Predictive Gaze During Observation of Irrational Actions in Adults with Autism Spectrum Conditions

Authors: Lauren E. Marsh, Amy Pearson, Danielle Ropar, Antonia Hamilton

Corresponding Author:

Lauren Marsh,
School of Psychology,
University of Nottingham,
Nottingham,
NG7 2RD,
Email: lauren.marsh@nottingham.ac.uk

Article accepted for publication in Journal of Autism and Developmental Disorders 26th August 2014, DOI 10.1007/s10803-014-2215-6

Abstract

Understanding irrational actions may require the observer to make mental state inferences about why an action was performed. Individuals with autism spectrum conditions (ASC) have well documented difficulties with mentalizing; however the degree to which rationality understanding is impaired in autism is not yet clear. The present study uses eye-tracking to measure online understanding of action rationality in individuals with ASC. Twenty adults with ASC and 20 typically developing controls, matched for age and IQ watched movies of rational and irrational actions while their eye movements were recorded. Measures of looking time, scan path and saccade latency were calculated. Results from looking time and scan path analyses demonstrate that participants with ASC have reduced visual attention to salient action features such as the action goal and the hand performing the action, regardless of action rationality. However, when participants with ASC do attend to these features, they are able to make anticipatory goal saccades as quickly as typically developing controls. Taken together these results indicate that individuals with autism have reduced attention to observed actions, but when attention is maintained, goal prediction is typical. We conclude that the basic mechanisms of action understanding are intact in individuals with ASC although there may be impairment in the top-down, social modulation of eye movements.

Keywords: autism, action understanding, rationality, eye tracking, social motivation

Research Highlights:

- Adults with ASC may have difficulty with action understanding or mentalizing
- Understanding action rationality involves both of these processes
- Here, autistic comprehension of irrational actions is explored using eye tracking
- ASC participants show reduced attention to action but typical rationality detection
- Reduced social motivation may be driving reports of action understanding impairment

1. Introduction

We can accumulate a large amount of social information about a person by observing how they act. For example, seeing a person with a letter walk along the street, we might predict he will stop at the post box. If he makes a detour to avoid walking under a ladder, we might further infer that he is superstitious. Thus, we are able to predict behaviour and make mental state judgements about a person merely by observing their actions. Cognitive processes for predicting actions and understanding mental states have been differentially implicated in autism spectrum condition (ASC). In this paper, we study eye gaze behaviour during observation of hand actions to determine if people with autism predict or understand actions differently.

Individuals with ASC have well documented social difficulties (Frith, 2003) which may include specific impairments in mentalizing and action understanding. Evidence for a mentalizing impairment in individuals with ASC has consistently been shown in their failure to represent anothers' false belief (Baron-cohen, Leslie, & Frith, 1985; Frith, 2001) and through poor comprehension of stories that involve mental state reasoning (Jolliffe & Baron-Cohen, 1999). Participants with ASC are also less able to identify and label the mental states of animated shapes when they are interacting in an intentional way, compared to when they are physically interacting (Castelli, Frith, Happé, & Frith, 2002; Marsh & Hamilton, 2011). Some of these mentalizing difficulties have been attributed to a failure to orient to relevant social cues in their environment (Klin, Jones, Schultz, Volkmar, & Cohen, 2002; Morris, Pelphrey, & McCarthy, 2002; Riby & Hancock, 2008) and this reduction in social looking correlates with ASC symptom severity (Klin et al., 2002; Speer, Cook, McMahon, & Clark, 2007 (although see Fletcher-Watson, Leekam, Benson, Frank, & Findlay, 2009; Freeth, Chapman, Ropar, & Mitchell, 2010; Speer et al., 2007).

In contrast, evidence for an action understanding impairment in autism is mixed. Individuals with autism show diminished anticipation of future actions (Boria et al., 2009; Cattaneo et al., 2007; Fabbri-Destro, Cattaneo, Boria, & Rizzolatti, 2009), reduced comprehension of complex action sequences (Zalla, Labruyere, & Georgieff, 2006; Zalla, Labruyère, Clément, & Georgieff, 2010) and reduced imitation of actions without objects (Stone, Ousley, & Littleford, 1997). However, individuals with ASC are able to complete anothers' action goal after witnessing their failed attempt (Aldridge, Stone, Sweeney, & Bower, 2000; Carpenter, Pennington, & Rogers, 2001) and are able to imitate in a goal-directed fashion (Hamilton, Brindley, & Frith, 2007). Recently, interest in implicit measures of action comprehension has increased. Tracking eye gaze provides an excellent way to record and probe the process of action comprehension in a natural, implicit and dynamic way. Studies of typical adults have shown that gaze during action observation is both predictive and socially oriented.

Predicitive gaze has been reported during action execution and action observation (Flanagan & Johansson, 2003). In their study Flanagan and Johansson (2003) asked participants to move three blocks in series from one location to another whilst their eye movements were recorded. During action execution, participants fixated start and end points of each action but made very few fixations between these locations. Furthermore, their eye movements were predicitive of their actions as they fixated the end point of their action 150ms prior to reaching it. Similarly, when participants observed movies of someone else performing the task, their eye movements were also predictive. Therefore, Flanagan and Johansson (2003) argue that predictive eye movements during action observation can be used as an index of goal understanding.

Eye movements during action observation have also been studied in participants with ASC. These studies show mixed results for both predictive gaze and social orienting. Typical predictive gaze during hand actions was shown by Flack-Ytter (2010). Five-year-olds with ASC, matched typically developing five-year-olds and a group of adults all made predictive eye movements to action goals during action observation. Furthermore, predictive eye movements occurred at the same speed in each group. These findings demonstrate that goal understanding for basic actions is intact in children with ASC (Falck-Ytter, 2010). However, when action prediction depends on the representation of another person's false belief, participants with autism fail to show predictive gaze (Senju et al., 2009). In a recent study where participants saw rational and irrational actions, Vivanti et al. (2011) demonstrated that both typically developing adolescents and adolescents with ASC orient to the face of an actor more after seeing an irrational action. This finding was suprising given the wealth of studes which show reduced social orienting in participants with ASC (Klin et al., 2002; Morris et al., 2002; Riby & Hancock, 2008; Speer et al., 2007). In the present paper, we will go beyond previous research by thoroughly assessing how adults with ASC respond when seeing goal-directed actions performed by a human or a non-human ball. We are particularly interested in the distinction between understanding the basic goal of an action and making inferences about irrational actions.

Studying irrational actions is important because these stimuli can draw on cognitive and neural resources for both basic comprehension of actions and mentalizing about why that action was performed. Brain scanning research shows that observing irrational actions engages brain systems associated with mentalizing in typically developing adults (Brass, Schmitt, Spengler, & Gergely, 2007). Given the mixed evidence for action understanding impairments in ASC and the clear mentalizing impairments, it is interesting to consider how irrational actions are processed in ASC. In a recent study, Marsh & Hamilton (2011) showed movies of rational and irrational actions to participants with ASC and matched typically developing adults during fMRI scanning. Responses to rational actions were similar across the typical and ASC groups, indicating basic action comprehension is intact in ASC. In contrast, responses to irrational actions differed. Responses in the medial prefrontal cortex (mPFC), a region closely associated with mentalizing, were greater when observing rational compared to irrational actions in typically developing participants. However, this differentiation was not observed in participants with ASC. This study was the first to demonstrate a clear difference in the processing of irrational actions in ASC but as yet, we do not understand the cognitive reasons for this neural difference. The aim of the present paper is to use eye tracking to assess whether adults with ASC are able to detect action rationality and if so, whether they use this information to make inferences about why the action was performed in an irrational manner. Furthermore, social orienting during action observation has not been directly studied and the effect of having social information available (such as faces and eyes) on predictive gaze will be explored. First, we consider some of the methodological issues that arise when using eye tracking to examine action observation.

1.1. Methodological considerations

Eye tracking methods have excellent potential for revealing the cognitive processes underlying action comprehension in an implicit and naturalistic situation. However, gaze data is complex and it is not yet clear which gaze parameters best capture rationality comprehension or which analysis methods to use. Different studies have used a wide variety of different analysis methods with no clear consensus. A further issue in using eye tracking to study rationality understanding is that most previous studies on this topic have studied infant and child eye movements. It is unclear whether reported gaze patterns are stable across time and that these measures are valid for adult eye tracking. In this section we review the findings from the child and infant studies of action observation, with a focus on the measures that have been selected and the cognitive processes that they are thought to reflect.

Looking time measures have been used to assess rationality understanding in typically developing infants (Elsner, Pfeifer, Parker, & Hauf, 2013). Modelled actions were either irrational (the model turned on a light with her forehead) or rationalised by an environmental constraint (a blanket wrapped around the models' shoulders prevented her from using her hands). An analysis of looking times revealed that infants looked longer at the rationalized action in which an environmental constraint impacted upon the action. The authors interpret this increased looking time during constrained actions to mean that the infants detected action rationality and spent time evaluating the environmental constraint imposed upon the action. However, this effect was only reported in one out of three trials.

Looking time was also used as a measure of rationality understanding in participants with ASC (Vivanti et al., 2011). In their study, Vivanti et al. (2011) showed ASC and typically developing children movies of irrational actions in which an actor performed an action with an unusual body-part (for example, closing a drawer with her shoulder) and matched rational actions in which the actor completed the same action but had her hands occupied. Results showed that both groups of participants looked longer at the face of the actor during irrational actions. Vivanti et al. (2011) propose that increased time looking at the face indicates the participants' attempt to rationalize the actors bahaviour by seeking more information about the actor and their intention. However, it is not possible to tell from these results whether participants in the ASC group actually use this information to make inferences about behaviour. In the present study, we will extend this finding by assessing how the presence of facial information contributes to action understanding and action prediction. By comparing movies where the face is visible to those where it is occluded, we are able to assess whether the face provides important cues that aid action prediction.

In a study of prospective looking, infants were habituated to an action in which a hand reached and grasped one of two objects. Following habituation, a test trial in which the two objects switched location was presented. At test, infants made more predicitve first looks to the previoulsy grasped object, not the previously grasped objects' location (Cannon & Woodward, 2012). Thus measures of first-goal-look and looking time to the different goal locations can indicate the degree of goal prediction used by the participant.

