Title: "Contextual priors do not modulate action prediction in children with autism"

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Abstract

Bayesian accounts of autism suggest that this disorder may be rooted in an impaired ability to estimate the probability of future events, possibly due to reduced priors. Here, we tested this hypothesis within the action domain in children with and without autism using a behavioural paradigm comprising a familiarization and a testing phase. During familiarization, children observed videos depicting a child model performing actions in diverse contexts. Crucially, within this phase, we implicitly biased action-context associations in terms of their probability of co-occurrence. During testing, children observed the same videos but drastically shortened (i.e., reduced amount of kinematics information) and were asked to infer action unfolding. Since during the testing phase movement kinematics became ambiguous, we expected children's responses to be biased to contextual priors, thus compensating for perceptual uncertainty. While this probabilistic effect was present in controls no such modulation was observed in autistic children, suggesting an impairment in using prior information when anticipating others' actions under situations of perceptual uncertainty.

Introduction

Understanding what others are doing and what they are going to do next constitutes a major hallmark of social cognition achievement (Sebanz and Knoblich, 2009).

Current prediction theories in the action domain suggest that the motor system plays a key role in the anticipation of others' actions (Aglioti et al., 2008; Jeannerod, 2001; Rizzolatti and Craighero, 2004; Wolpert and Flanagan, 2001). Central to these theories is the concept of motor simulation, which assumes that anticipatory mechanisms rely on the covert re-enactment of the motor programs used to perform the observed movements. On this view, prediction would be accomplished by using our motor system as an internal forward model. However, there is evidence challenging this approach by showing that motor experience is not necessarily required to anticipate action unfolding (Vannuscorps and Caramazza, 2015, 2016) and that similar predictive performance can be achieved possibly by relying on previous observational experience with others' actions (de Klerk et al., 2016). Nevertheless, despite differences on the role of motor experience in action prediction, most of these views collectively assume that the motor system or, at least, some related structures (i.e., the ventral premotor cortex) are critically involved in predictive processing (Schubotz, 2007).

A critical challenge for action prediction accounts in general is explaining how the motor system allows action prediction under situations of perceptual uncertainty (Brass et al., 2007; Kilner et al., 2007). Indeed, similar movement kinematic patterns can be associated with different actions, making it difficult to move backwards from observed data to hidden motor representations about possible underlying causes.

Current predictive coding models based on Bayesian inference provide a solution to this "inverse problem" by suggesting that, particularly when visual evidence is ambiguous, the motor system benefits from top-down expectations about others' likely behaviours given previous similar experiences (Friston et al., 2011; Kilner et al., 2007).

Top-down predictions, however, are not only based on past visual or motor experience with others movements (Aglioti et al., 2008; Amoruso et al., 2014; Calvo-Merino et al., 2005) but also on prior knowledge about the context in which actions are typically observed (Amoruso et al., 2016; Wurm and Schubotz, 2012). Furthermore, it has been shown (Wurm and Schubotz, 2016) that, when perceptual information is impoverished, context plays a key role in aiding action recognition. Indeed, specific environmental scenarios are often indicative of which actions are likely to occur in them (e.g., we typically crack eggs in the kitchen), thus constraining predictive processing. In Bayesian terms:

$$P\ (\text{Action}|\text{Kinematics, Context}) \propto P\ (\text{Kinematics}|\text{Action, Context})\ P\ (\text{Action}|\text{Context})$$

where *P* (Action|Kinematics, Context) is the posterior probability of an action conditioned on observed kinematics and context, *P* (Kinematics|Action, Context) is the likelihood of the action given observed kinematics and context, and *P* (Action|Context) is the prior probability of the action given the context.

In other words, the prior defines a hypothesis space of what actions are feasible in that context (Baker et al., 2009). In particular, it has been suggested that priors can be classified in structural and contextual ones (Series and Seitz, 2013). Structural priors reflect default expectations, which may be innate or acquired through long-term learning and, thus, not easily malleable. A common example is given by the expectation that light comes from above. Contextual priors, conversely, are expectations acquired through short-term learning and bound to a specific spatio-temporal framework, cue, or task instruction.

Socio-motor impairments, including difficulties in action comprehension, are considered to be among the core deficits associated with Autism Spectrum Disorders (ASD, American Psychiatric Association, 2013). It has been recently proposed that this deficit might be related to atypical predictive processing (Lawson et al., 2014; Pellicano and Burr, 2012; Sinha et al., 2014). Interestingly, these accounts root their explanations in Bayesian inference and suggest that the integration between prior knowledge and sensory evidence may be affected in ASD. Central to some of these accounts is the hypothesis that ASD individuals are less influenced by prior knowledge, leading to a greater reliance on bottom-up sensory signals.

Despite the explanatory power of Bayesian approaches on ASD and the great attention they have received in the last years, only a few empirical studies (Chambon et al., 2017) have attempted to test its core assumptions within the action domain (i.e. individuals with ASD do not rely on contextual priors to explain away movement kinematics). Thus, experimental testing is necessary to advance comprehension in the field (Palmer et al., 2017).

Here, we aimed to directly test this hypothesis by comparing the ability to predict others' actions in children with and without autism. To this aim, we developed a behavioural paradigm consisting of a probabilistic learning task (familiarization) followed by an action prediction task (testing). During familiarization, children observed videos depicting a child grasping different objects to either interact or not with another child and were asked to predict action unfolding. Crucially, within this phase, we implicitly biased the association between the action and the context in terms of their probability of co-occurrence to induce contextual priors with different weights. During testing, children observed the same videos but these were shortened so that the amount of visual kinematics information was drastically reduced and were asked again to predict action unfolding.

