories postulate atypical predictive processing in ASC; in accordance with the two approaches described above, they also suggest an inability to use prior information in ASC to make predictions about their environment. While the predictive coding approach has its origins in visual perception, it further differs from the other two accounts (Ruffman 2014; Sinha et al. 2014) in its proposed underlying mechanism. More precisely, predictive coding theories claim that the perception of one's environment is not only guided by plain sensory input, but also biased by our expectations on what the world looks like (Clark 2013). Through a hierarchically structured system, our brain continuously compares incoming sensory information (bottom-up) with downward predictions (top-down). Information that does not match is reported backwards as a prediction error in order to adjust and improve future predictions. Pellicano and Burr (2012) claim that individuals with ASC have problems using prior information for executing downward predictions and that sensory input dominates their perception. Similar suggestions have been made by others (Brock 2012; Mottron et al. 2006; Van de Cruys et al. 2014). Their claims fit well with observed behaviors in ASC, such as insistence on sameness or repetitive movements. Since individuals with ASC are, according to predictive coding theory, impaired in predicting upcoming events, they need additional exposure to stimuli in order to become comfortable with them. Their desire for sameness could be the result of coping with or avoiding these constant uncertainties. Also, repetitive movements such as finger flipping or rocking might be a result of the drive to minimize uncertainty (Pellicano and Burr 2012).

The predictive coding account could also explain social interaction problems in ASC. Given that social situations are complex and often uncertain, we have to rely more on our priors when predicting other agents (Lawson et al. 2014). Chambon et al. (2017) found that adults with ASC rely to a lesser extent on prior beliefs, namely the belief that people tend to act reciprocally towards each other; when one acts cooperativelly, the other would too. In this task, participants had to infer the intention of one or two actors that manipulated objects. They could either rely on visuo-motor information (when only one actor was present) or on prior social beliefs (when two actors were present). Individuals with ASC did not have problems making inferences relying on visuo-motor information, but demonstrated difficulties inferring intentions based on prior information that was social (i.e. the two actors acting reciprocal).

However, since most studies on predictive coding in ASC focus mainly on visual perception, empirical findings regarding action processing are rare. Research in this area is also becoming increasingly important for the development of new behavioral and cognitive training programs, as well as for the improvement of diagnostic tests (Haker et al. 2016). The goal of behavioral treatments is to change behavior and improve social and communication skills, as well as fostering a better general functioning (Jensen and Sinclair 2002).

Predictive coding theory offers information on how to gain best improvement within individuals with ASC, for example that it is important during training to keep social situations very simple at the beginning and to expose individuals with many repetitions over a longer period of time. Predictive coding theory could further be a valuable tool for psychoeducation within ASD. According to Haker et al. (2016) it already helped their autistic participants to better understand their own symptoms, as the theory explains both behavioral and perceptual aspects. The theory can also help in creating diagnostic tests for ASD that are more sensitive and suitable for adults. So far available tests are often not sensitive enough to diagnose autism in adults, as symptomatology is often concealed by acquired coping strategies. Perceptual peculiarities within adults with ASD may thus not be obvious, which is why more subtle diagnostic tools are necessary (Haker et al. 2016; Van de Cruys et al. 2014). More studies on this issue would be helpful in order to inform recent theories and to improve the current clinical situation for individuals with ASC.

On the basis of these three theories, we examined whether individuals with ASC use prior information as well as typically developed people when making action anticipations. Moreover, we specifically investigated if they encode the particular goal of the action. Since anticipating other's action goals is related to social competencies in typically developed children (Krogh-Jespersen et al. 2015), altered goal understanding in ASC could be a possible cause for social interaction and communication difficulties (Krogh-Jespersen et al. 2018; Zalla et al. 2006, 2010). These considerations are very well linked to other prominent theories of socio-cognitive deficits in ASC (e.g. Frith et al. 1991). Only a few studies have directly addressed goal anticipation in ASC so far (e.g., Zalla et al. 2006). For example, in an eye-tracking study, two-year-old children with ASC did not anticipate a manual reaching action based on its goal but on its movement path (Krogh-Jespersen et al. 2018). Based on Woodward's (1998) influential looking-time paradigm, children were familiarized with a human actor reaching for one of two objects. In the test trials, the objects' position changed places and participants observed an uncompleted reaching action, as the hand stopped before completing the movement. In contrast to the comparison group, children with ASC anticipated the actor to reach for the other object in the old location. This implies that children with ASC processed the spatiotemporal movement pattern instead of the action goal. When the context changes and participants are confronted with the changed position of the targets in the test trials, individuals with ASC might generate their anticipations based on the spatiotemporal information and not on the goal. The changed position of the objects and the incomplete movement confronts participants with a decision: Is the hand going to take the same path or is it going to reach towards the same goal? What we do not know from this task is whether children did not process the goal of the action at all or whether the information of the movement path dominated over the information of the goal.

Studies using simpler paradigms, which require processing of both types of information simultaneously, report equal performance between individuals with and without ASC (see Hamilton 2009, for a review). For example, 5years-old and adults with ASC accurately anticipated the movements of a hand placing objects into a container (Falck-Ytter 2010). However, this setup only included one possible action goal. Individuals with ASC could have based their anticipations on the movement of the hand and/or on the goal (container). Thus, conclusions on whether anticipations were based on movement trajectories or the action goal are not possible. Individuals with ASC could have simply relied on the spatiotemporal information.