Predictive eye movements during irrational actions has been assessed in one previous study of typically developing 6- and 12- month old infants (Gredebäck & Melinder, 2010). In this study, infants saw movies of rational and irrational feeding actions. During a rational action, one adult picks up a piece of banana with a spoon and brings it to a second adults' mouth. In an irrational action, the first adult picks up the banana and places it on the back of the recipients hand, who then eats the banana from her hand. Latency to fixate the end point of the action (head or hand) was calculated for each condition. Results showed that rational actions were anticipated faster than irrational actions. However there are a number of methodological problems with the way in which the stimuli was constructed for this type of analysis. Firstly, latency of fixation measures are extremely sensitive to the action kinematics and timing used (Rotman, Troje, Johansson, & Flanagan, 2006), two features that were not matched between conditions in this study. Secondly, predictive eye movements are driven by the action goal (Eshuis, Coventry, & Vulchanova, 2009) and the speed of prediction is determined by goal salience (Henrichs, Elsner, Elsner, & Gredebäck, 2012). In their study, Gredeback and Melinder (2009) use the recipients' head and hand as the two action goals but these are not matched for saliency or predictability. These goal differences could result in the reduced anticipatory looking to the hand that is reported. In order to effectively measure anticipatory looking, actions need to be carefully matched for kinematics, timing, goal saliency and goal predictability. Additionally, previous studies that use latency of goal fixation as a measure take only the speed of action prediction as the measure of interest and do not account for differences in scan path prior to the predictive fixation. It is interesting to investigate where participants gather their information from, prior to making a predictive saccade as this may reveal systematic differences in the way in which goals are predicted between individuals.

A final, critical issue in this area is statistical independence in data analysis. There is increasing recognition that double-dipping in the analysis of rich datasets can inflate false-positives and is not good practice (Kriegeskorte, Simmons, Bellgowan, & Baker, 2009). This is particularly an issue when data-analysis methods are not standardised and there are many possible approaches which could lead to different results. To avoid these problems, we first record data from a sample of typical undergraduate students and explore a number of analysis techniques. We used this dataset to 1) establish whether eye tracking can be used to assess rationality comprehension in adults, 2) to develop an algorithm that distinguishes fixations and saccades and labels the location of the fixations, and finally 3) to explore different analysis techniques that best capture the viewing patterns for these movies and to establish an analysis protocol for the main study. For simplicity, a full report of this pilot study is presented in supplementary information and will not be considered further within the main article. Following the pilot study, we then recorded data from two new participant samples – adults with ASC and adults matched for age and IQ. We applied our analysis protocol to these independent datasets, and report the results in full.

1.2. Summary

Overall, this paper has two aims. First, we aim to test if eye gaze is modulated by action rationality, and if this modulation differs between typical and autistic participants. If participants with ASC have good basic action understanding, we would expect both typical and ASC participants to show the same patterns of gaze when viewing rational actions. If participants with ASC have trouble detecting irrational actions, we would expect their gaze patterns for these stimuli to differ from the typicals, possibly conforming to the pattern for rational actions. Finally, if participants with ASC can detect irrational actions but do not interpret them, we would expect differences in gaze behaviours that reflect reasoning about action, such as looking at the actors face (Vivanti et al., 2011).

Second, we aim to test if eye gaze is influenced by the social form of an action (full actor visible, face occluded or ball moving independently) and whether this differs between typical and autistic participants. Gaze effects which are tied to action rationality should be stronger when viewing a full person compared to a moving ball. Such influences may also be stronger in typical participants than in participants with autism. By comparing actions where the face is visible to those where the face is occluded, we will also be able to assess whether the face provides important cues for action prediction and whether these cues are used effectively by individuals with ASC. Together, these analyses will give important insights into the cognitive processes underlying action comprehenion in typical and autistic adults.

2. Material and Methods

2.1. Participants

Twenty adults with ASC (19 male) and 20 typically developing adults (19 male) matched to the ASC group for age and IQ took part in the main study. Participants were recruited through local colleges, universities and through ASC support groups. Care was taken during recruitment to match groups on age and full scale IQ, measured by the Weschler Adult Intelligence Scale (WAIS). Groups were not significantly different in age ($t(38)=1.9$, $p=0.06$) or IQ ($t(38)=1.25$, $p=0.22$) but as the groups are not similar enough to be considered matched (Carolyn & Bonita, 2004) , all analyses were also run on a subset of 17 participants from each group that were better matched for age ($t(32)=0.85$, $p=0.40$) and IQ ($t(32)=0.65$, $p=0.95$). These groups were selected by only using the ASC participants who were matched to a typically developing participant within five years of age and 10 IQ points. Given that the phenomenon examined in this study is unlikely to change throughout adulthood, the marginal age effects for the full group are unlikely to be important. Indeed, the pattern of results was very similar when using the matched subset of participants so we only report the statistics from the full group analysis here (statistics for the subgroups can be found in Supplementary Information, Tables S6-S8). Participants with autism had a diagnosis of high functioning autism (n=7), autism spectrum condition (n=2) or Aspergers syndrome (n=11). Diagnosis was confirmed using the ADOS Module 4 (Lord et al., 2000). One participant failed to meet criteria for autism spectrum on both the social and communication subscales of the ADOS but he had a clear diagnostic history and scored well above the threshold for autism on the Autism Quotient. Therefore, his data has been included in the full analysis. Typically developing participants reported no diagnoses of developmental disorders. All participants also completed the Autism Quotient (AQ, Baron-Cohen, Wheelwright, Skinner, Martin, & Clubley, 2001) and typically developing participants scored significantly lower than the ASC participants on this measure of autistic traits ($t(37)=3.95$, $p<0.001$). See Table 1 for participant characteristics.

[Table 1 about here]

2.2. Stimuli/Apparatus

Eye movements were measured using a portable Tobii 1750 infrared recording system which sampled at a rate of 50Hz with 1° precision and 0.5° accuracy. A standard five point calibration procedure was successfully completed prior to each recording.

A set of experimental stimuli were developed for three social conditions and three action types (see Figure 1A). In each movie a red ball started on the left of the screen and was moved to one of two transparent containers on the right. The movement trajectory of the ball between the start point and the goal was either a straight action or a curved action that moved in an arc. Both straight and curved actions were matched for timing on a frame by frame basis such that the start and end point of the action coincided. All movies lasted 3.7 seconds. A red barrier was superimposed over the top of each movie using VirtualDub software. Two versions of the curved action movies were created. In one version, the barrier was placed between the start point and the goal such that the action had to curve over the barrier to reach the goal, thus making the curved trajectory rational. In the second version the position of the barrier had no bearing on the action trajectory and so the action was irrational. Movies for these three action types (rational straight, rational curved and irrational curved) were created for both the top and bottom goal and were carefully matched so that the action trajectories were mirror imaged. This formed a base set of six movies that were then manipulated by varying the amount of social information available. In the human face condition, movies were not edited further so the head and torso of the actor were fully visible. In the human no face condition, a black strip was superimposed over the top of each movie so that the face was occluded but the torso of the actor was still visible. To generate the movies in which the ball moved independently, the coordinates of the ball were recorded for each frame of each movie. A red ball was then drawn over the top of a still shot of the background image in the appropriate position for each frame. Frames were then combined to make movies with identical movement trajectories as the human action conditions. This video editing was all completed using Matlab. The final set of stimuli comprised 18 movies (three action types to each of two goals for three social conditions). Rational straight movies were created and included in the design to prevent the participant from always expecting the action to take a curved trajectory. However, as only rational curved and irrational curved movies are matched on action trajectory, only eye movements during these movies will be analysed. Two action goals were used within this stimulus set so that the participant had to attend to features of the action in order to make a predictive saccade to the correct action goal. If only one goal was used, predictive saccades may occur without any attention to the actions. Movies were carefully matched for trajectory and timing between goals and so we do not predict differences in viewing patterns between the action goals. We therefore collapse our analyses across both goal locations and do not consider action goal further.

[Figure 1 about here]

2.3. Design

A mixed two (group) by two (rationality) by three (social form) design was employed. Movies were presented in separate blocks of face, no face and ball trials. Each block contained 8 repetitions of each action in a random order. Thus in total, 48 movies were presented per block and the block lasted for approximately 6 minutes. To maintain alertness, participants were also asked to respond to three questions about the movies at random intervals within each block. These were simple memory questions about the visual properties of the movie such as the colour of different objects in the scene, the end location of the ball or the location of the barrier (a full list of questions used can be found in supplementary information). Answers to these questions were not analysed. All participants watched six blocks of movies (two blocks of each social form) in a counterbalanced order.

2.4. Procedure

The study was approved by the School of Psychology ethics committee. All testing took place in a quiet room at the participant's college, their home or at the university. Participants sat approximately 64cm from the Tobii monitor with a table and a number keypad in front of them. They completed the five-point calibration procedure at the start of each of the six experimental blocks. During each block, the experimenter sat watching the live gaze replay and prompted the participant to 'keep watching' if they looked away from the screen. Following the last block of movies, participants were shown each of the six action types again (with the actor fully visible) and asked to rate the rationality for each of the movies using a battery of 6 statements. These items were: 'The actor was efficient at reaching the goal', 'This action seemed weird', 'The movement in this action was unusual', 'This action was unnatural', 'This action was normal' and 'I would complete this action differently'. Participants were asked whether they agreed or disagreed on a scale of one to five. The score on negative items was reversed and a total rationality score was computed for each participant for each movie (maximum score of 30 indicated most rational). In addition to the eye-tracking task, all participants completed the Weschler Adult Intelligence Scale (WAIS) and the autism quotient (AQ) and participants with ASC completed the ADOS Module 4 with a trained examiner.