Based on Bayesian models, we hypothesized that during testing, where movement kinematics become ambiguous, typically developing (TD) children would be biased toward contextual priors learned during familiarization, compensating for perceptual uncertainty. Conversely, since individuals with autism may be less influenced by prior knowledge, we expected not such compensation in ASD children.

Methods

Participants

Twenty-four high-functioning ASD children (mean age = 8.66, SD = 1.63 years) and twenty-four TD children (mean age = 9.04, SD = 1.08 years) took part in the current study. We determined the sample size for our mixed within- and between-subject 4 × 2 design (probability × group) through the G* power software (Faul, Erdfelder, Buchner, & Lang, 2009) by expecting a large effect size (f = 0.4) based on a previous study showing a large-association effect (r = 0.46) between autistic traits and contextual modulation of action perception (Amoruso et al., 2018), and setting the significance level at 0.05, and the desired power (1−β) at 0.95.

Children with ASD were recruited at the IRCCS Stella Maris Foundation, Pisa, Italy and at the Scientific Institute IRCCS E. Medea, Polo Friuli Venezia Giulia, and had previously received a diagnosis of ASD according to the DSM-5 criteria by independent clinicians and confirmed by a score above the threshold for ASD on the Autism Diagnostic Observation Schedule (ADOS, Lord, Rutter, DiLavore, Risi, Gotham, & Bishop 2012). We controlled also that all patients had no history of neurological or medical problems. TD children were recruited at primary schools in Udine (Italy). The two groups were 1:1 matched for age (ASD = 8.66 ± 1.63; TD = 9.04 ± 1.08; t (46) = -0.937, p = 0.353), gender (male: female ratio 22:2), and non-verbal IQ as measured by the Raven's Colored Progressive Matrices (ASD = 107.91 ± 10.62; TD = 102.5 ± 10.32; t (46) = 1.791, p = 0.079). See Table 1 for participant's characteristics.

The study was approved by the local Ethics Committee (Comitato Etico Regionale Unico, Friuli Venezia Giulia, Italy) and was carried out in accordance with the ethical standards of the 1964 Declaration of Helsinki. All participants were naive to the aims and hypothesis of the experiment. Parents/guardians of all participants provided their informed written consent, and children gave their verbal assent to participate.

Stimuli

The videos were recorded in color at 25 frames per second with a Sony Alpha ILCE-7K camera and were further edited with the Adobe Premiere Pro CS3 3.0 Software. Length was matched across videos so that they had an equivalent duration: 25 frames for a total of 1,000 ms in the familiarization phase and 15 frames for a total of 600 ms in the testing phase. All videos depicted a male child (10 years-old) performing reach-to-grasp movements on two different objects (i.e., an apple or a glass) with his right hand in front of another child (10 years-old). Depending on the kinematics, each object could be grasped to perform either an individual or an interpersonal action (i.e., grasping-to-eat or drink vs. grasping-to-offer). Kinematics differences between individual and interpersonal actions were mainly provided by the type of power grip used: either from the side with a spherical grasp or from the top with a cylindrical grasp, respectively. Crucially, each of these actions was recorded associated with different contextual cues. In the case of the object "apple", the two possible contextual cues were an orange or a violet dish. In the case of the object "glass", the two possible cues were a blue or a white tablecloth.

Stimuli validation

A total of 80 videos (Object [5] x Action type [2] x Contextual-cue [2] x Versions [4]) were originally recorded. Please note that by "Versions" we mean different video recordings of the same action. Apart from the apple and the glass videos that were selected for the final experimental design; a cup, a pair of scissors and a spray-cleaner were also used in this initial phase. All the objects could be manipulated by the actor in order to perform either individual (i.e., eating, drinking, cutting or spraying, respectively) or interpersonal actions (i.e., offering it to another child) in the presence of two different contextual cues (i.e., a dish, a tablecloth, a tray, a notebook, or a cloth with different colours, respectively). In order to validate the stimuli, we conducted a preliminary rating study on the 80 videos by asking 10 TD children (4 females; mean age = 9 ± 1.24 years) to watch the first 25 snapshots (i.e., 2 frames before the child made fully contact with the object) and to recognize the action.

Overall, the rationale behind this preliminary study was selecting those actions that had comparable discriminability in order to rule out any cofounding effect related to intrinsic objects' properties (e.g., affordance). The Friedman ANOVA yielded an effect of object ($X^2 = 10.37$, $p = 0.03$). Pairwise comparisons with the Wilcoxon matched-pairs test indicated that those objects that elicited the most similar levels of accuracy and were far from being significantly different from each other (p = 0.918) were the apple (M = 86.3; SD = 12.7) and the glass (M = 86.6; SD = 16.3), while the other objects led to an accuracy level of: cup (M= 93.8; SD = 12.67), scissors (M=85.9; SD = 13.22) and spry cleaner (M=91.6; SD = 9.74). Thus, actions directed to the apple and the glass were selected for the final experiment.

Task and procedure

To test whether children with ASD benefit of prior probabilistic information to predict action unfolding, we developed a friendly paradigm consisting of a familiarization and a testing phase (see Fig. 1 and supplementary Videos 1–8 for examples).