In sum, these findings suggest that individuals with ASC are able to anticipate an action, when they can rely on movement information or speed, such as transporting balls into a bucket (Falck-Ytter 2010) or bringing a phone to the ear (Braukmann et al. 2018). As was demonstrated by Krogh-Jespersen et al. (2018), movement information seems to be a strong source of information in ASC when anticipating actions. However, this does not tell us whether individuals with ASC do not process the goal of the action at all. Uithol and Paulus (2014) claimed that anticipating an action is more difficult when two possible goals are available because then additional information is necessary to anticipate the action. Are individuals with ASC able to anticipate an action when they cannot only rely on movement patterns, but have to process the specific action goal? No study has yet investigated whether individuals with ASC anticipate an action as goal-directed in a context in which they are provided with enough cues about the agent's goal and cannot just rely on movement information.

Previously outlined theoretical notions claim that one's own experiences have an impact on anticipating other's actions (Clark 2013; Ruffman 2014). According to that, older participants have more lifelong experience and, under a predictive coding point of view, also more chances to improve their top-down predictions, such as that "agents act towards goals". Empirical evidence so far suggests that individuals with ASC seem to have some basic goal-encoding abilities of other's actions, although these abilities seem to show restrictions when situations become more complex (Hamilton 2009). Previous studies on goal anticipation in ASC so far mostly include young children ranging from 10 months (Braukmann et al. 2018) to 5 years of age (Falck-Ytter 2010). We do not know whether and to what extent these goal-directed anticipatory abilities might still develop throughout adolescence in a more complex setup. It could further be that the ability for statistical learning is still improving between childhood and adulthood in ASC, as is the case for neurotypical individuals (see Schuwerk and Paulus 2015). Moreover, deficits in Theory of Mind are less evident in older aged individuals with ASC, suggesting improvement of social cognitive abilities over the course of life (Lever and Geurts 2016). Studies that include a wide age range of individuals with ASC are needed to investigate socio-cognitive developmental changes from childhood into adulthood.

The current study addressed two questions: First, do children, adolescents and adults with ASC anticipate another agent's action in a task which requires goal understanding and cannot be solved by simply anticipating previously observed movement patterns? Second, given the claim that individuals with ASC have problems using prior information (Pellicano and Burr 2012; Ruffman 2014) we wanted to investigate whether frequent repetitions of an action lead to an increase in goal-directed action anticipations. When individuals with ASC observe an agent reaching a goal numerous times, are they able to use that information to make action anticipations, indicating statistical learning in the domain of action goals?

The paradigm from Paulus et al. (2017, experiment 3) was employed for the present study, which allowed us to address these questions in a sample of participants with and without ASC. Participants observed an agent always walking to one of two goals, whereas the goal's position varied between trials. If individuals with ASC do consider the agent's goal and do not only rely on spatiotemporal movement information when anticipating actions, we should observe goal-directed action anticipations in participants with ASC. However, according to predictive coding theories (e.g. Pellicano and Burr 2012) and the statistical learning approach (Ruffman 2014), we hypothesized that individuals with ASC have problems using prior information and therefore expected that they need more time to learn the action goal than typically developed participants. We further expected higher performance with increased age, since lifelong experience might improve top-down predictions. Given the claim that individuals with ASC generally have problems anticipating other's actions (Sinha et al. 2014; Schuwerk et al. 2016), we predicted that individuals with ASC show less anticipations than typically developed individuals, regardless of whether or not their anticipations were goal-directed.

Methods

The study's data is available at https://osf.io/dqt6w/?view_only=340895d63ba242278f1faf90451772ae. Due to protection of data privacy and to prevent inferences on individual data, demographic information is not shared in this data set. Only preprocessed eye-gaze data is provided.

Participants

The final sample included 143 participants in total. The participants or their caregivers gave informed written consent before starting the procedure. The study was approved by the local ethics board. To be included in the ASC group, participants had to provide a medical certificate containing proof of an ASC diagnosis according to the International Classification of Diseases-10th Revision criteria (World Health Organization 1993) by a qualified clinical psychologist or psychiatrist. Participants from the ASC group were recruited via local associations, clinics and private-practice physicians. The comparison group was recruited via birth-records or from our lab's participant pool. Participants came from a larger city in Germany. Travel costs were reimbursed. Additionally, adult participants received payment for participation and children received individual presents.

Children and Adolescents

Thirty children with ASC (mean age = 9.73 years, *SD* = 1.86) and 29 comparison children (mean age = 9.34, *SD* = 1.72) took part in the study. Seventeen children from the ASC group were diagnosed with Asperger Syndrome, six children with childhood autism, two with atypical autism and five with high-functioning autism. From the children without ASC, one was diagnosed with an attention-deficit hyperactivity disorder (ADHD), one with an attention deficit disorder and dyslexia, one with specific phobias, one with an adaption disorder and one child was diagnosed with a sensomotoric processing disorder. Since these are all highly comorbid conditions of ASC, children with these conditions were included in the comparison group to guarantee close matching of the participants (Schwartz and Susser 2011). Choosing a comparison group that only includes healthy individuals (often referred to as "well controls") is not an adequate representation of the general population, leading to bad validity and creating bias (Schwartz and Susser 2011). Further, preliminary analyses have revealed the same pattern of results for all three age groups, when individuals from the comparison group, who reported such conditions, were excluded.