2.5. Data Processing

The data processing algorithms and the analysis approach used in this study was defined based on a pilot study of an independent sample of 20 undergraduate students completing the same task (see Supplementary Information). All data processing was completed using in-house scripts written in Matlab. To ensure data quality, individual trials were excluded from the analysis if more than 20% of eye movement samples were missing during the critical action period (from the time at which the ball started to move until the time the ball enters the goal location, see Table 3, Step 1 for trial exclusion rates at this level of analysis). Data samples could be missing due to blinks, the participant looking outside of the frame of the movie or eye-tracker failure. Within included trials, eye movement samples were then classified as fixations or saccades using a velocity-based algorithm with a threshold of 60 degrees/sec (Salvucci & Goldberg, 2000). Data samples with a velocity above this threshold were marked as occurring during a saccade and excluded from further analysis. Three levels of analysis were then conducted in order to identify attention to actions (looking time analysis), where saccades into the goal came from (saccade-origin analysis) and the time at which saccades from the hand to the goal location were initiated (goal-latency analysis). These analysis techniques are detailed in sections below.

2.5.1. Looking Time Analysis:

A looking time analysis was conducted to see if allocation of attention to features of the scene differed between action types, social form and group membership. Each movie scene was divided into 6 areas of interest (AOIs). AOIs were defined by a close fitting rectangle around each of the goal locations, the start point, barrier and face. A moving area of interest was created for the ball by drawing a sphere (radius 70 pixels) around the central co-ordinate of the ball at each frame of each movie. To account for spatial sampling errors, a margin of one visual degree was added to each of these AOIs (see Figure 1B). Looking time was calculated for each AOI as the percentage of data samples falling within the AOI over the course of each movie for each participant. Percentage of data samples that were within the frame of the movie but not within an AOI was calculated as ‘background’. Data was only analysed from AOIs relevant to the task, that is: the barrier, the face, the goals and the hand/ball. Data from these AOIs was submitted to a repeated measures ANOVA with group as a between subjects factor, and rationality and social form as within subjects factors. Specific predictions about the effects in each of these AOIs are presented in Table 2.

2.5.2. Saccade-origin Analysis:

The saccade-origin analysis was conducted in order to see where people were attending immediately prior to making a saccade to the action goal. This measure indicates where participants gathered information from in order to predict the action outcome. Trials were only included in this analysis if there was a saccade to the goal of the action present within the trial (see trial inclusion rates in Table 3, Step 2). To calculate where goal saccades came from, eye movement samples for each trial were divided into gaze segments between saccades. The gaze position of these segments was labelled according to the focus of the majority of samples within the segment. An algorithm was written in Matlab to generate these labels (see Supplementary Information for details). The first saccade into the target goal was identified and the origin of this saccade was recorded. For each movie type, the percentage of saccades from each AOI into the target goal was calculated for each participant. Data was only analysed for saccades from AOIs that are relevant to the task: the face, the goals and the hand/ball. The % of saccades originating in each of these regions was submitted to a repeated measures ANOVA with group as a between subjects factor, and rationality and social form as within subjects factors. Specific predictions about the effects in each of these AOIs are presented in Table 2.

2.5.3. Goal-Latency Analysis:

Latency of goal prediction was analysed to assess whether action type, social form or group membership modulate how quickly participants predict the action goal when they are attending to the hand. Trials were only included in this measure when the participant made a predictive saccade from the hand to the action goal before the hand reached the goal (see Table 3 for trial inclusion rates). Latency of prediction was calculated by subtracting the time that the ball reached the goal from the time that the saccade to the goal was initiated. Thus negative fixation latencies indicate faster anticipation of the action. Outliers were removed if they were ±3 standard deviations from the mean. These data were then analysed using a hierarchical linear mixed model which accounted for the different amounts of data contributed by each participant. A participant identifier was entered as a hierarchical variable to account for correlation within subjects.

[Tables 2 and 3 about here]

2.5.4. Task Engagement:

As the number of trials included in each analysis is hierarchical, and dependent upon the presence of eye movement features that reflect attention to the actions, it is possible to use the number of trials included at each stage of the analysis as a measure of task engagement. For example, the number of trials included in the looking time analysis (Step 1, Table 3) reflects the data quality of each group as trial exclusion at this stage is primarily due to missing data. The number of trials included in the saccade analysis (Step 2, Table 3) indicates the degree to which participants within each group attended to the action goal and finally, the inclusion rates for the latency analysis (Step 3, Table 3) indicate the degree to which participants in each group are actively predicting the action end point correctly. The number of excluded trials was calculated at each level of the analysis for each level of social form, each level of rationality and for each group. These data were analysed using a repeated measures ANOVA with group as a between subjects factor and rationality and social form as between subjects factors.

3. Results

3.1. Behavioural Ratings

Mean ratings are presented in Figure 2. A two (rationality) by two (group membership) mixed ANOVA revealed a main effect of rationality ($F(1,34)=5.02$, $p=0.03$) in which rational curved actions were rated as more rational than irrational curved actions. No effect of group ($F(1,34)=3.08$, $p=0.09$) and no interaction between rationality and group ($F(1,34)=0.13$, $p=0.72$) was found.

[Figure 2 about here]

3.2. Looking Time Analysis

Percentage looking time in each AOI was calculated for each movie type and is presented in Figure 3a and Table 4. Overall, participants spend time looking at the start (yellow), the goals (green/red) and the hand (orange), with a portion of each trial spent looking at the background, missing data or the edge of the screen (dark blue, grey, black respectively). To examine this data, two (rationality) by three (social form) by two (group) mixed ANOVAs were conducted for looking time to the target goal, non-target goal and ball. In trials when the face was visible, a two (rationality) by two (group) mixed ANOVA was conducted on looking time to the face. All reported results are significant after Bonferroni correction for multiple comparisons.

In the analysis of looking time to the target goal (Figure 3b), a significant main effect of social form of the stimulus was found. Bonferroni corrected t-tests revealed that looking time on the target goal was longer during actions in which the ball moved independently, compared to when an agent was present. A main effect of group was also found indicating that typical participants looked longer at the target goal than the autistic participants. No effect of rationality and no interactions were found. Full statistics are given in Table 4a.

In the analysis of looking time to the non-target goal (Figure 3c), a main effect of social form was also found. This means that participants looked longer at the non-target goal during actions in which the ball moved independently, compared to actions performed by a human agent. The non-target goal was also looked at longer during irrational actions compared to rational actions. There was no main effect of group on looking time to the non-target goal. No interactions were significant. Statistics are presented in Table 4b.

The analysis of looking time to the ball (Figure 3a, orange), a main effect of group revealed that typical participants looked longer at the ball compared to ASC participants. No effects of social form, or rationality were observed and no interactions were significant. Statistics are presented in Table 4c.

In the analysis of looking time to the barrier (Figure 3d), a main effect of social form indicated that participants looked longer at the barrier during human actions compared to those completed by the ball. A rationality effect shows that participants also look longer at the barrier during rational compared to irrational actions. An interaction between rationality and social form was also found. This interaction shows that the bias for looking at the barrier more during rational actions is greater during actions performed by a human compared to those performed by the ball. Statistics are presented in Table 4d.

Participants looked at the face (Figure 3a, purple) for the same amount of time, irrespective of rationality and group membership. There were no significant interactions between these variables (see Table 4e).

[Table 4 and Figure 3 about here]

3.3. Saccade-Origin Analysis

The origin of saccades to the goal was analysed and results are presented in Figure 4a and Table 5. As with the looking time analysis, two (rationality) by three (social form) by two (group) mixed ANOVAs were conducted on percentage of saccades from the non-target goal and from the ball to the target goal. In trials when the face was visible, a two (rationality) by two (group) mixed ANOVA was conducted on percentage of saccades from the face. Again, only significant results that survived Bonferroni correction are reported.

In the analysis of saccades from the non-target goal (Figure 4b), there was a main effect of rationality. This effect showed that more saccades to the goal came from the non-target goal when the action was irrational. No effects of social form or group were found. No interactions were significant. Statistics are presented in Table 5a.

The analysis of saccades from the ball found a main effect of group and revealed that typical participants made more saccades from the ball to the goal, compared to ASC participants (Figure 4c).

There were no effects of social form, or rationality on the number of saccades from the ball to the goal. No interactions were significant. See Table 5b for statistics.

The analysis of the number of saccades from the face found no effect of rationality or group membership and no interactions between these variables. See Table 5c.

[Table 5 and Figure 4 about here]

3.4. Goal-Latency Analysis

The mean latency of each saccade from the hand to the goal was calculated for each movie type and is presented in Figure 6. Social form, rationality and group were entered into a full factorial mixed linear model. A main effect of social form indicated that participants were faster to anticipate actions in the ball condition, compared to the no face condition. This effect was present when outliers were included or excluded from analysis. No main effect of group membership or action rationality was found (see Table 6 for statistics).

[Table 6 and Figure 5 about here]

3.5. Task Engagement

The mean number of trials excluded for each participant group at each stage of analysis is presented in Table 3. Three (social form) by two (rationality) by two (group) mixed ANOVAs were conducted on the number of excluded trials for each stage of analysis (looking time, saccade and latency). In all three ANOVAs there was a main effect of group in which ASC participants had more excluded trials than the typically developing group. There were no effects of rationality, social form or interactions between rationality, group or social form (see Table 3 for trial exclusion rates by group and Table 7 for statistics). Figure 6 shows the rates of trial exclusion at step one as a function of trial number through block for both the typically developing and ASC groups. While task engagement reduced over the course of a block for both groups, the decline in task engagement for the ASC group was much greater. Beyond this initial exclusion stage based on data quality, the patterns of exclusion remain similar. The ASC group fail to look at the goal of the action in more trials than the typically developing group (exclusion step two) and only make saccades from the hand to the goal in 13% of trials, compared to 30% of trials for the typically developing group (exclusion step three). In summary, each of these levels of exclusion reflect reduced task engagement in participants with ASC.

[Table 7 and Figure 6 about here]

4. Discussion

The current study aimed to test if gaze behaviour during action observation is modulated by the rationality of an action, the social form of the actor and whether or not a participant has autism spectrum condition. To investigate this, we developed a robust gaze data analysis algorithm using a pilot dataset and then applied our methods to gaze data from adults with and without autism. We examined data in terms of looking time to particular areas of interest, the origin of saccades to the action goal and latency of first goal fixation. First we discuss the results in relation to our two key questions of how eye movements are modulated by action rationality and by social form and whether these markers are present in participants with ASC.