During familiarization, videos depicted a child grasping either an apple from a plate or a glass from a tablecloth to perform individual or interpersonal actions (i.e., eating/drinking and giving the object to the other child, respectively). Videos were stopped 2 frames before the child model made full contact with the object. Thus, even though participants observed the pre-shaping of the hand during the reaching phase of the movement and not the grasping movement itself, the amount of visual information given was high. In a two-alternative forced choice (2AFC) task, participants were asked to watch the videos and predict action unfolding. Importantly, during the familiarization, we implicitly manipulated prior expectations by setting the probability of co-occurrence between actions and contextual-cues (i.e., the colour of the plate and the tablecloth) to 10%, 40%, 60% or 90% (see Fig. 1A-B).

During the testing phase (Fig.1C), children observed the same videos and were asked again to predict action unfolding. However, in this case, the amount of sensory evidence was drastically reduced by shortening the videos so to occlude the last 400ms (i.e., last 10 frames). We reasoned that during this phase, where movement kinematics became ambiguous, children’s responses would be biased toward contextual priors acquired during familiarization, thus compensating for perceptual uncertainty. Of note, even though participants observed only the initial part of the videos (i.e., either the initial 25 or 15 frames depending on the phase), when these were originally recorded, the child actor was asked to perform the full action to provide veridical kinematics information.

Each participant performed the full experimental session in the same day. Before the experimental session, children were initially introduced to the objects and received demonstrations about the different possible ways of manipulating them. More specifically, we gave children specific examples by showing the overall action with the original objects used in the videos and explicitly named the associated labels (e.g., "This is how we grasp an apple when we want to eat it"). Furthermore, children were asked to grasp the objects and perform the complete action themselves to promote simulation.

The experimental session consisted of two blocks and lasted ~40min. Each of these blocks comprised a familiarization phase (80 trials) immediately followed by a testing phase (40 trials). Thus, the overall experiment consisted of 240 trials, 160 of familiarization and 80 of testing. Short breaks were allowed between blocks and phases. Neither explicit information about the associations between contextual-cues and actions nor trial-by-trial feedback was provided. Thus, participants were completely naïve to the existence of underlying statistical regularities. This was further confirmed after the experiment during the debriefing session, in which participants were explicitly informed about the existence of action-color associations. Interestingly, some children reported to have noticed a relationship between them but, critically, only two TD children reported the *exact* content of the abstract rule (e.g., "every time an orange plate appeared it was more likely to see the child grasping the apple for eating"). This ensures that, overall, no explicit knowledge about the underlying associations was evident for either TD or ASD children and that observed effects are unlikely to stem from attentional aspects regarding the ability or inability to attend to a contextual cue.

It is worth noting that half of the overall trials involved the object "apple" and the other half the object "glass". While for one object we biased 10-90% the action-cue association (i.e., in

90% of the trials the action “eat” was combined with the presence of the orange plate, and in the other 10% of the trials it was combined with a violate plate), for the other object we biased 60-40% (i.e., in 60% of the trials the action “drink” was combined with the presence of the blue tablecloth, and in the other 40% it was combined with a white tablecloth). Importantly, this probabilistic structure was kept identical within participants in the two consecutive experimental blocks but the actions associated to high or low probabilities were counterbalanced between participants. Importantly, during the testing phase, all possible action-contextual cues associations were equally presented (10 trials for each action); for a total of 20 trials for each of the 4 probabilities of context-action associations established in the familiarization phase.

Trial structure

The trial structure was the same in the familiarization and testing phase, with the exception of video duration. Trials started with a fixation cross lasting 3,000 ms and it was followed by the video-clip presentation lasting 1,000 ms in the familiarization and 600 ms in the testing blocks. After the video-clip, a frame was presented with the verbal descriptors of the two possible actions (e.g., “mangiare” or “bere” and “offrire”, in English “to eat” or “to drink” and “to give”, respectively; one located on the right and the other on the left) written in white on a black background. This frame remained on the screen until a response was recorded. Participants were requested to give their responses by pressing with the index finger the computer keys “z” (for left choices) or “m” (for right choices). The keys were covered with white stickers in order to facilitate localizing their position on a QWERTY keyboard. The location of the two descriptors was counterbalanced, ensuring that in half of the trials a descriptor was presented on the left and, in the other half, on the right. This procedure enabled us to prevent participants from planning their response in advance on the basis of the spatial location of the descriptors.

Results

Neuropsychological results

Before the experiment, we assessed social perception abilities in all children using the Italian Version of the NEPSY-II (Urgesi et al., 2011). This battery includes two tests that evaluate theory of mind (ToM, i.e., the capacity to interpret other's intentions, desires and beliefs), and affect recognition (i.e., identification of emotional facial expressions). In addition, the ToM test can be divided in a verbal (ToM A) and a contextual (ToM B) part, with the former one evaluating intention understanding of social situations from verbal or pictorial descriptions; and the latter one, assessing the capacity to understand how certain emotions are linked to specific contexts (see Table 1). As in Narzisi et al. (2013), the scores obtained for each participant at each test were expressed as scaled scores with respect to the normative values for the corresponding chronological ages, thus improving the approximation of the data to the normal distribution.