The adolescent sample comprised 19 participants for the ASC group (mean age = 15.05, *SD* = 1.54) and 19 for the comparison group (mean age = 15.11, *SD* = 1.33). One additional adolescent of the ASC group had to be excluded as no IQ measure could be obtained. Ten of the adolescents with ASC were diagnosed with Asperger Syndrome, five with childhood autism, two with atypical autism, one with high-functioning autism and one with Asperger Syndrome and high functioning autism. For the comparison group, no psychiatric diagnoses were reported.

To assess verbal and nonverbal IQ, children and adolescents were tested with either four subtests of the Wechsler-Intelligence Scale for Children (WISC-IV; Wechsler 2003; German version by Petermann and Petermann 2007), or the same subtests of the Wechsler-Intelligence Scale for Adults (WAIS-IV; Wechsler 2008; German version by Petermann 2013), namely "vocabulary", "similarities", "matrix reasoning" and "picture completion". These subtests were used as this is the minimum number of subtests necessary to get an estimate of verbal and nonverbal IQ score. For adults, different tests were used as measures for verbal and nonverbal IQ (see below). Additionally, caregivers filled the German adaptions of the Social Responsiveness Scale (SRS), to measure autistic traits (German version by Bölte and Poustka 2008), and the Social Communication Questionnaire (SCQ), a screening to assess communication skills and social functioning across the whole lifetime (*lifetime form*) and in the most recent 3 months (*current form*; Rutter et al. 2001; German version by Bölte and Poustka 2006). Independent samples *t* tests revealed no group differences in verbal and non-verbal IQ as well as for age. As expected, the groups differed in their SRS and SCQ scores. See Table 1 for descriptives of the measures and detailed results of the group comparison.

Adults

The adult sample comprised 22 participants in the ASC group (mean age = 33.86, *SD* = 13.10) and 24 in the comparison group (mean age = 38.46, *SD* = 14.55). One adult of the comparison group reported a suspected diagnosis of ASC and was therefore excluded. Another two adults of the ASC group were excluded due to missing demographic data and control measures. From the ASC group 18 adults were diagnosed with Asperger Syndrome, three with atypical autism and one with high-functioning autism. One participant from the comparison group was diagnosed with depression and one reported burn-out. As in the children

Table 1 Mean scores with standard deviations and range in brackets of the demographics and control measures for children, adolescents and adults with ASC and neurotypicals

	ASC	NT	Group comparison		
			t value	*p* value	Cohen's *d*
Children					
Sample size	*n* = 30	*n* = 29			
Age in years	9.73 (1.86; 5–13)	9.34 (1.72; 5–12)	$t(57) = 0.83$	.408	0.22
Verbal IQ (WISC-IV)	109.93 (14.83; 88–152)	105.59 (13.88; 81–136)	$t(54) = 1.13$	.263	0.31
Non-verbal IQ (WISC-IV)	104.23 (15.29; 67–131)	111.86 (15.02; 88–147)	$t(57) = -1.93$	.058	0.51
SRS T-Score	84.80 (10.30; 62–100)	47.04 (9.43; 25–70)	$t(56) = 14.53$	< .001	3.88
SCQ current form sum score	16.80 (6.19; 3–33)	6.07 (3.85; 0–14)	$t(49.18) = 7.94$	< .001	2.26
SCQ lifetime form sum score	23.57 (8.27; 5–38)	6.54 (3.75; 0–14)	$t(41.04) = 10.22$	< .001	3.19
Adolescents					
Sample size	*n* = 19	*n* = 19			
Age in years	15.05 (1.54; 13–18)	15.11 (1.33; 13–17)	$t(36) = -0.11$	.911	0.04
Verbal-IQ (WISC-IV)	101.79 (21.24; 53–134)	108.05 (12.14; 93–136)	$t(36) = -1.12$	.272	0.37
Non-verbal IQ (WISC-IV)	103.32 (22.12; 45–135)	115.53 (17.32; 90–147)	$t(36) = -1.90$	.066	0.63
SRS T-score	82.95 (12.41; 59–100)	45.32 (12.58; 23–70)	$t(36) = 9.28$	< .001	3.09
SCQ current form sum score	15.00 (8.03; 4–37)	6.89 (3.50; 0–13)	$t(24.87) = 4.02$	< .001	1.61
SCQ lifetime form sum score	20.79 (6.48; 10–39)	4.84 (3.22; 0–10)	$t(36) = 9.61$	< .001	3.20
Adults					
Sample size	*n* = 22	*n* = 24			
Age in years	33.86 (13.10; 19–63)	38.46 (14.55; 20–67)	$t(44) = -1.12$	.268	0.34
Verbal IQ (MWT-B)	113 (15.18; 75–136)	117.96 (17.42; 92–145)	$t(44) = -1.03$	0.311	0.31
Non-verbal IQ (CFT-20-R)	103.14 (21.65; 54–142)	108.25 (14.88; 90–145)	$t(44) = -0.94$	.352	0.28
AQ (short form)	21.41 (7.98; 5–32)	5.67 (3.25; 0–12)	$t(27.31) = 8.62$	< .001	3.30