4.1. Eye movements reflecting rationality comprehension

A number of eye tracking measures reflected the rationality of the observed action in both typical and ASC participants. Firstly, participants looked longer at the non-target goal and they made more saccades from the non-target to the target goal during irrational actions. Both of these findings suggest that participants are making goal prediction errors whilst watching irrational actions. As the action is curved for no reason, participants anticipate the action goal incorrectly and look at the non-target goal. Additionally, increased time spent looking at the non-target goal may reflect participants' reasoning about why the ball was not placed in the non-target goal. Perhaps they were searching for an environmental constraint which altered the actors' intention mid-action. This is consistent with the idea that participants try to rationalise an irrational action by seeking an explanation for their behaviour (Vivanti et al., 2011). However, unlike Vivanti et al., (2011) the present study reports no increase in looking at the face of the actor following an irrational action in either the ASC or the typical group. This difference might arise because the present task has less social context or because the face of the actor was not informative in determining the goal of the action.

Looking time to the barrier also differed between rational and irrational actions in both typical and ASC groups. Participants looked longer at the barrier during rational actions, suggesting that they are evaluating the environmental constraint that impacts upon the action. This is consistent with the pattern of results reported by (Elsner et al., 2013) in infants. It goes beyond previous findings as we demonstrate that the bias for looking at the barrier more during rational actions is increased for human actions compared to those completed by the moving ball. This implies that a greater level of evaluation of the action constraint occurs during human actions and therefore may reflect mentalizing about why the actor performed the action in this way.

Surprisingly, the speed of action prediction was not modulated by action rationality in typically developing or ASC participants. This is inconsistent with previous evidence that irrational actions are anticipated more slowly than rational actions, at least in a study without matching of action trajectories (Gredebäck & Melinder, 2010). In our stimuli, we carefully matched hand trajectories between rational and irrational actions, and find no differences in the latency of saccades to the goal for these different types of action. Thus, our data suggest that predictive saccades are closely linked to the kinematics of the observed action. Furthermore, as participants with ASC made predictive saccades to the goal as quickly as typically developing participants, it seems that their basic goal understanding is intact. This is consistent with other studies implicating good goal comprehension in ASC (Dinstein et al., 2010; Falck-Ytter, 2010; Hamilton, Brindley, & Frith, 2009; Marsh & Hamilton, 2011).

4.2. The impact of social form on eye movements

The social form of the actor had an impact on gaze behaviour in a number of ways for both typical and ASC participants. All participants looked longer at both action goals during actions performed by a ball compared to those performed by a human agent. Additionally, participants were faster to predict the action goal when it was completed by a ball compared to the human actions. Both of these findings can be explained by the reduced amount of information on the screen during these ball videos. As the human is absent and there is less to look at, participants look at the goal more quickly and maintain their fixations for longer. Alternatively, this pattern of results can also be explained be a different mechanism. When the actor is not visible, the goal location can only be inferred through close monitoring of the location of the ball in relation to each of the possible goal locations. Therefore, participants may make repeated saccades between the ball and the possible goal locations until the true action goal is evident. This gaze behaviour will also result in increased time spent looking at the action goals and faster action prediction compared to when the human was present.

The faster anticipation of ball, compared to human actions that we report in this study is contrary to previous findings which report that participants are more likely to make anticipatory saccades to an action goal during human actions and more likely to visually track the object when it is self-propelled (Flanagan & Johansson, 2003 but see Eshuis et al., 2009). Unlike previous studies, in our stimuli there were two possible goals so participants must make a decision about which goal is correct, rather than always looking to the same goal. A further difference is that we account for the location that anticipatory saccades came from. In previous studies, it is assumed that anticipatory saccades are made from the hand to the goal and only the speed of this prediction is measured. In this more complex analysis protocol, we are able to determine the degree to which participants do make these hand-to-goal saccades and only measure the speed of prediction under these circumstances. It is interesting to note here that in only 30% of trials typically developing participants made anticipatory saccades from the hand to the goal. This indicates that anticipatory gaze is not mandatory and automatic, at least in cases where more than one possible goal is present. In addition, we report no increase in looking at the ball when it is self-propelled and we actually found increased looking at the ball when it is moved by a human hand in the pilot study (although this was not replicated in the main study).

Social form had very little impact on gaze behaviours that are related to rationality understanding. We predicted that gaze effects that are tied to rationality understanding would be stronger for the human actions compared to those in which the ball moved independently but only one AOI yielded this pattern of results. Participants spent longer looking at the barrier during actions rational actions compared to irrational actions and this increase was greater for actions performed by a human. As mentioned previously, this may be due to the participant making more effort to evaluate the environmental constraints during human actions. As there were no other interactions between rationality and social form, we conclude that the rationality of actions is computed for humans and balls in a remarkably similar fashion. This is consistent with an emerging body of research which reports mentalizing and action understanding computations are similar for human agents and animated shapes or objects (Castelli, Happé, Frith, Frith, & Happe, 2000; Ramsey & Hamilton, 2010; Marsh, Mullett, Ropar & Hamilton, submitted).

Surprisingly, participants spent very little time looking at the face of the actor during movies where the face was visible. For both typical and ASC participants, the average percentage of looking time within the face AOI was less than 5% which equates to approximately 185ms per trial. This contrasts with previous studies that report dramatic social orienting to the face and, in particular the eyes, of an agent on screen (Birmingham, Bischof, & Kingstone, 2008b; Klin et al., 2002). In those studies, typical participants spent approximately 20% of the viewing time looking at the faces and even longer looking at the eyes (70-80%). However, in those studies, the stimulus showed a social interaction involving more than one agent (Birmingham, Bischof, & Kingstone, 2008a). The stimuli used in the present study showed only one, largely static agent who did not make eye contact with the participant. This may account for the lack of social orienting to the face in both typical and ASC participants.

In addition to the distinct lack of social orienting to the face, we also demonstrate that having facial information available in this scenario does not facilitate action prediction. This is demonstrated by the finding that predictive saccades to the action goal were not faster when the face was visible compared to when it was occluded. Furthermore, very few direct saccades from the face to the goal were made (this gaze behaviour was seen in less than 2% of trials). As the stimuli were designed so that the actors' face, and importantly his gaze, was not informative about the goal of the action, it is likely that participants learnt that the facial information was not useful when observing these actions. As the action was the key feature of each movie, orienting to the hand, rather than the face, is more informative. Indeed, typically developing participants look at the hand more than the ASC participants, indicating that participants with ASC show less orienting to the task-relevant action features. However, as this effect was seen in both human and ball actions, it is difficult to argue that this orienting to the action is social orienting. It could be that the reduction in looking at the hand in ASC is a product of reduced attention to biological motion (Blake, Turner, Smoski, Pozdol, & Stone, 2003; Klin, Lin, Gorrindo, Ramsay, & Jones, 2009).

4.3. Attention and Task engagement

The results that have been discussed so far reflect a very similar pattern of results between typical and ASC participants. The realm in which we see group differences emerge in this task is when we consider measures that reflect attention to the action. For example, ASC participants look at the action goal for less time than the typically developing participants. There were also more trials in which the ASC participants failed to look at an action goal at all. Additionally, they look less at the hand or ball performing the action and as such, they also make less saccades from the hand to the action goal. A reduction in social attention in ASC has previously been reported for faces (Riby & Hancock, 2008) and eyes (Speer et al., 2007) but this is the first to show reduced attention to actions. If individuals with ASC fail to spontaneously orient to others' actions this may impact their ability to interpret and predict the actions of other people. However, this difficulty does not seem to be due to an inability to process the information about others actions as ASC participants are showing typical gaze markers of rationality detection and action prediction when they do attend. Instead, they fail to spontaneously orient to the most useful information in a scene. As this reduction in orientation to actions does not vary with rationality or social form it seems that it does not reflect a specific social deficit for human actions or for unusual actions. Rather, these group differences may reflect a general attentional orienting deficit in individuals with ASC (Renner, Klinger, & Klinger, 2006; Sasson et al., 2007).

An alternative explanation for reduced looking time at the ball and for the reduction in the number of saccades from the ball to the goal for participants with ASC is that individuals with ASC may have poor gaze control (Grynszpan et al., 2012). This poor control of eye movements manifests in reduced smooth pursuit of moving objects (Takarae, Minshew, Luna, Krisky, & Sweeney, 2004) and more variable accuracy of saccadic gaze shifts (Takarae, Minshew, Luna, & Sweeney, 2004). Perhaps the ASC participants in this study have impaired modulation of their own gaze and therefore have difficulty tracking the movement of the action by maintaining fixation on the moving ball or making an accurate saccade from the ball to the action goal. The present data cannot distinguish visual and attentional explanations for these effects so further research is required to elucidate the mechanisms that lead to the reduced monitoring of actions in individuals with ASC.

We also report a reduction in task engagement in the ASC group over the course of the experiment. This is demonstrated by the number of trials excluded from the analysis due to missing data. It is unlikely that the increase in missing data in the ASC group is due to eye-tracker failure as strict calibration procedures were passed prior to the start of each block and live gaze visualisation was used to check that tracking continued throughout the experiment. Instead, participants with ASC were more likely to look outside of the frame of the movie, or away from the screen during the task. We note that it is not possible in the current context to determine if participants with autism are less engaged because they dislike the stimuli themselves, or because they are less motivated to comply with the experimenters request to watch the video.

Both findings of reduced attention to actions and reduced task engagement are consistent with the social motivation hypothesis of ASC which predicts reduced social orienting and engagement (Chevallier, Kohls, Troiani, Brodkin, & Schultz, 2012). Perhaps participants with ASC were less engaged in the task because they lacked the motivation to please the experimenter by maintaining attention during this arduous task. The social motivation theory also proposes that individuals with ASC have the underlying competence to process social stimuli yet spontaneously fail to do so. In this task we demonstrate that participants with ASC are able to detect action rationality and to predict rational and irrational actions to the same degree as typically developing individuals. However, this is only the case if we only use the trials in which participants with ASC were attending to the actions. The reduction in number of trials in which participants with ASC attended to the actions is indicative of reduced spontaneous action prediction and comprehension.

4.4. Conclusions

The present study provides a thorough examination of the eye tracking measures which reflect action rationality and the social form of the agent. We report very few differences in action observation between ASC and typically developing adults which provides support for the idea that individuals with ASC are sensitive to action rationality. This is an important finding as understanding action rationality is a developmental step between action understanding and mentalizing. The gaze measure which was most sensitive to action rationality was the time spent looking at the barrier, and this varied in the same way in both typical and autistic participants. We therefore conclude that rationality understanding is intact in individuals with ASC.