We compared social perceptual abilities between groups by means of independent sample t-tests. A significant difference between groups was observed in ToM A [t (46) = - 4.22, p = 0.0001; ASD children, M = 6.27, SD = 4.66; TD children, M = 11.12, SD = 3.13], with ASD children scoring lower than the TD ones. However, no significant differences between groups were observed for the ToM B [t (46) = - 0.54, p = 0.58; ASD children, M = 9.42, SD = 3.08; TD children, M = 9.87, SD = 2.63] or for the affect recognition test [t (46) = 1.50, p = 0.13; ASD children, M = 6.77 ± 1.95, TD children, M = 7.76 ± 2.57], even though the ASD group tended to have lower scores than the TD one.

Action prediction results

Behavioral reaction time (RT) performance was acquired during the testing phase. RT were trimmed at 2.5 standard deviations (SD) above their mean. In addition, RTs < 100ms were considered accidental button presses and removed from the analysis. We run a repeated-measures analysis of variance (RM-ANOVA) considering group (ASD, TD) as between-subjects variable and the different probability conditions (10%, 40%, 60%, 90%) and blocks (1, 2) as within-subjects variables. The analysis yielded a main effect of group ($F_{1, 46} = 6.98$, $p = 0.011$, $\eta_p^2 = 0.13$), indicating that TD children (mean = 1608.13; SD = 571.05) were faster than the ASD ones (mean = 1969.95; SD = 491.57); and a main effect of block ($F_{1, 46} = 11.52$, $p = 0.001$, $\eta_p^2 = 0.20$), showing an overall learning effect with reduced RT in the second block (mean = 1709.17; SD = 540.3) as compared to the first one (mean = 1868.92; SD = 573.4). No other effects were observed (all *p*s > 0.32).

Accuracy data from the familiarization and testing phases were converted into *d* prime values (*d′*), a bias-corrected measure of sensitivity in discriminating between 2 categories (Macmillan and Kaplan, 1985), in this case, between individual vs. interpersonal actions. We also calculated a measure of response criterion (c), which reflects the existence of a bias in providing a specific response.

We run an exploratory RM-ANOVA in the familiarization phase considering group (ASD, TD) as between-subjects variable and the different probability conditions (10%, 40%, 60%, 90%) and blocks (1, 2) as within-subjects variables. This analysis yielded non-significant differences (all *p*s > 0.22). Nevertheless, we decided to collapse the 4 probability conditions during familiarization due to their unequal number of trials resultant from the probabilistic manipulation. An independent t-test comparing the overall *d′* scores obtained during the familiarization revealed no differences (t (46) = -1.305, $p = 0.198$) between the TD (M = 1.414, SD = 0.37) and ASD (M = 1.239, SD = 0.53) groups (see Fig. 2). Furthermore, non-significant differences were observed for the *c* values (t (46) = -1.683, $p = 0.099$), suggesting that predictive performance in both groups was comparable when the amount of visual kinematics information was high and that their responses were not biased in terms of identifying individual or interpersonal actions.

Then we run the RM-ANOVA on the *d′* responses obtained during the testing phase. Here, we find a main effect of probability ($F_{3, 138} = 5.212$, $p = 0.001$, $\eta_p^2 = 0.10$) and an interaction between probability and group ($F_{3, 138} = 3.271$, $p = 0.023$, $\eta_p^2 = 0.06$). No effects or interactions including the factor block were found (all *p*s > 0.13). Post-hoc comparisons performed with the Newman-Keuls test on the interaction (MSE = 0.41039, df = 119.67) indicated that, within the ASD group, performance under the different probability conditions did not differ (all *p*s > 0.55). Conversely, TD children were better at predicting others' actions under the highest probability condition as compared to the low and intermediate ones (90% vs. 10%, $p = 0.0001$; 90% vs. 40%, $p = 0.002$; 90% vs. 60%, $p = 0.04$). Moreover, the performance of the TD and ASD groups only differed for the highest probability condition (90%). Specifically, the 90% condition in the TD group significantly differed from the 90% ($p = 0.04$), 60% ($p = 0.01$), 40% ($p = 0.01$), and 10% ($p = 0.02$) conditions of the ASD group, with larger *d'* values in the TD than in the ASD group (see Fig. 2).

Again, no significant main effects or interactions were observed for response criterion *c* values (all *p*s > 0.11)**.**

Correlations results

Finally, we examined the relationship between the probabilistic effect and measures of social perception, symptomatology and psychopathology. In order to account for the probabilistic effect, we calculated a beta index for each participant based on their performance on the familiarization and the testing phases, separately. Briefly, standardized beta coefficients were estimated across trials at the individual participant level by running a regression analysis with accuracy and probability as the dependent and independent variables, respectively. Thus, this measure provides an estimate of the strength of the probabilistic effect on children's performance. Since responses were coded on the basis of movement kinematics, positive betas indicate that, as the probability of action-context association increases, the prediction of action unfolding increases, in keeping with the use of contextual priors to disambiguate action kinematics. In contrast, negative betas reflect the inverse relationship, that is, as probability increases, action prediction decreases, pointing to a tendency to respond counterintuitively with respect to the context. Betas close to zero reflect that children mostly relied on body kinematics and were less influenced by the context. Thus, a negative relationship between symptom severity and individual beta value would point to weaker use of contextual prior in more impaired children.

The Pearson correlations between the beta index and the neuropsychological measures run separately for each group yielded non-significant effects neither in ASD (ToM A: $r = -0.16$, $p = 0.42$; ToM B: $r = -0.001$, $p = 0.99$; emotion recognition: $r = 0.05$, $p = 0.78$) nor TD children (ToM A: $r = -0.16$, $p = 0.42$; ToM B: $r = -0.35$, $p = 0.08$; emotion recognition: $r = 0.11$, $p = 0.60$).