ASC autism spectrum condition, *NT* neurotypical comparison group, *WISC-IV* Wechsler-Intelligence Scale for children, 4th edition, *SRS* Social Responsiveness Scale, *SCQ* Social Communication Questionnaire current form/lifetime form, *MWT-B* Mehrfachwahl-Wortschatztest (German multiple choice vocabulary test), *CFT-20-R* culture-fair test 20-R (non-verbal IQ regarding general mental capacity), *AQ* autism-spectrum quotient (short form; cut-off criterion: score ≥ 17)

Independent-groups *t* tests present comparison between the two groups comparison group, these two participants were not excluded from analysis due to better matching of the groups. For an estimation of verbal IQ, a vocabulary test was used (Mehrfachwahl-Wortschatz-Intelligenztest, MWT-B; Lehrl 2005). For non-verbal IQ the Culture-Fair Test 20-R (CFT-20-Weiß 2006) was implemented. Additionally, adults filled the short form of the autism-spectrum quotient (AQ; with a cut-off criterion of score ≥ 17; Baron-Cohen et al. 2001; German version by Freitag et al. 2007) to evaluate autistic traits. The groups significantly differed in their AQ scores, but not in age or IQ (see Table 1).

Stimuli

The stimulus material included one introductory movie and ten test movies. The movies had the size of 1280 × 1024 pixels and were created with Adobe CS 5.5 (Adobe Systems Inc., San Jose, CA).

First, an introductory movie was presented to familiarize participants with the setup and the occluder. The movie included a rabbit that was sitting at the end of a horizontal path leading from the right side to the left side of the screen. A transparent occluder was situated in the middle of the path. As the occluder turned opaque, a voice stated "Look, the rabbit" and the rabbit started to move to the other side of the path through the occluder.

The other ten movies contained a path that was leading to two different goals, namely a house and a forest (see also Fig. 1). At the crossroad, where the path divided and led to the different goals, an occluder was overlaid. Occluders are often used in action anticipation paradigms as they facilitate anticipatory eye-movements rather than a constant fixation on the agent (cf. Paulus et al. 2011; Schuwerk et al. 2016; von Hofsten et al. 2007). The agent, a pig, was situated on the left side of the path. After jumping twice in order to catch the participant's attention, the occluder turned opaque and the pig started to move towards the occluder along the path. The pig disappeared for 3.5 s behind the occluder and reappeared on one of the paths to walk to its goal. The movie lasted 17 s in total and ended after the pig reached the goal.

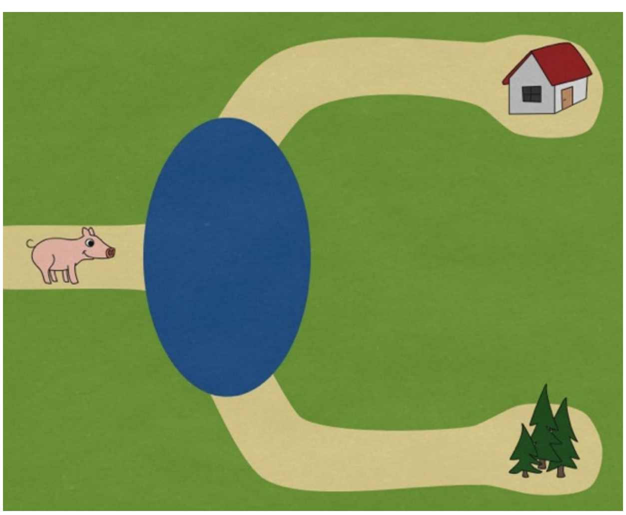

Fig. 1 Example of a test movie. The agent is located at the left side of the screen. The opaque occluder overlies the crossroad between both paths. On the right side, two target objects are located

Setting and Procedure

Participants' eye-gaze was recorded with a corneal reflection eye-tracker (Tobii T60, Tobii Technology, Sweden). Stimuli were presented on a 17-in (43.18 cm) TFT flat-screen monitor and the gaze data was recorded at 60 Hz with an average accuracy of 0.5° visual angle. For movie presentation the software Tobii Studio (Tobii Technology, Sweden) was used.

To familiarize participants with the setup of the occluder, the introductory movie was presented first. Then the ten movies, in which the agent always walked to the same one of the two goals, were shown in a row. Within participants, the position of the target object (lower or upper path) was counterbalanced throughout the ten movies in a fixed order. Thus, participants could not conclude any pattern in the objects' position, disentangling simple path learning from goal anticipations. Additionally, we counterbalanced between participants which of the objects (house or forest) served as the goal.

Measures

To define fixations and saccades, the Tobii Studio standard fixation filter was used with a velocity threshold of 35 pixels/window and a distance threshold of 35 pixels. Following previous research (Paulus et al. 2011; Schuwerk et al. 2016), two areas of interest were situated on the sections where the paths reappeared from the occluder and each occupied 10.13% of the screen. Another AOI covered the whole screen (100%) and was used to control for missing data in the other two AOIs in the test-phase. Participants' gaze behavior was measured during the time period in which the pig disappeared behind the occluder (3.5 s). To analyze their gaze behavior, three different measures were used. These are described below. In all three measures, the very first trial was not included into analysis, as participants could not have any expectations of the agents' goal preference for that trial.

Frequency of Action Anticipations

To assess participants' amount of anticipatory fixations over the trials to either the short or long path, irrespective of which one of the two paths they fixated, a score was calculated: A first fixation to either one of the paths was coded with 1; if participants fixated somewhere else on the screen but did not look at either one of the paths during the test phase, this was coded with 0 (Schuwerk et al. 2016).