Group differences emerged when looking at the measures which reflect attention and task engagement. Participants with ASC showed reduced orienting to actions, regardless of action rationality and the social form of the actor. This finding could reflect a general attentional orienting deficit or poor gaze control in ASC. There were also differences in the amount of missing data between participant groups and this may reflect reduced social motivation to conform to task demands in ASC. However when participants with ASC were attending to the actions, they show good action comprehension and prediction.

6. References

Aldridge, M. a, Stone, K. R., Sweeney, M. H., & Bower, T. G. R. (2000). Preverbal children with autism understand the intentions of others. *Developmental Science*, *3*(3), 294–301. Retrieved from http://doi.wiley.com/10.1111/1467-7687.00123

Baron-cohen, S., Leslie, A. M., & Frith, U. (1985). Does the autistic child have a "theory of mind." *Cognition*, *21*, 37–46.

Baron-Cohen, S., Wheelwright, S., Skinner, R., Martin, J., & Clubley, E. (2001). The autism-spectrum quotient (AQ): Evidence from asperger syndrome/high-functioning autism, malesand females, scientists and mathematicians. *Journal of autism and …*, *31*(1). Retrieved from http://link.springer.com/article/10.1023/A:1005653411471

Birmingham, E., Bischof, W. F., & Kingstone, A. (2008a). Social attention and real-world scenes: The roles of action, competition and social content. *The Quarterly Journal of Experimental Psychology*, *61*(7), 986–998. doi:10.1080/17470210701410375

Birmingham, E., Bischof, W., & Kingstone, A. (2008b). Gaze selection in complex social scenes. *Visual Cognition*, *16*(2), 341–355. doi:10.1080/13506280701434532

Blake, R., Turner, L. M., Smoski, M. J., Pozdol, S. L., & Stone, W. L. (2003). Visual recognition of biological motion is impaired in children with autism. *Psychological Science*, *14*(2), 151–157. doi:10.1111/1467-9280.01434

Boria, S., Fabbri-Destro, M., Cattaneo, L., Sparaci, L., Sinigaglia, C., Santelli, E., … Rizzolatti, G. (2009). Intention understanding in autism. *PloS one*, *4*(5), e5596. doi:10.1371/journal.pone.0005596

Brass, M., Schmitt, R. M., Spengler, S., & Gergely, G. (2007). Investigating action understanding: inferential processes versus action simulation. *Current biology : CB*, *17*(24), 2117–21. doi:10.1016/j.cub.2007.11.057

Cannon, E. N., & Woodward, A. L. (2012). Infants generate goal-based action predictions. *Developmental science*, *15*(2), 292–8. doi:10.1111/j.1467-7687.2011.01127.x

Carolyn, B. M., & Bonita, P. K.-T. (2004). Methodological Issues in Group-Matching Designs: a Levels for Control Variable Comparisons and Measurement Characteristics of Control and Target Variables. *Journal of Autism and Developmental Disorders*, *34*(1), 7–17.

Carpenter, M., Pennington, B. F., & Rogers, S. J. (2001). Understanding of others' intentions in children with autism. *Journal of autism and developmental disorders*, *31*(6), 589–99.

Castelli, F., Frith, C., Happé, F., & Frith, U. (2002). Autism, Asperger syndrome and brain mechanisms for the attribution of mental states to animated shapes. *Brain*, *125*, 1839–1849. Retrieved from http://brain.oxfordjournals.org/content/125/8/1839.short

Castelli, F., Happé, F., Frith, U., Frith, C., & Happe, F. (2000). Movement and mind: a functional imaging study of perception and interpretation of complex intentional movement patterns. *NeuroImage*, *12*(3), 314–25. doi:10.1006/nimg.2000.0612

Cattaneo, L., Fabbri-destro, M., Boria, S., Pieraccini, C., Monti, A., Cossu, G., & Rizzolatti, G. (2007). Impairment of actions chains in autism and its possible role in intention understanding, *104*(45), 17825–17830.

Chevallier, C., Kohls, G., Troiani, V., Brodkin, E. S., & Schultz, R. T. (2012). The social motivation theory of autism. *Trends in cognitive sciences*, *16*(4), 231–9. doi:10.1016/j.tics.2012.02.007

Dinstein, I., Thomas, C., Humphreys, K., Minshew, N., Behrmann, M., & Heeger, D. J. (2010). Normal movement selectivity in autism. *Neuron*, *66*(3), 461–9. doi:10.1016/j.neuron.2010.03.034

Elsner, B., Pfeifer, C., Parker, C., & Hauf, P. (2013). Infants' perception of actions and situational constraints: An eye-tracking study. *Journal of experimental child psychology*, *116*(2), 428–42. doi:10.1016/j.jecp.2012.11.014

Eshuis, R., Coventry, K. R., & Vulchanova, M. (2009). Predictive Eye Movements Are Driven by Goals , Not by the Mirror Neuron System, *20*(4), 438–440.

Fabbri-Destro, M., Cattaneo, L., Boria, S., & Rizzolatti, G. (2009). Planning actions in autism. *Experimental brain research. Experimentelle Hirnforschung. Expérimentation cérébrale*, *192*(3), 521–5. doi:10.1007/s00221-008-1578-3

Falck-Ytter, T. (2010). Young children with autism spectrum disorder use predictive eye movements in action observation. *Biology letters*, *6*(3), 375–8. doi:10.1098/rsbl.2009.0897

Flanagan, J. R., & Johansson, R. S. (2003). Action plans used in action observation. *Nature*, *424*, 769–771.

Fletcher-Watson, S., Leekam, S. R., Benson, V., Frank, M. C., & Findlay, J. M. (2009). Eye-movements reveal attention to social information in autism spectrum disorder. *Neuropsychologia*, *47*(1), 248–57. doi:10.1016/j.neuropsychologia.2008.07.016

Freeth, M., Chapman, P., Ropar, D., & Mitchell, P. (2010). Do gaze cues in complex scenes capture and direct the attention of high functioning adolescents with ASD? Evidence from eye-tracking. *Journal of autism and developmental disorders*, *40*(5), 534–47. doi:10.1007/s10803-009-0893-2

Frith, U. (2001). Mind blindness and the brain in autism. *Neuron*, *32*(6), 969–979.

Frith, U. (2003). *Autism: explaining the enigma*. Blackwell Publishing.

Gredebäck, G., & Melinder, A. (2010). Infants' understanding of everyday social interactions: a dual process account. *Cognition*, *114*(2), 197–206. doi:10.1016/j.cognition.2009.09.004

Grynszpan, O., Nadel, J., Martin, J.-C., Simonin, J., Bailleul, P., Wang, Y., … Constant, J. (2012). Self-monitoring of gaze in high functioning autism. *Journal of autism and developmental disorders*, *42*(8), 1642–50. doi:10.1007/s10803-011-1404-9

Hamilton, A. F. D. C., Brindley, R., & Frith, U. (2009). Visual perspective taking impairment in children with autistic spectrum disorder. *Cognition*, *113*(1), 37–44. doi:10.1016/j.cognition.2009.07.007

Hamilton, A. F. D. C., Brindley, R. M., & Frith, U. (2007). Imitation and action understanding in autistic spectrum disorders: how valid is the hypothesis of a deficit in the mirror neuron system? *Neuropsychologia*, *45*(8), 1859–68. doi:10.1016/j.neuropsychologia.2006.11.022

Henrichs, I., Elsner, C., Elsner, B., & Gredebäck, G. (2012). Goal salience affects infants' goal-directed gaze shifts. *Frontiers in psychology*, *3*(October), 391. doi:10.3389/fpsyg.2012.00391

Jolliffe, T., & Baron-Cohen, S. (1999). The Strange Stories Test: a replication with high-functioning adults with autism or Asperger syndrome. *Journal of Autism and Developmental Disorders*, *29*(5), 395–406. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/10587886

Klin, A., Jones, W., Schultz, R., Volkmar, F., & Cohen, D. (2002). Visual fixation patterns during viewing of naturalistic social situations as predictors of social competence in individuals with autism. *Archives of general psychiatry*, *59*(9), 809–16.

Klin, A., Lin, D. J., Gorrindo, P., Ramsay, G., & Jones, W. (2009). Two-year-olds with autism orient to non-social contingencies rather than biological motion. *Nature*, *459*(7244), 257–61. doi:10.1038/nature07868

Kriegeskorte, N., Simmons, W. K., Bellgowan, P. S. F., & Baker, C. I. (2009). Circular analysis in systems neuroscience: the dangers of double dipping. *Nature Neuroscience*, *12*(5), 535–40. doi:10.1038/nn.2303

Lord, C., Risi, S., Lambrecht, L., Cook, E. H., Leventhal, B. L., DiLavore, P. C., … Rutter, M. (2000). The autism diagnostic observation schedule-generic: a standard measure of social and communication deficits associated with the spectrum of autism. *Journal of Autism and Developmental Disorders*, *30*(3), 205–223. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/11055457

Marsh, L. E., & Hamilton, A. F. D. C. (2011). Dissociation of mirroring and mentalising systems in autism. *NeuroImage*, *56*(3), 1511–9. doi:10.1016/j.neuroimage.2011.02.003

Marsh, L.E., Mullett, T.L., Ropar, D. & Hamilton, A.F. de C. (submitted) Responses to irrational actions in action observation and mentalising networks of the human brain.

Morris, J. P., Pelphrey, K. A., & McCarthy, G. (2002). Visual scanning of faces in autism. *Journal of autism and developmental disorders*, *32*(4), 249–61.