Then, within the ASD group, we correlated the beta index with the ADOS calibrated severity scores (Gotham et al., 2009) to check if autism severity explained the observed effect. However, no association was found between the ADOS CSS and the beta indexes (familiarization phase: $r = -0.01$, $p = 0.94$; testing phase: $r = -0.02$, $p = 0.91$).

Finally, we correlated the beta index with the Child Behaviour Checklist (CBCL) subscales (see Table 2). The CBCL (Achenbach and Ruffle, 2000), constitutes a parent report for the screening of emotional and behavioural problems in childhood. Of note, one of the CBCL subscales measures children´s anxiety. This is of particular interest since a series of recent studies indicate the existence of a strong negative association between anxiety levels and unpredictability in ASD (Boulter et al., 2014; Chamberlain et al., 2013). In other words, unexpected events constitute a potential stressor that triggers increase levels of anxiety in ASD individuals. Indeed, all the constellation of symptoms characterized as "restricted and repetitive behaviours" (e.g., insistence on sameness, rituals and difficulty in tolerating change) are thought to represent compensatory strategies to mitigate uncertainty and make life as much predictable as possible.

The analysis involving the CBCL subscales showed a significant negative correlation between the beta index obtained during the testing phase and anxiety (r = - 0.559, p = 0.036, one-tailed; Bonferroni corrected). See Fig. 3. Importantly, no correlation between anxiety and beta was found for the familiarization (r = 0.058, p = 0.79), suggesting that the association was specifically related to atypical predictive processing in uncertain environments.

Discussion

Bayesian models postulate that human observers optimize sensory processing by combining perceptual information with previous knowledge about the statistical regularities of the world (Knill and Pouget, 2004). An appealing Bayesian approach to ASD suggests that autistic impairments might be related to a reduced influence of prior probabilistic knowledge when interpreting variations in incoming inputs (Pellicano and Burr, 2012). Furthermore, since priors can be operationalized as expectations in predictive coding models (Kording and Wolpert, 2004), this deficit can also be interpreted in terms of poor predictive abilities (Schuwerk et al., 2016; Sinha et al., 2014).

Here, we tested this hypothesis by examining how ASD and TD children tracked the probabilities of action-context co-occurrence and used this knowledge to predict others' actions under situations of perceptual uncertainty (i.e., low amount of movement kinematics information). Overall, we found that both groups were able to accurately predict action unfolding when perceptual information about kinematics was high (i.e., during familiarization). However, during testing, where movement kinematics became ambiguous, only TD children were able to capitalize on priors (i.e. probabilistic distribution of the action-context associations) to help disambiguation and accurately predict action unfolding. Conversely, ASD children were able to predict the correct action above chance level, but their responses were not biased by the prior probabilistic distributions. Pearson analysis correlating task performance with social cognition and symptom severity found no evidence that ASD-related differences in these domains could account for the pattern of observed responses. Interestingly, however, the anxiety subscale of the CBCL negatively correlated with ASD performance during testing but not during familiarization, suggesting that higher levels of anxiety were associated with the reduced effect of probabilistic knowledge during action prediction only in uncertain environments.

It has been proposed that social impairments in ASD may be linked to difficulties in perceiving and recognizing other people' actions (Fecteau et al., 2006; Iacoboni and Dapretto, 2006). According to this theory, this might be due to deficits in processing biological motion (Blake et al., 2003) or, more broadly, to aberrant activity in the action observation network (AON) that prevents from properly coding others' movement kinematics (Theoret et al., 2005). However, this theory has been recently challenged by evidence showing that individuals with ASD exhibit functionally intact perceptual signals for interpreting others' behaviours (Cusack et al., 2015) as well as comparable activity in the AON (Dinstein et al., 2010). For a systematic review see (Hamilton, 2013). In line with these latter studies, we found no differences between ASD and TD children either during familiarization or during testing in the weakly associated condition (i.e., 10%), suggesting that both groups were able to correctly identify observed actions on the basis of perceptual movement kinematics. This is also in keeping with previous studies investigating action prediction in adults with ASD and showing normal bottom-up sensory processing (Chambon et al., 2017) and with Bayesian accounts, suggesting that it is not sensory processing itself what is compromised in ASD but its interpretation.

While no differences between groups were observed during familiarization, the testing phase revealed different patterns of behavioural performance. TD children showed a clear bias towards priors learnt during familiarization that was completely absent in the ASD group. Specifically, when the amount of perceptual evidence was drastically reduced (i.e., shortened videos), TD children were better at predicting others' actions in the high-probability condition as compared to those with lower probability. This is in accordance with Bayesian proposals suggesting that ambiguous visual evidence leads to an increased reliance on contextual priors and greater perceptual bias. It can be argued, however, that children were not interpreting diminished movement kinematics by using learnt priors but rather ignoring them and solely responding based on the contextual cues. In other words, an alternative explanation to our findings could be phrased in terms of general learning of cue-response pairings rather than Bayesian inference. Nevertheless, this seems unlikely. Indeed, both ASD and TD children performed above chance level (~68 % and ~66 %, respectively) in the testing phase for the low-probability condition (i.e., 10%), namely, when contextual cues violated the expectations triggered by the high-probability condition (e.g., observing the action "give" in the context of an orange plate when this cue was strongly associated with the action "eat"). In these "incongruent" testing trials, children still tended to predict the action signalled by movement kinematics rather than that expected from the context (i.e., answer "give" instead of "eat"), thus indicating they were using kinematics to predict action unfolding when contextual priors were not reliable. Accordingly, it has been shown that when contextual cues are not available, information from observed movement kinematics forms the basis for action inference (Soriano et al., 2018). It is worth noting, however, that the current design does not allow to determine whether contextual modulations occurred directly on the kinematics level or on other higher levels of action representation (i.e., intention), which remains an open question for future studies.