Type of Anticipation: First Fixation Score

To analyze whether participants fixated either the path leading to the target or the other path, a First Fixation Score was generated (see e.g. Paulus et al. 2011). Therefore, a first anticipatory gaze to the path that led to the goal object was coded with 1 and a first anticipatory gaze to the other path was coded with − 1. If none of the two paths were fixated during the anticipatory period (the time the pig was behind the occluder), but fixations were directed somewhere else on the screen, this was coded as 0. No fixations to the screen at all were treated as missing values. For analysis, following Paulus et al. (2017), the nine trials were grouped into three blocks, which contained three trials each (block 1 contained trial 2, 3 and 4; block 2 contained trial 5, 6, 7; block 3 contained trial 8, 9, 10).

A repeated measures ANOVA was performed with the first fixation score as the dependent variable, the within-subject-factor block (first, second, third) and the between-subject-factors age group (children, adolescents, adults) and diagnosis group (ASC, neurotypical).

Type of Anticipation: Differential Looking Score (DLS)

In order to control for corrective eye-movements a DLS, which represents the relative amount of time spent on one AOI in relation to the other (see e.g. Senju et al. 2009), was calculated. Hence, the total looking time to the non-goal related AOI was subtracted from the total looking time to the goal related AOI and divided by the sum of overall total looking time to both AOIs. To investigate participants' learning behavior over time more precisely, a regression coefficient analysis was performed with the DLS as the dependent variable (Lorch and Myers 1990). Therefore, individual regression slopes for each participant were calculated over the nine trials and regression coefficients (intercept and slope) for each participant were extracted to compute further tests. First, one sample *t* tests were performed for each age and diagnosis group separately, to see whether intercept and slope were significantly different from zero.

For the DLS, in total 3.28% of the gaze data was missing in the experimental group. In the comparison group 1.91% of all trials had missing values. For these cases, the mean of the respective age group and diagnosis group was inserted. For the First Fixation Score, missing values were not replaced, as these scores were averaged over the trials (see "Results" section). In total 17 participants had missing values, with a maximum of three missing trials per participant ($n=1$). The other 16 participants had only one or two missing trials.

Results

Frequency of Action Anticipations

Individuals with ASC anticipated in 73.08% of the test trials and participants from the comparison group anticipated in 77.62% of trials. To assess participants' overall number of anticipations (irrespective of whether they fixated the path leading to the goal or the other path), a generalized estimating equations model (GEE; Zeger and Liang 1986) was conducted with an unstructured working correlation matrix, a logit link function and a binomial distribution. Diagnosis group, age, trial and the interaction of diagnosis group with age were inserted as the predictor variables. As can be seen in Table 2, neither one of the predictors had a significant influence on the frequency of action anticipations. That is, individuals with ASC showed equal numbers of action anticipations as did neurotypical individuals.

Type of Anticipation: First Fixation Score

The repeated measures ANOVA revealed a significant main effect of diagnosis group, $F(1, 136)=6.36$, $p=.013$ $\eta_p^2=.05$, and a main effect of block, with $F(1.98, 269.79)=10.28$, $p<.001$, $\eta_p^2=.07$. Overall, the comparison group showed a significantly higher looking bias towards the goal-directed path ($M=0.47$, $SE=0.05$) than the ASC group ($M=0.31$, $SE=0.05$). To examine the main effect of block, Bonferroni-adjusted post hoc analysis revealed a significant difference between block one ($M=0.25$, $SD=0.55$) and two

Table 2 Results of the generalized estimating equations model with the predictors of diagnosis group, age, trial and interaction of diagnosis group and age on the frequency of action anticipations

Predictor	B	SE	Wald	*df*	*p* value	Exp (B)	95% Confidence interval for Exp (B)	
							Lower	Upper
Group	−0.39	0.52	0.55	1	0.460	0.68	0.25	1.89
Age	−0.50	0.45	1.47	1	0.225	0.61	0.27	1.36
Trial	−0.01	0.03	0.08	1	0.777	0.99	0.95	1.04
Group × age	0.32	0.27	1.40	1	0.236	1.38	0.81	2.34

($M = 0.46$, $SD = 0.52$; $p \leq .001$, Cohen's $d = 0.39$), and between block one and three ($M = 0.44$, $SD = 0.53$; $p = .002$, Cohen's $d = 0.35$). The comparison between block two and three was not significant ($p = 1.000$, Cohen's $d = 0.04$). This indicates an expected learning effect over the three blocks. There was no significant main effect of age, $F(2, 136) = 0.62$, $p = .542$, $\eta_p^2 = .01$, no significant interaction effect of diagnosis group and block, $F(1.98, 269.79) = 0.20$, $p = .82$, $\eta_p^2 = .001$, no interaction effect of age group and block, $F(3.97, 269.79) = .12$, $p = .98$, $\eta_p^2 = .002$, and no significant interaction effect of diagnosis group, age group and block, $F(3.97, 269.79) = 2.04$, $p = .090$, $\eta_p^2 = .03$. Thus, we did not find any differences between age groups, but found that typically developed individuals made more goal-directed anticipations than individuals with ASC.

Following Paulus et al. (2017), one sample *t* tests against chance level were calculated separately for each age group, diagnosis group and block to see whether participants showed a looking bias towards the goal-directed AOI that was significantly different from chance (see in Fig. 2).