Ramsey, R., & Hamilton, A. F. D. C. (2010). Triangles have goals too: understanding action representation in left aIPS. *Neuropsychologia*, *48*(9), 2773–6. doi:10.1016/j.neuropsychologia.2010.04.028

Renner, P., Klinger, L. G., & Klinger, M. (2006). Exogenous and endogenous attention orienting in autism spectrum disorders. *Child Neuropsychology*, *12*, 361–382. Retrieved from http://www.tandfonline.com/doi/abs/10.1080/09297040600770753

Riby, D. M., & Hancock, P. J. B. (2008). Viewing it differently: social scene perception in Williams syndrome and autism. *Neuropsychologia*, *46*(11), 2855–60. doi:10.1016/j.neuropsychologia.2008.05.003

Rotman, G., Troje, N. F., Johansson, R. S., & Flanagan, J. R. (2006). Eye movements when observing predictable and unpredictable actions. *Journal of neurophysiology*, *96*(3), 1358–69. doi:10.1152/jn.00227.2006

Salvucci, D. D., & Goldberg, J. H. (2000). Identifying fixations and saccades in eye-tracking protocols. (A. Duchowski, Ed.)*Proceedings of the symposium on Eye tracking research applications ETRA 00*, *469*(1), 71–78. Retrieved from http://portal.acm.org/citation.cfm?doid=355017.355028

Sasson, N., Tsuchiya, N., Hurley, R., Couture, S. M., Penn, D. L., Adolphs, R., & Piven, J. (2007). Orienting to social stimuli differentiates social cognitive impairment in autism and schizophrenia. *Neuropsychologia*, *45*(11), 2580–8. doi:10.1016/j.neuropsychologia.2007.03.009

Senju, A., Southgate, V., White, S., & Frith, U. (2009). Mindblind eyes: an absence of spontaneous Theory of Mind in Asperger Syndrome. *Science*, *325*(5942), 883–885. Retrieved from http://discovery.ucl.ac.uk/134660/

Speer, L. L., Cook, A. N. E., McMahon, W. M., & Clark, E. (2007). Face processing in children with autism: Effects of stimulus contents and type. *Autism*, *11*(3), 265–277. doi:10.1177/1362361307076925

Stone, W. L., Ousley, O. Y., & Littleford, C. D. (1997). Motor Imitation in Young Children with Autism : What ' s the Object ?, *25*(6), 475–485.

Takarae, Y., Minshew, N. J., Luna, B., Krisky, C. M., & Sweeney, J. a. (2004). Pursuit eye movement deficits in autism. *Brain : a journal of neurology*, *127*(Pt 12), 2584–94. doi:10.1093/brain/awh307

Takarae, Y., Minshew, N. J., Luna, B., & Sweeney, J. a. (2004). Oculomotor abnormalities parallel cerebellar histopathology in autism. *Journal of Neurology, Neurosurgery & Psychiatry*, *75*(9), 1359–1361. doi:10.1136/jnnp.2003.022491

Vivanti, G., McCormick, C., Young, G. S., Abucayan, F., Hatt, N., Nadig, A., … Rogers, S. J. (2011). Intact and impaired mechanisms of action understanding in autism. *Developmental psychology*, *47*(3), 841–56. doi:10.1037/a0023105

Zalla, T, Labruyere, N., & Georgieff, N. (2006). Goal-directed action representation in autism. *J Autism Dev Disord*, *36*(4), 527–540.

Zalla, Tiziana, Labruyère, N., Clément, A., & Georgieff, N. (2010). Predicting ensuing actions in children and adolescents with autism spectrum disorders. *Experimental brain research. Experimentelle Hirnforschung. Expérimentation cérébrale*, *201*(4), 809–19. doi:10.1007/s00221-009-2096-7

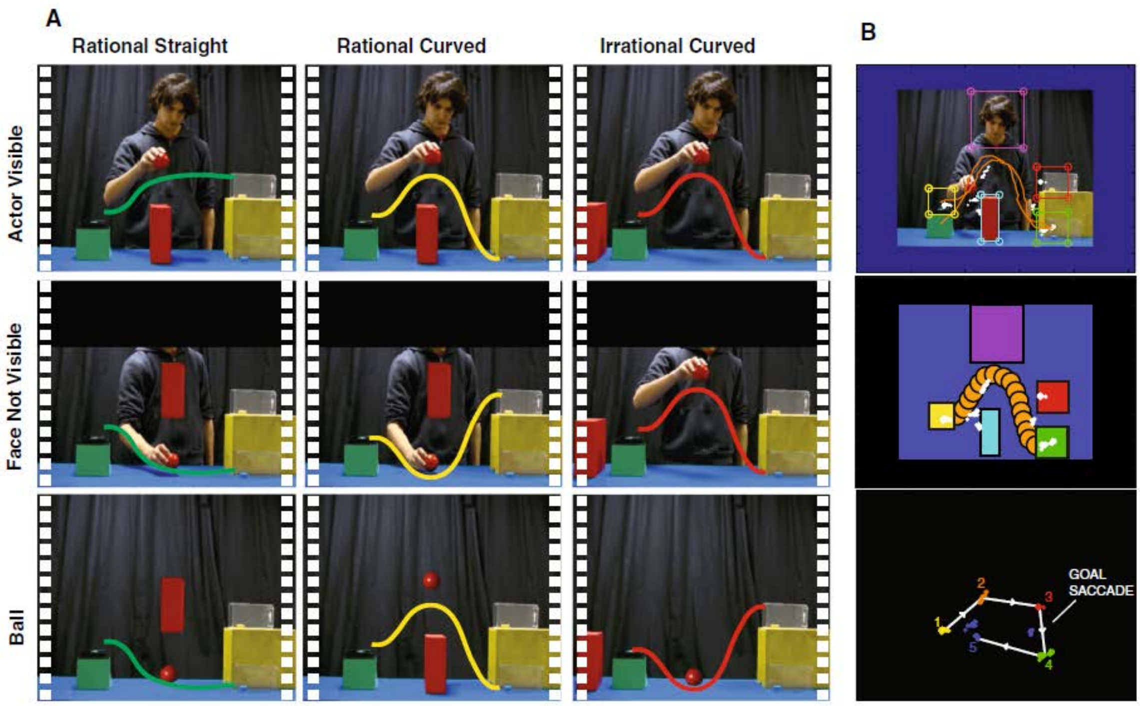

Figure 1A: The middle frame from each movie category. In each movie the ball starts on the green box on the left and is moved to one of two boxes on the right. The movement paths are visualised by coloured lines over the frame. These lines do not appear in the movie. For each movie category, two movies were made; one ending in the top goal and one ending at the bottom goal. Action trajectories for the top goal movies were mirror images of those ending at the bottom goal.

Figure 1B: Panel representing the stages of analysis. Top: Raw sample data (white dots) overlaying a still frame of a rational curved movie. Areas of interest (AOIs) are drawn over the scene. Middle: A schematic diagram of the AOIs used in this study with sample data plotted in white dots. Looking time is calculated as the percentage of samples falling within each AOI. Bottom: Data samples are labelled according to the AOI they fall within (colours correspond to the middle panel). The first saccade into the goal is identified. The origin of this saccade is used in the saccade analysis and the timing of this saccade is used in the latency analysis.

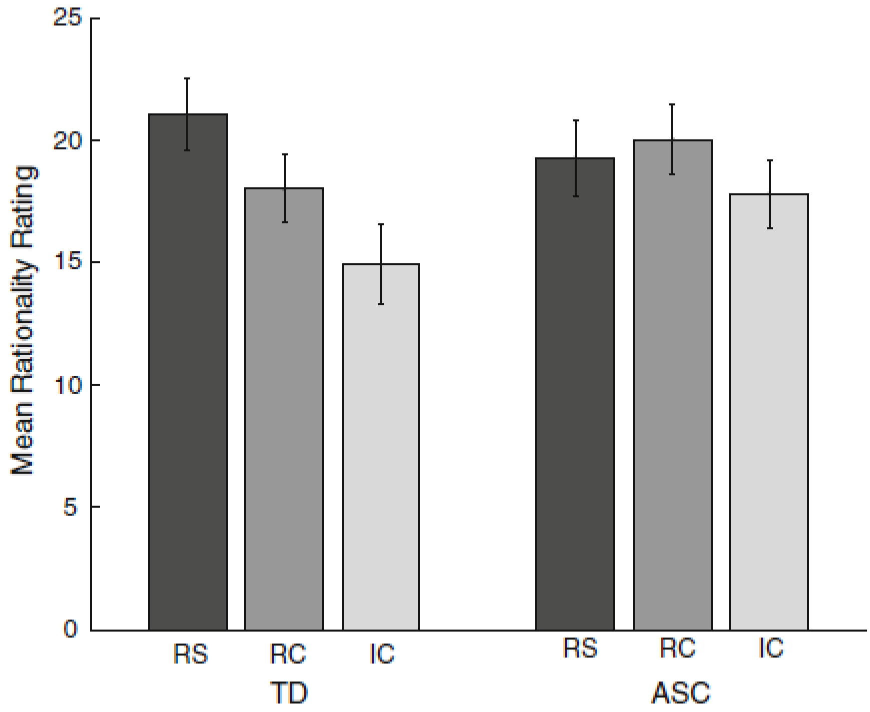

Figure 2: Behavioural ratings of rationality as a function of group and action type. Actions were rational straight (RS, dark grey bars), rational curved (RC, mid-grey bars) and irrational curved (IC, light grey bars). Rationality score was calculated as the total rating from a battery of six statements (maximum = 30).