Interestingly, performance in the testing phase remained stable in the ASD group irrespectively of the probabilistic condition (i.e., ~68 %), suggesting that they mainly based their responses on movement kinematics and did not benefit from using contextual priors. It is unlikely that this pattern of results reflects a greater ability of ASD children to ignore the color cue and to focus on the task at hand (i.e., anticipating action unfolding based on kinematics). Indeed, were this the case, better performance of ASD as compared to TD children would be expected in the 10% probability condition, where context and movement kinematics pointed to incongruent predictions. Conversely, performance of ASD and TD children was comparable when context was unreliable and only differed, with better predictive performance in the TD group, when context provided reliable cues. Accordingly, previous studies have shown that ASD individuals typically exhibit enhanced access to the details of a scene, which reflects a general bias toward processing local features and elements (Dakin and Frith, 2005). On this view, what would be actually expected is a higher ASD attentional bias directed toward the color feature (Wang et al., 2015). Indeed, there is evidence (Maule et al., 2017) showing that ASD individuals are better than TD controls at recognizing whether colors were part of an original set or not. Furthermore, no differences were observed between ASD and TD children in the non-verbal contextual task of the NEPSY-II (see also Narzisi et al., 2013), which evaluates the capacity to interpret how others' intentions can be linked to specific contexts, making it unlikely that the observed results could be explained by a deficit in contextual integration. Thus, the overall pattern of results suggests that, even though ASD children perceive and recognize action kinematics to the same extent as TD children when enough perceptual information is provided (i.e., in the familiarization phase) or when context provides unreliable cues (i.e., 10% condition during testing), they do not benefit of prior probabilistic information to predict action unfolding.

A limitation of the current study, however, is that it cannot disentangle whether ASD children were unable to track regularities and learn the action-context associations or learnt them but did not use them to predict others’ actions. Previous evidence seems to support the former option by showing that ASD children exhibit a general deficit in using arbitrary cues to make inferences (Ames and Jarrold, 2007) as well as impairments in tracking implicit regularities and form action predictions (Schuwerk et al., 2016).

However, it is worth mentioning that other studies have shown that ASD children are able to use statistical information from the environment to a similar extent as TD children. For instance, Manning et al. (2017) tested how ASD and TD children used reward probabilities in a decision-making task under stable or volatile contexts (i.e., fixed vs. fluctuating probabilities). Based on the Bayesian proposal suggesting that autistic observers are less biased to prior information (Pellicano and Burr, 2012), they hypothesized that ASD children would assign more weight to recent trials and would not flexibly update their behaviour in response to uncertainty in volatile contexts. In contrast, they found similar learning rates and updating profiles in both groups, suggesting that, at least under some situations, ASD children can use contextual priors to interpret sensory information.

Yet, difficulties may arise when ASD individuals are presented with more complex tasks in which uncertainty is linked to social information. Indeed, in our task, uncertainty was tightly related to the possibility of an agent interacting –or not- with another. Thus, it is likely that the differences between groups detected by our paradigm may have arisen from the social setting of the task.

Finally, our finding of a negative correlation between anxiety and task performance in the testing phase is in line with current proposals suggesting that atypical predictive abilities in

ASD are associated to increased levels of anxiety (Sinha et al., 2014). In particular, the non-relying on prior knowledge to explain away sensory information makes the world to appear more unstable and unpredictable and this is sufficient to trigger a stress response (Boulter et al., 2014; Chamberlain et al., 2013). This might explain a wide range of ASD symptoms, such as insistence on sameness and repetitive behaviors, which can be conceived as coping strategies to reduce anxiety. Notably, no correlation was observed during familiarization, thus highlighting to a specific link between anxiety traits and poor predictive processing only under situations of perceptual uncertainty.

Interestingly, Manning et al. (2017) also explored the possible link between children's anxiety and task performance. However, they did not find correlations between these aspects. Nevertheless, the task used by Manning et al. did not comprise social situations and this may explain their negative result. Thus, our findings point to the fact that the link between anxiety and prediction abilities in ASD might be particularly related to handling uncertainty in social environments. While here we provide preliminary support for this suggestion, we acknowledge that our current design does not allow to establish, whether ASD predictive deficits are specific for the social domain or can also be extended to the non-social one. Of note, recent evidence (Ego et al., 2016; Tewolde et al., 2018) seems to point to the fact that ASD children can actually predict non-social/physical events such as the trajectory of a flying bird or the movement of a car. Nevertheless, future studies directly comparing the differential role of social vs. non-social cues within the same sample of participants are necessary to shed light on this aspect.