Children

Results for the children in the comparison group revealed a significant looking bias towards the goal-directed path in block 1, $t(28) = 4.43$, $p < .001$, Cohen's $d = 0.82$, block 2, $t(28) = 5.44$, $p < .001$, Cohen's $d = 1.01$, and block 3, $t(27) = 6.24$, $p < .001$, Cohen's $d = 1.18$. However, the group of children with ASC did not show a goal-directed looking bias in the first block, $t(29) = 1.56$, $p = .13$, Cohen's $d = 0.28$, but in the second, $t(29) = 3.76$, $p = .001$, Cohen's $d = 0.68$, and third block, $t(29) = 2.98$, $p = .006$, Cohen's $d = 0.54$. This suggests that children with ASC may need more time to learn the action goal.

Adolescents

Similarly, the comparison group of the adolescents anticipated in all blocks goal-directed, Block 1 with $t(18) = 3.19$, $p = .005$, Cohen's $d = 0.73$, Block 2 with $t(18) = 6.03$, $p < .001$, Cohen's $d = 1.38$, and block 3 with $t(18) = 4.04$, $p = .001$, Cohen's $d = 0.93$. The looking bias of the adolescents with ASC was not significantly different from chance in the first block, $t(18) = .89$, $p = .39$, Cohen's $d = 0.20$, whereas they performed goal-directed anticipations in the second, $t(18) = 3.46$, $p = .003$, Cohen's $d = 0.79$, and third block, $t(18) = 6.12$, $p < .001$, Cohen's $d = 1.40$, indicating slower learning of the action goal in ASC.

Adults

For the adults, one sample *t* tests for the comparison group revealed a significant looking bias towards the goal-directed path in the first block, $t(23) = 2.74$, $p = .012$, Cohen's $d = 0.56$, the second block, $t(23) = 3.87$, $p = .002$, Cohen's $d = 0.79$, and the third block, $t(23) = 5.18$, $p < .001$, Cohen's $d = 1.06$. In comparison, adults with ASC did not show a significant goal-directed looking bias in block 1, $t(21) = 1.82$, $p = .08$, Cohen's $d = 0.39$, but in block 2, $t(21) = 3.74$, $p = .001$, Cohen's $d = 0.80$. In block 3, the looking bias was not significantly different from chance, $t(21) = 1.68$, $p = .108$, Cohen's $d = 0.36$. Performance of adults with ASC declined in the last trials.

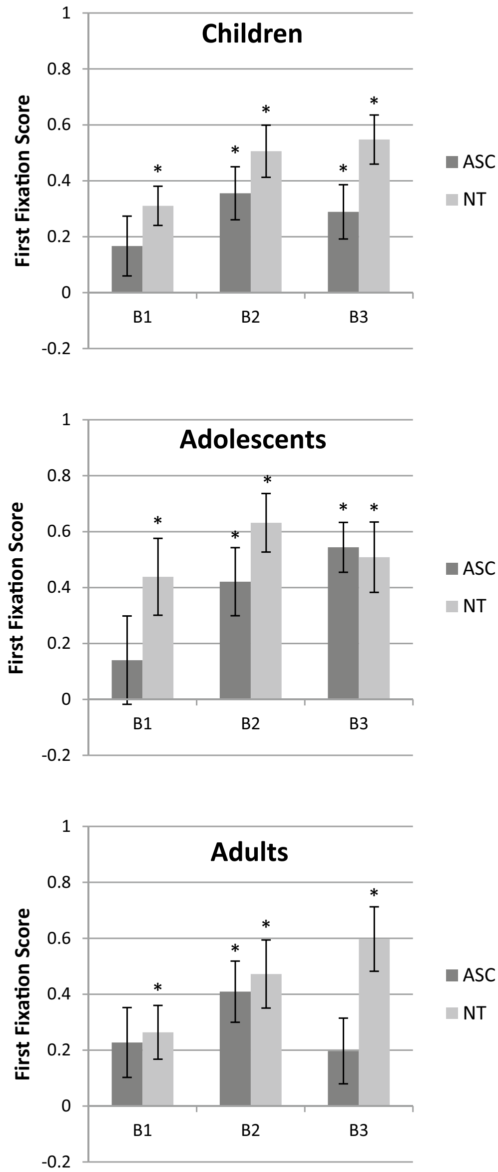

Fig. 2 Descriptives of the First Fixation Score per age group and diagnosis group over the three blocks. Stars indicate a significant difference from chance

Type of Anticipation: Differential Looking Score

Results can be seen in Table 3. One sample *t* tests showed that the intercept of the children and adolescents was significantly different from chance in each of the groups with the typically developed participants, indicating goal anticipations from early trials on. However, the intercept of children and adolescents with ASC was not significantly different from chance. They did not anticipate the goal in the first test trials. In contrast, the significant results for the slopes of the children and adolescents with ASC suggested an improvement in learning over time. The adults with ASC seemed to show goal encoding from the beginning on, without linear improvement over time, demonstrated by the non-significant result of the *t* test for the slope.