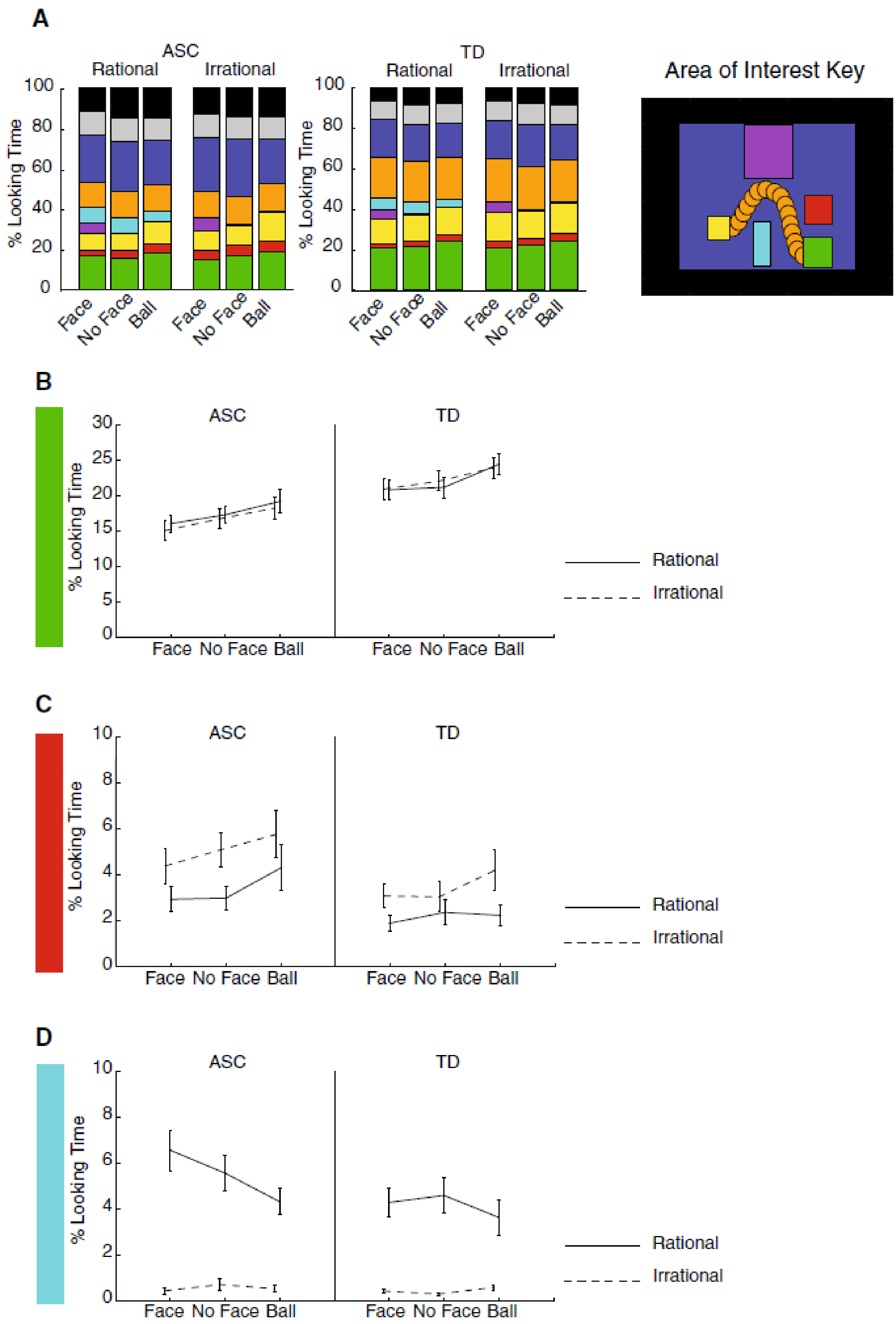

Figure 3A: Percentage looking time for each AOI in ASC (left) and typically developing (right) participants. These are displayed as a function of action type (rational- right cluster and irrational – left cluster) and social form. Colours correspond to the AOI key. Grey segments indicate the percentage of samples during a saccade (excluded from analysis) and black segments indicate missing data.

Figure 3B: Percentage looking time to the target goal as a function of group (ASC – left, TD – right), action type (rational – solid lines, irrational – dashed lines) and social form.

Figure 3C: Percentage looking time to the non-target goal as a function of group (ASC – left, TD – right), action type (rational – solid lines, irrational – dashed lines) and social form.

Figure 3D: Percentage looking time to the barrier as a function of group (ASC – left, TD – right), action type (rational – solid lines, irrational – dashed lines) and social form.

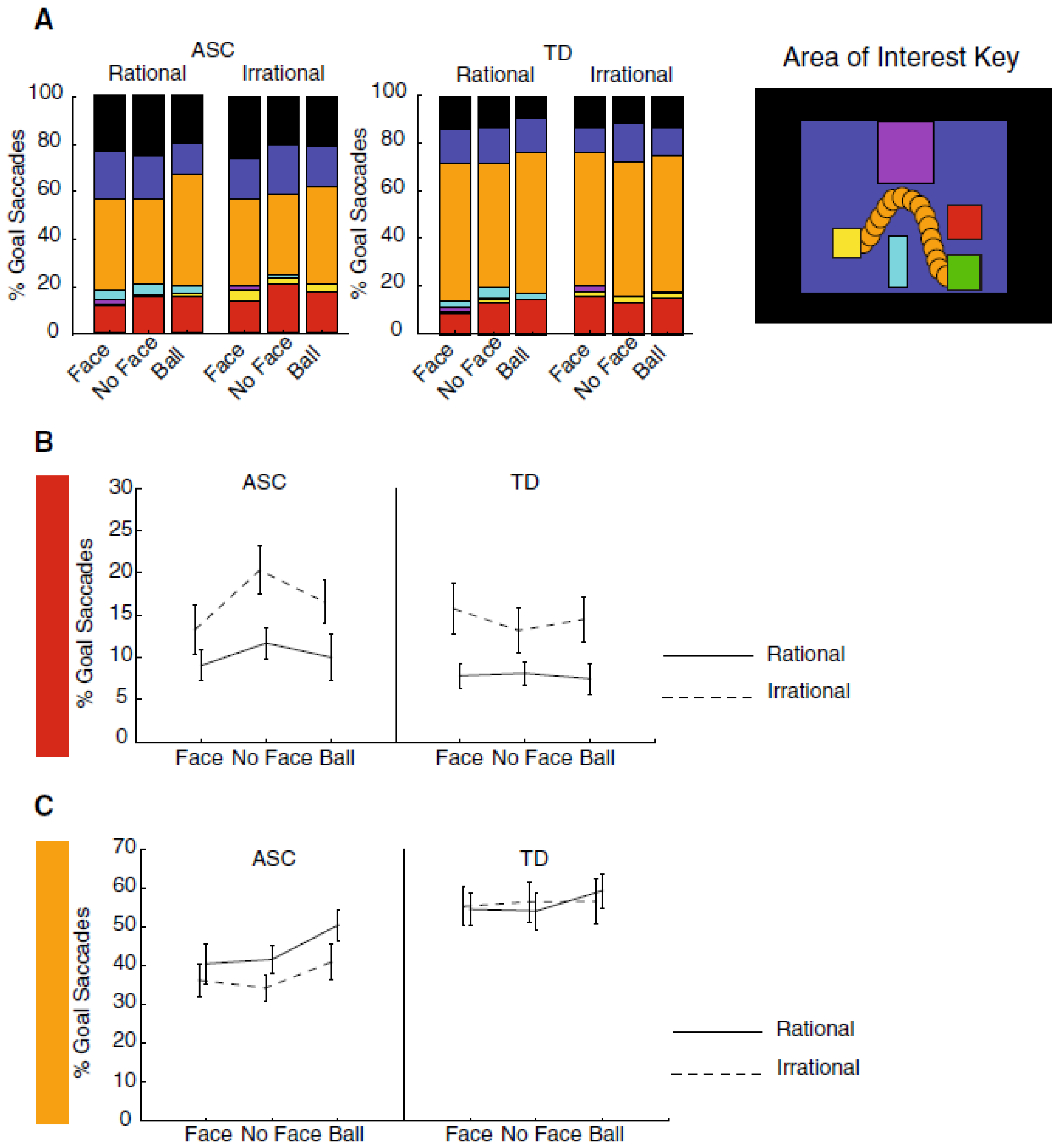

Figure 4A: Percentage of goal saccades originating in each AOI in ASC (left) and typically developing (right) participants. These are displayed as a function of action type (rational- right cluster and irrational – left cluster) and social form. Colours correspond to the AOI key. Black segments indicate the percentage of trials in which no goal saccade was made.

Figure 4B: Percentage of goal saccades that originated in the non-target goal as a function of group (ASC – left, TD – right), action type (rational – solid lines, irrational – dashed lines) and social form.

Figure 4C: Percentage of goal saccades that originated from the hand as a function of group (ASC – left, TD – right), action type (rational – solid lines, irrational – dashed lines) and social form.

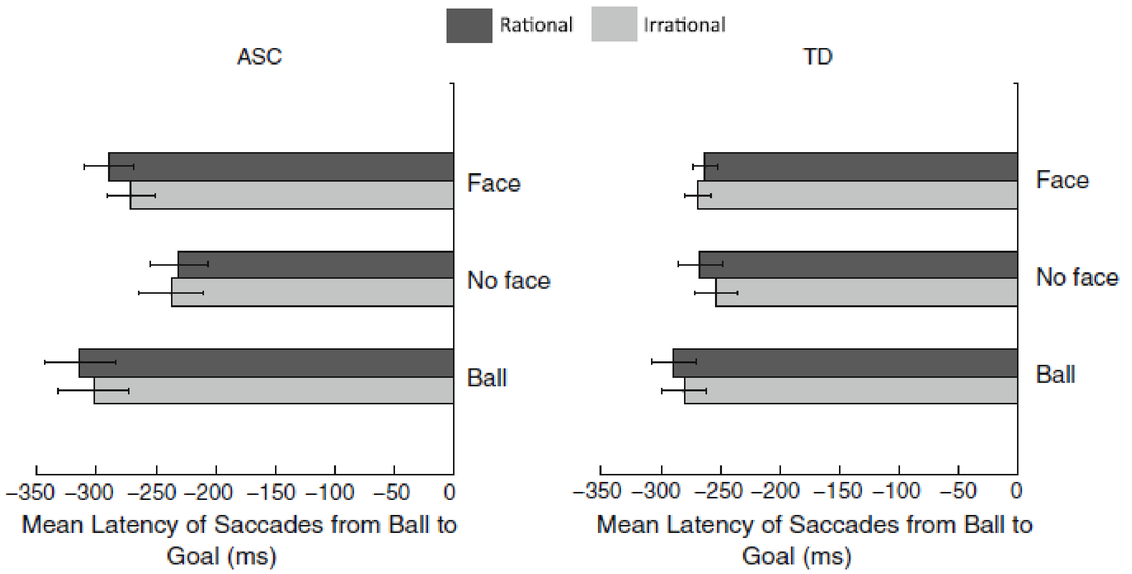

Figure 5: Mean latency of goal fixation as a function of group (ASC – left, TD – right), action type (rational – dark grey bars, irrational – light grey bars) and social form.