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Figure Legends

Fig.1. Experimental design. (A) Full schema of probabilities allocation during a familiarization block (80 trials) in a hypothetical participant. In the example, low and high probabilities are assigned to actions performed with the object “apple”, while intermediate probabilities are assigned to the object “glass”. This distribution was counterbalanced across participants. The experiment included 2 blocks of familiarization (80 trials each) and 2 of testing (40 trials each). During the familiarization (B) children observed videos depicting a child performing individual or interpersonal actions and predicted action unfolding. During this phase, we implicitly manipulated action-context associations in terms of their probability of co-occurrence to 10%, 40%, 60% and 90%. During testing (C), participants performed the

same task but in this case the amount of perceptual information was drastically reduced (i.e., videos lasted 600ms).

Fig. 2. Action prediction results. Participants' performance (*d′*) in predicting the course of the observed actions during the familiarization and the testing phases for action-context "weak association" (10%), "intermediate associations" (40/60%) and "strong association" (90%). Asterisks indicate significant comparison ($p < 0.05$). Error bars represent SEM.

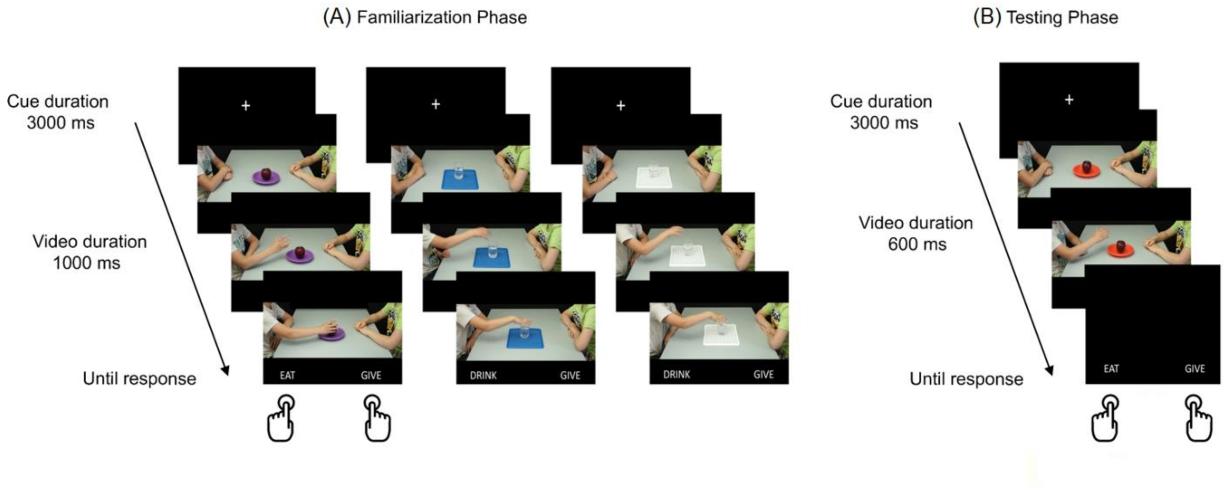
Fig. 3. Pearson correlation. Relationship between beta coefficients for ASD participants based on their performance on the prediction task and the parent-report anxiety scores. CBCL questionnaires were returned by 23 out of the 24 ASD children's parents. In addition, one child was removed from the analysis since the anxiety score had a Cook distance of 2.5. Thus, the analysis was performed on a reduced sample ($n = 22$).