Discussion

The current study examined whether individuals with ASC anticipate another agent's action based on the goal or on the movement pattern and, whether their action anticipations become more accurate over time, which would demonstrate frequency learning of action goals. A third question was concerned with whether there are developmental differences in these abilities. To this end, children, adolescents and adults with and without ASC were presented with an agent that repeatedly walked along several paths towards one of two targets. The target's location was changed in each trial in a randomized order to ensure goal encoding instead of position encoding. Results demonstrated that participants with ASC made less goal-directed anticipations, as they needed more time to encode the goal of the action. This suggests that individuals with ASC have problems using prior information, as proposed by predictive coding theories (Pellicano and Burr 2012) and the statistical learning approach (Ruffman 2014). Nevertheless, individuals with ASC anticipated the action of the agent as goal-directed after several trials. Interestingly, there is no evidence that individuals with ASC generally fail to encode someone's action as goal-directed, which is discussed further in the next section.

Table 3 Results of the regression coefficient analysis per age group and diagnosis group for the DLS

Age group	Diagnosis group	Intercept		Slope	
		M	*p*	*M*	*p*
Children	ASC	0.16	.095	0.04	.046
	NT	0.25	.001	0.05	.001
Adolescents	ASC	0.10	.446	0.07	< .001
	NT	0.5	.001	0.02	.441
Adults	ASC	0.30	.015	0.01	.569
	NT	0.26	.023	0.04	.038

ASC autism spectrum condition, *NT* neurotypical comparison group

Individuals with ASC Show Goal Anticipations

According to our results, individuals with ASC anticipate an action as goal-directed to a lesser extent than typically developed people. But, if they are provided with enough opportunities to learn about an agent's goal, they are able to use this information to anticipate future behavior. The current study is, to our knowledge, the first to demonstrate that individuals with ASC do not only base their action anticipations on movement trajectories, but are able to take the specific action goal into account. Due to our results, the claim that individuals with ASC rely only on low-level features when anticipating other's actions (Krogh-Jespersen et al. 2018), cannot be confirmed. Instead, it seems that when individuals with ASC are provided with enough, non-ambiguous cues (i.e. an agent repeatedly takes different paths leading to the same goal), they can rely on hierarchically higher and more abstract information to anticipate future actions.

Our findings are in line with recent accounts that argue against a global impairment in action understanding in ASC, but for social cognitive strategies that are different from the ones used by typically developed individuals (Hamilton 2009). Also, Uithol and Paulus (2014) stress the need to reflect on the commonly used umbrella term "action understanding", as this is not something an individual "has" or "doesn't have", but rather comprises several different cognitive processes that are involved in action anticipation. This could be even more the case for individuals with social cognitive impairments, such as ASC.

Individuals with ASC Show Less Efficient Statistical Learning

Interestingly, our results indicate that overall and especially in the first trials, individuals with ASC made less goal-directed anticipations, whereas individuals from the comparison group already anticipated the goal-related path from early trials on. This could be observed for both first anticipations (First Fixation Score) as well as when corrective eye movements were included in the measure (DLS). Given these results it seems that individuals with ASC need more time to learn about the goal of an observed action. Our findings do not indicate that they are not at all able to learn from prior information; it just seems that they need more repetitions. They might consider spatiotemporal features to a greater extent than typically developing persons on the expense of goal-related information, even though they possess basic goal-encoding abilities. The present study is the first to show that individuals with ASC can encode information about the specific goal of an action after frequent observation and anticipate the action accordingly.

Comparable results were reported by Schuwerk et al. (2016). They found that individuals with ASC profit less from previous observation when anticipating an agent's action. In their study, participants observed four repetitions in a similar paradigm and could not improve their anticipations throughout these trials as good as neurotypically developed individuals. Nevertheless, the previous repeated observation, in contrast to efficiency considerations, was the driving mechanism for action anticipations in ASC in their study. Gordon and Stark (2007) reported similar differences from a sequential learning task. In this task, individuals with ASC improved only when receiving specific training trials. Many other studies using implicit learning tests found compatible results (e.g. Kourkoulou et al. 2012; Mostofsky et al. 2000; Scott-Van Zeeland et al. 2010). Our findings contemplate these results and demonstrate that statistical learning is an influential mechanism also in social cognitive processes. The findings of the current study are thus in line with Ruffman's (2014) theoretical claim that individuals with ASC have problems with statistical learning. In particular, he claims that statistical learning abilities are crucial to learn about regularities in our environment and finally, help to combine observed behavior with mental states. Since individuals with ASC have weaker statistical learning skills, this could explain reduced social-cognitive abilities. Further studies could additionally distinguish whether these deficits are limited to the social domain or also affect non-social stimuli, such as learning about machines. This would, in a next step, be informative for the scope and limits of statistical learning abilities in ASC, and thus enrich theoretical accounts.

The present findings also inform recent predictive coding theories. Our findings fit well with the assumption that individuals with ASC have difficulties using sufficient priors and instead rely more on incoming sensory information (Lawson et al. 2014; Pellicano and Burr 2012; Van de Cruys et al. 2014). Predictive coding theories claim that perception in ASC is less biased by their prior expectations on how the world looks like, so individuals with ASC might perceive sensory information less distorted than typically developed. In our study, individuals with ASC might have had problems in either forming a prior over the trials (i.e. agent walks to goal A) or in using such a prior (in a rather changing context), or even a combination of both. A recent study by Chambon et al. (2017) speaks for problems in forming a prior. In their study, participants with ASC were able to extract statistical regularities from observed behaviors but had problems using social priors. Whereas statistical regularities were inferred from the just observed behavior, social priors are based on their "a priori" experience. In our case, it could be that the prior "agents act towards goals", an assumption that is based on participants prior experience, was not as easily used by individuals with ASC as by typically developed. On the contrary, Van de Cruys et al. (2014) argues for problems in generalizing priors to new situations in ASC. It is further hypothesized that individuals with ASC could have problems in taking contextual information into account (Gomot and Wicker 2012; Lawson et al. 2014). As stated by Tewolde et al. (2017), it is not clear how broad "prior information" is defined by predictive coding theories. We cannot tell from our study whether the change in context (objects swap position) either helped or hindered forming the prior because of an inability to generalize the prior to a new context.