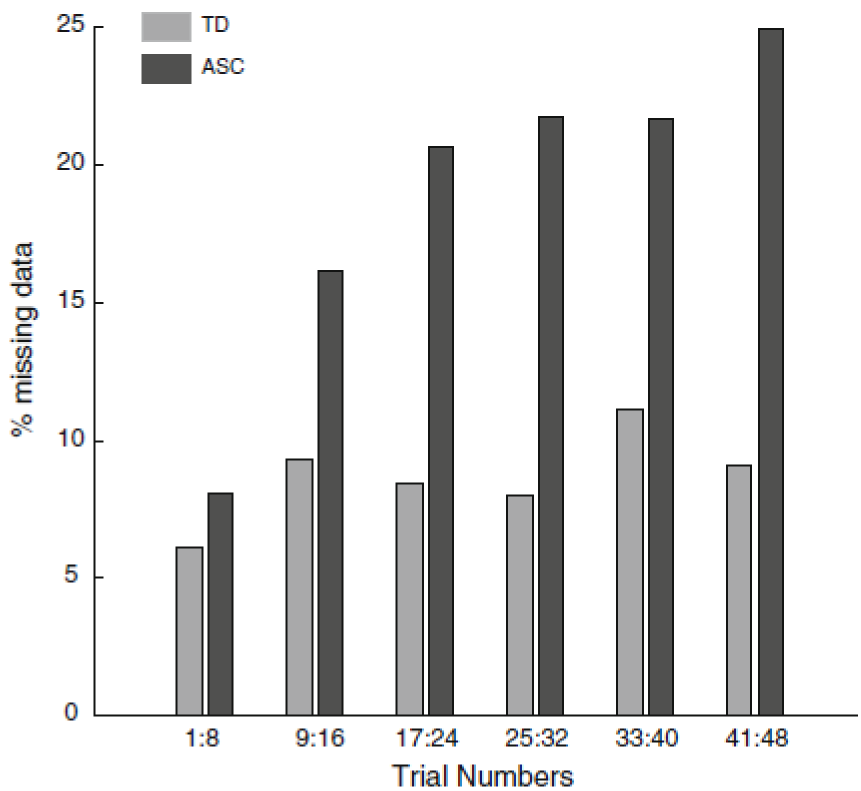

Figure 6: Percentage of excluded trials as a function of trial number through each of the six sets of movies (48 movies per set) and group membership (Typically Developing: light bars, ASC: dark bars)

Table 1: Participant characteristics for the matched typically developing group (TD) and the ASC group. p indicates the p-value of the paired samples t-test comparing the TD and ASC groups on each attribute.

	TD	ASC	p
n	20	20	
Age	18.9 ± 4.0 (16-29)	22 ± 6.1 (16-32)	0.06
FSIQ	101.8 ± 17.5 (76-139)	94.7 ± 18.3 (69-132)	0.22
VIQ	103.1 ± 17.5 (80-142)	96.4 ± 19.8 (71-143)	0.26
PIQ	99.3 ± 15.6 (75-127)	92.8 ± 17.2 (68-136)	0.21
AQ	17.4 ± 4.5 (10-27)	24.9 ± 7.3 (14-40)	<0.01
ADOS	-	10.6 ± 4.1 (4-17)	

Abbreviations: n- sample size; FSIQ – full scale intelligence quotient; VIQ – verbal intelligence quotient; PIQ – performance intelligence quotient; AQ – autism quotient; ADOS – autism diagnostic observation schedule total score.

Table 2. Predictions of typical gaze modulation for each AOI for each level of analysis.

Level of Analysis	AOI	Prediction
Looking Time How long does the participant look at this AOI?	Target Goal	Greater for rational than irrational as participants don't make errors
	Non-Target Goal	Greater for irrational than rational if participants make an error in perceiving goal
	Ball	Greater for ball conditions (than face/noface) based on Flanagan & Johannson (2001)
	Barrier	Greater for rational than irrational as participants detect rationality
	Face	Greater for irrational as participants look for reasons for rationality
Saccade-Origin Which AOI does the saccade to the goal come from?	Non-Target Goal	Greater for irrational than rational if participants make an error in perceiving goal
	Ball	Greater for ball conditions (than face/noface) based on Flanagan & Johannson (2001)
	Face	Greater for irrational as participants look for reasons for rationality
Goal-Latency How early does saccade from hand to goal occur?	Hand to Goal	Earlier saccades for social stimuli (face/noface) if human movements predicted better than nonhuman

Table 3: Inclusion criteria and the number of trials included at each stage of analysis for the typically developing and ASC groups.

Analysis Level	Inclusion Criteria	ASC		TD	
Total trials completed		5760		5760	
		Include	**Exclude**	**Include**	**Exclude**
Step 1: Looking time analysis	<20% samples missing	4329	1431	5320	440
Step 2: Saccade analysis	Saccade to goal present	2457	1872	3804	1516
Step 3: Latency Analysis	Goal saccade from hand present	725	1732	1744	2060

Table 4: Statistics for the looking time analysis for each area of interest. Values are the F statistic (or t-statistic when post hoc t-tests are used), degrees of freedom and p-values. Effects reported in bold type are significant after Bonferroni correction for multiple tests. [a] indicates the tests where α was 0.01 and [b] indicates tests where α was 0.0167.

Main Effects	**direction**	**F/(t)**	**df**	**p**
a) ANOVA 1: Looking Time to Target Goal				
Social Form		**8.26**	**2,76**	**<0.01[a]**
	ball > face	**(3.37)**	**39**	**<0.01[b]**
	ball > no face	**(3.13)**	**39**	**<0.01[b]**
	no face > face	(0.97)	39	0.34[b]
Rationality		0.03	1,38	0.87[a]
Group	**TD > ASC**	**9.30**	**1,38**	**<0.01[a]**
b) ANOVA 2: Looking Time to Non-Target Goal				
Social Form		**9.11**	**2,76**	**<0.01[a]**
	ball > face	**(3.50)**	**39**	**<0.01[b]**
	ball > no face	**(2.67)**	**39**	**<0.01[b]**
	no face > face	(2.21)	39	0.03[b]
Rationality	**irrational > rational**	**17.71**	**1,38**	**<0.01[a]**
Group		2.16	1,38	0.15[a]
c) ANOVA 3: Looking Time to Ball				
Social Form		0.02	2,76	0.98[a]
Rationality		2.82	1,38	0.10[a]
Group	**TD > ASC**	**10.10**	**1,38**	**<0.01[a]**
d) ANOVA 4: Looking Time to Barrier				
Social Form		**16.32**	**2,76**	**<0.01[a]**
	face > ball	**(3.78)**	**39**	**<0.001[b]**
	no face > ball	**(5.63)**	**39**	**<0.001[b]**
	no face > face	(1.62)	39	0.11[b]
Rationality	**rational > irrational**	**129.13**	**1,38**	**<0.001[a]**
Group		1.67	1,38	0.21[a]
Social Form x Rationality		**19.04**	**2,76**	**<0.01[a]**
	R – I face > R – I ball	**4.83**	**39**	**<0.01[b]**
	R – I no face > R – I ball	**6.41**	**39**	**<0.01[b]**
	R – I no face > R – I face	1.11	39	0.28[b]
e) ANOVA 5: Looking Time to Face				
Rationality		1.53	1,38	0.22[a]
Group		0.24	1,38	0.62[a]

Table 5: Statistics for the saccade analysis for each area of interest. Values are the F statistic (or t-statistic when post hoc t-tests are used), degrees of freedom and p-values. Effects reported in bold type are significant after Bonferroni correction for multiple tests. [a] indicates the tests where α was 0.0167, [b] indicates tests where α was 0.025 and [c] indicates tests where α was 0.0125.

Main Effects	direction	F/(t)	df	p
a) ANOVA 1 : Number of Saccades from Non-Target Goal to Goal				
Social Form		2.69	2,76	0.08[a]
Rationality	**irrational > rational**	**6.60**	**1,38**	**<0.01[a]**
Group		0.56	1,38	0.45[a]
b) ANOVA 2: Number of Saccades from Ball to Goal				
Social Form		3.75	2,76	0.03[a]
Rationality		1.19	1,38	0.28[a]
Group	**TD > ASC**	**6.31**	**1,38**	**<0.01[a]**
c) ANOVA 3: Number of Saccades from Face to Goal				
Rationality		0.13	1,38	0.72[a]
Group		0.01	1,38	0.93[a]

Table 6: Statistics for the latency of goal saccade analysis. Values are the F statistic (or t-statistic when post hoc t-tests are used), degrees of freedom and p-values. [a] indicates the tests where α was 0.05, [b] indicates tests where α was 0.0167 and [c] indicates tests where α was 0.0083.

Main Effects	direction	F/(t)	df	p
a) Linear Mixed Model: Latency of Saccades from the Ball to the Goal				
Social Form		**11.32**	**2,1818**	**<0.01[a]**
	no face > ball	**(4.35)**	**1244**	**<0.01[b]**
	no face > face	(2.25)	1163	0.02[b]
	face > ball	(2.11)	1271	0.04[b]
Rationality		0.26	1,1818	0.61[a]
Group		0.33	1,1818	0.57[a]

Table 7: Statistics for the task engagement analysis at each level of trial exclusion. Values are the F statistic (or t-statistic when post hoc t-tests are used), degrees of freedom and p-values. Effects reported in bold type are significant after Bonferroni correction for multiple tests. [a] indicates the tests where α was 0.0167.

Main Effects	direction	F/(t)	df	p
a) ANOVA 1 : Number of excluded trials in Looking Time Analysis				
Social Form		0.63	2,76	0.53[a]
Rationality		0.13	1,38	0.73[a]
Group	**ASC > TD**	**13.12**	**1,38**	**<0.01[a]**
b) ANOVA 2: Number of excluded trials in the Saccade Analysis				
Social Form		1.16	2,76	0.32[a]
Rationality		4.59	1,38	0.04[a]
Group	**ASC > TD**	**16.28**	**1,38**	**<0.01[a]**
c) ANOVA 3: Number of excluded trials in the Latency Analysis				
Social Form		1.08	2,76	0.35 [a]
Rationality		0.71	1,38	0.41[a]
Group	**ASC > TD**	**15.04**	**1,38**	**<0.01[a]**