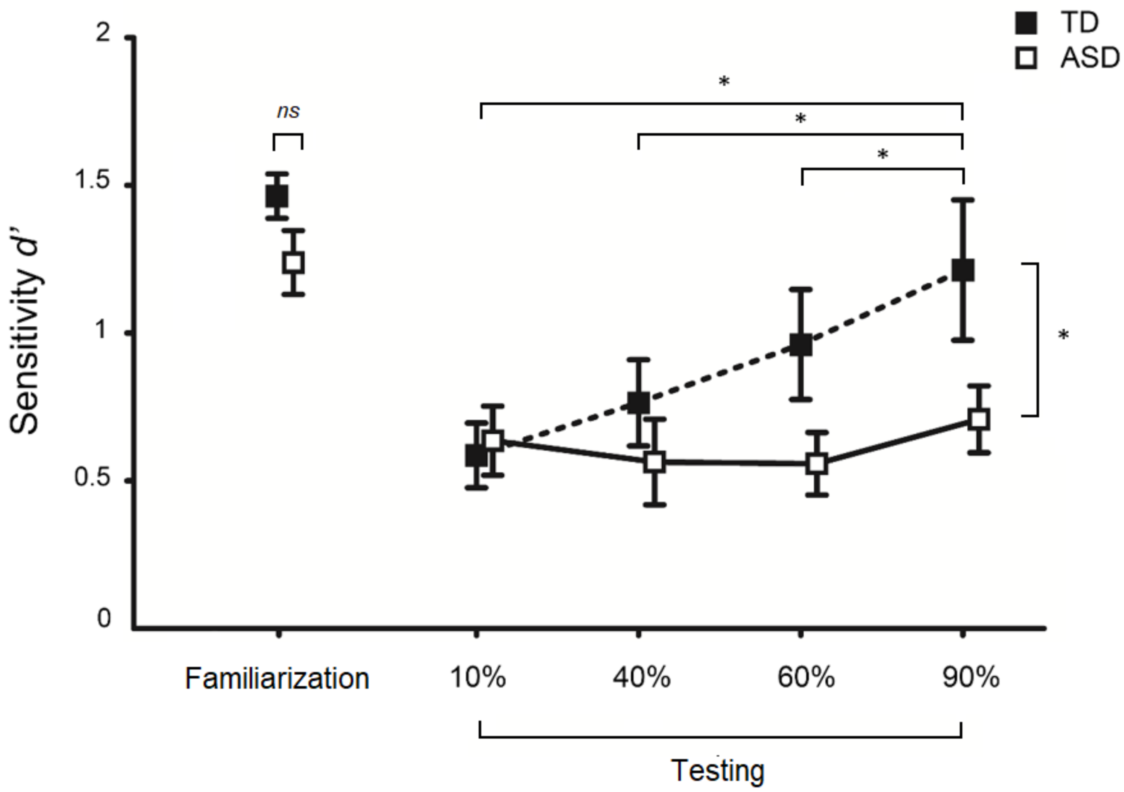
Table 1

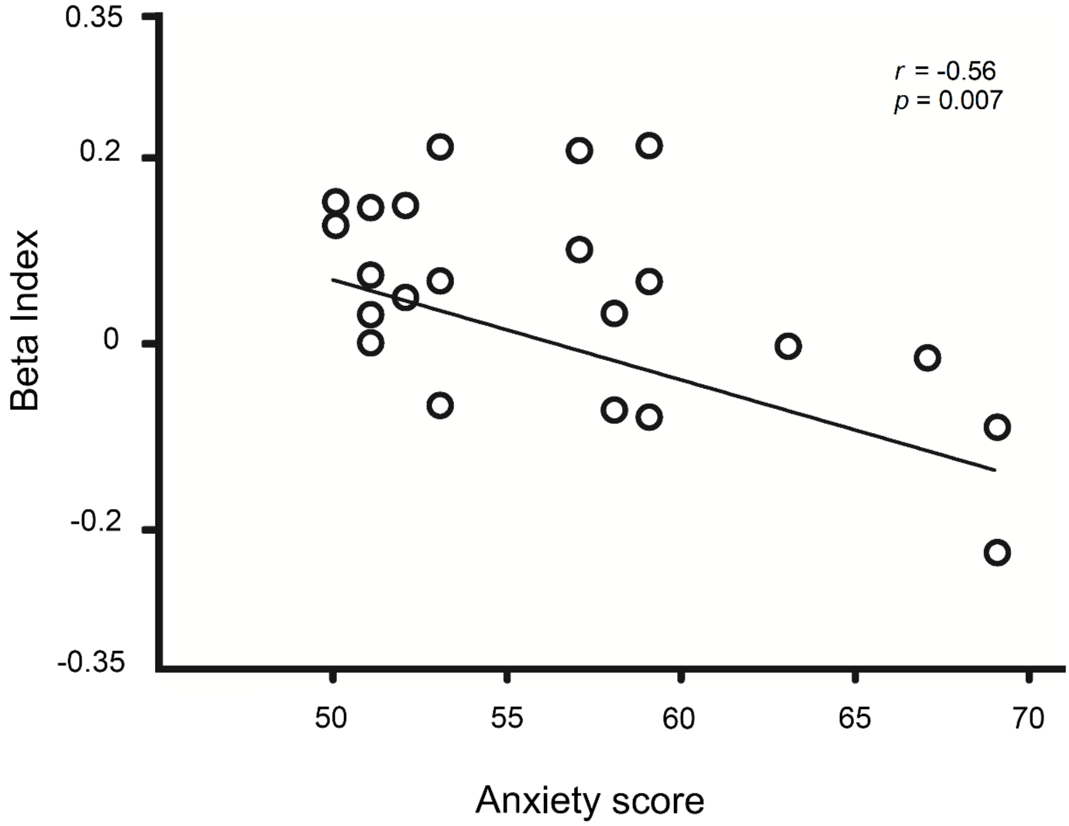
	ASD	**TD**
***N* (male:female ratio)**	22:2	22:2
Age mean (SD)	8.66 (1.63)	9.04 (1.04)
Age range	7-12	7-11
IQ mean (SD)	107.91 (10.62)	102.08 (10.2)
IQ range	80-130	80-120
ToM A	6.27 (4.66)	11.12 (3.13)
ToM B	9.42 (3.08)	9.87 (2.63)
Emotion Recognition	6.77 (1.95)	7.76 (2.57)
ADOS CSS mean (SD)	5.75 (1.29)	
ADOS CSS range	4-9	

Table 2.

Syndrome	**Mean t scores (SD)**	**range**
Anxious/depressed	56.31 (6.17)	50-69
Withdrawn/depressed	61.5 (7.07)	50-79
Somatic complaints	53.27 (4.38)	50-64
Social problems	62.4 (7.04)	50-78
Thought problems	61.27 (7.76)	50-74
Attention problems	61.22 (9.12)	52-92
Rule breaking behaviour	56.13 (5.68)	50-72
Aggressive behaviour	56.09 (4.83)	50-67


(A) Familiarization Phase
(B) Testing Phase
Cue duration
3000 ms
Video duration
1000 ms
Until response
Cue duration
3000 ms
Video duration
600 ms
Until response
EAT
GIVE
DRINK
GIVE
DRINK
GIVE
EAT
GIVE


TD
ASD
Sensitivity d'
2
1.5
1
0.5
0
ns
*
*
*
*
Familiarization
10%
40%
60%
90%
Testing


0.35
0.2
0
-0.2
-0.35
Beta Index
r = -0.56
p = 0.007
50
55
60
65
70
Anxiety score

657