Interestingly, we did not find general age differences in our study. It seems that the ability for statistical learning in order to make goal-directed anticipations is stable across development in ASC, at least from around 10 years of age onwards. Nevertheless, as compared to the two younger age groups, in our adult sample we did find a slightly different gaze pattern: They showed a looking bias to the goal after several trials, but this bias attenuated with trial repetition. This could be due to boredom or a decline in motivation in ASC. Paulus et al. (2017, study 3) reported analogous results.

In sum, our results suggest that individuals with ASC have difficulties integrating previous information into their action anticipations and are thus in line with recent theoretical notions (e.g. Pellicano and Burr 2012; Ruffman 2014). Moreover, our results also support recent suggestions for clinical practice. Haker et al. (2016) delineated how predictive coding theories can improve diagnosis and treatment of ASC. Our results fit very well with their suggestion to provide individuals with ASC a familiar environment that causes only little surprise. New sensory input should be offered step-by-step and repeatedly over a longer period of time. This might help with learning behavioral strategies and with slowly acquiring varied representations of the world (Haker et al. 2016). Similarly, Van de Cruys and colleagues (2014) emphasized on the role of scaffolding while learning, and state that individuals could learn high-level predictions when being extensively exposed to different situations. Our results not only suggest that individuals with ASC need more repetitions and a changing context to learn such higher-level predictions, they also support the practical suggestion for a gradual exposure from simple to more naturalistic settings (Van de Cruys et al. 2014).

No Group Difference in Overall Anticipation Rate

We cannot confirm the hypothesis that individuals with ASC have a reduced tendency to engage in action anticipation as compared to typically developed individuals (Sinha et al. 2014). We neither found group differences in the amount of action anticipations, nor did we find a change of the amount of action anticipations throughout the test trials or between age groups. This suggests that already from the second trial onwards, individuals with ASC anticipated the reappearance of the agent. Our findings do not support the assumption that a general impairment in predictive abilities is the cause for social cognitive problems in ASC.

Interestingly, our results are not in line with a recent study by Schuwerk et al. (2016) who reported a weaker tendency to generate action anticipations in 10-year-old children and adults. A reason for our diverging results from Schuwerk et al. (2016) could be that in our stimuli the goals (e.g., the house/forest) were visible throughout the entire trial. This could have had an eliciting effect on visual action anticipations. In Schuwerk et al.'s study (2016), the target was only present before the agent started to move and was invisible for most of the time. Analogously, Goldberg et al. (2002) showed that individuals with ASC had problems making motion anticipations when targets were not present. Studies from goal perception in typically developing infants also confirmed the facilitating effect of salient targets on anticipatory eye-movements (e.g. Adam et al. 2016; Gredebäck et al. 2009; Henrichs et al. 2012). In sum, it seems that anticipating other's actions might be easier in some situations than in others and that specific situational aspects influence active action processing in ASC. Further examination of anticipatory abilities in ASC by systematically manipulating social contexts is necessary.

Limitations and Open Questions

In line with previous research on action anticipation (Falck-Ytter 2010; Schuwerk et al. 2016) we did not find any age differences between individuals with ASC, indicating that the use of prior information to anticipate other's action goals is stable across development, or at least from childhood to adulthood. Nevertheless, little is known about the development of social cognitive abilities in later adulthood in ASC (Lever and Geurts 2016). Most research on cognitive differences between individuals with and without ASC concentrates on early childhood, but little is known about how these differences manifest in older ages (Powell et al. 2017). Typical aging is associated with a decline in relevant cognitive domains, such as executive functions (e.g. Verhaeghen and Cerella 2002), Theory of Mind (e.g. Charlton et al. 2009), or action anticipation (e.g. Diersch et al. 2016). For the case of ASC, it was suggested that age-related declines might happen faster in some domains, whereas in other domains similar declines to neurotypically developed are observed; sometimes an ASC-diagnosis even has a "protecting" effect (Geurts and Vissers 2012; Lever and Geurts 2016). Given this puzzle, it would be interesting to study action anticipation within older adults with ASC.

Further, although our results suggest that individuals with ASC have difficulties using prior information for their action anticipations, it is still an open question whether they have problems with the acquisition of the information (i.e. that the agent walks to goal A) or with the use of that information in a changing environment. In our study, the context changed as the position of the goals varied. We do not know if individuals with ASC are not that flexible in their use of prior information and thus have difficulties including contextual changes in their action anticipations. We leave it to future studies to disentangle this issue in greater detail.

Conclusion

The current study demonstrates that children, adolescents and adults with ASC anticipate the goal of an action and do not merely process movement information when making action anticipations. However, individuals with ASC needed more time to learn about the goal of an action compared to typically developed individuals, which suggests that the ability to use prior information is attenuated in ASC. This is in line with theories claiming that such an impairment causes social cognitive problems in ASC. In sum, our findings contribute to the understanding of the cognitive mechanisms underlying communication and interaction problems in ASC.

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