Young children with autism spectrum disorder use predictive eye movements in action observation

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Does a dysfunction in the mirror neuron system (MNS) underlie the social symptoms defining autism spectrum disorder (ASD)? Research suggests that the MNS matches observed actions to motor plans for similar actions, and that these motor plans include directions for predictive eye movements when observing goal-directed actions. Thus, one important question is whether children with ASD use predictive eye movements in action observation. Young children with ASD as well as typically developing children and adults were shown videos in which an actor performed object-directed actions (human agent condition). Children with ASD were also shown control videos showing objects moving by themselves (self-propelled condition). Gaze was measured using a corneal reflection technique. Children with ASD and typically developing individuals used strikingly similar goal-directed eye movements when observing other’s actions in the human agent condition. Gaze was reactive in the self-propelled condition, suggesting that prediction is linked to seeing a hand–object interaction. This study does not support the view that ASD is characterized by a global dysfunction in the MNS.

Keywords: autism spectrum disorders; mirror neuron system; forward models; action prediction; eye movements

1. INTRODUCTION

Autism spectrum disorder (ASD) is defined by social impairments (American Psychiatric Association 1994), but the exact nature of these impairments remains a matter of debate (e.g. Dinstein et al. 2008). According to a recent hypothesis, individuals with ASD fail to map observed actions onto motor representations of these actions, owing to a dysfunctional mirror neuron system (MNS; Dapretto et al. 2006). ‘Mirror neurons’, first found in the premotor area (F5) of the macaque, respond both when the animal performs a particular transitive (object-directed) action and when the animal observes another individual perform a similar action (Gallese et al. 1996). This suggests that mirror neurons constitute a basic link between self and other and, potentially, a dysfunction in the MNS could explain why individuals with ASD often have difficulties understanding other people. This view is supported by studies showing reduced activation in the MNS during observation of actions in ASD compared with controls (e.g. Oberman et al. 2005; Theoret et al. 2005). To the authors’ knowledge, none of the studies directly supporting the ‘broken mirror’ theory of ASD have used stimuli containing transitive actions. This is noteworthy, given that mirror neurons fire in response to transitive actions, while they do not respond to intransitive actions, or when objects are presented in isolation (Gallese et al. 1996).

Electrophysiological data suggest that mirroring is an anticipatory process (Nishitani & Hari 2000; Kilner et al. 2004; Aglioti et al. 2008). Furthermore, behavioural studies of typically developing humans show that strikingly similar predictive eye movements are used both when one executes transitive actions oneself and when one observes similar actions performed by other people (Flanagan & Johansson 2003), and that predictive gaze during action observation is inhibited by simultaneous execution of simple sequential finger movements, but not by rehearsing sequences of numbers (Cannon & Woodward 2008). These results indicate that predictive eye movements in action observation reflect an engagement of motor plans in the observer.

Against this background, it was reasoned that if children with ASD have a dysfunctional MNS and consequently use general purpose visual mechanisms in action observation, their gaze is expected to track the actor’s hand, and arrive reactively at goal sites. Conversely, if children with ASD use action plans in action observation, gaze should predict upcoming goals by moving to the goal sites ahead of time. These alternative scenarios were evaluated using an eye-tracking method.

2. MATERIAL AND METHODS

(a) Participants

Final samples: 18 children with ASD (mean/s.d. age = 5.1 years/10.5 months, 15 males); 13 typically developing children (mean/s.d. age = 5 years/1.8 months, nine males); nine typically developing adults (mean/s.d. = 21.9 years/30 months, three males). All children with ASD had a formal diagnosis including autistic syndrome (n = 8), Asperger’s syndrome (n = 1) and pervasive developmental disorder, not otherwise specified (PDD-NOS; n = 9).

(b) Stimuli

In the human agent condition (figure 1), an action sequence (nine identical trials) in which a hand moved three objects to a box was shown. Both the three reach-to-grasp actions (directed at the objects) and the three placement actions were analysed. Children with ASD were also shown a control stimulus in which the objects moved by themselves to the box in which characteristics of the objects, movement trajectory, velocity profile and end effects (movement of the happy face on box and the sound for placement actions) were matched closely to the human agent condition.

(c) Procedure

The children were told that they were going to look at some short movies on the computer, and if they were inattentive during recording, they were reminded to keep looking at the monitor. Between stimuli, attention-getting animations were shown until the participants looked at the monitor.
the predictive eye movements are unlikely to reflect a domain general mechanism for prediction (Cattaneo et al. 2007).

Hobson & Hobson (2008) and Hobson & Lee (1999) found that children with ASD are skilled at imitating chains of goal-directed actions, but less likely than controls to imitate exactly how the actions are performed (i.e. the ‘style’) in spite of intact fine motor planning skills (for related findings, see Stone et al. 1997; Carpenter et al. 2001; Hamilton et al. 2007). Imitation of goal-directed actions is probably facilitated by rapid eye movements to other’s action goals, as shown in the present study. Interestingly, the distinction between imitation of goals versus ‘style’ in ASD fits with imaging data of the putative MNS in ASD. Observing intransitive manual actions and facial expressions, children with ASD activate the premotor cortex less than controls (Oberman et al. 2005; Theoret et al. 2005; Dapretto et al. 2006). By contrast, when shown transitive actions, preliminary data—from magnetoencephalography (MEG) and functional magnetic resonance imaging (fMRI), respectively—indicate no difference in terms of primary and premotor activation areas when comparing ASD with neurotypical individuals (Avikainen et al. 1999; Saron et al. 2009).

Although self-propelled objects moving to a box can be perceived as goal-directed (Heider & Simmel 1944; Gergely & Csibra 2003), they do not elicit predictive eye movements. Anticipatory gaze performance is only found when there is a hand–object interaction (Flanagan & Johansson 2003; Falck-Ytter et al. 2006; Eshuis et al. 2009). Thus, it seems that humans can understand the meaning of actions without mirroring, but that mirroring is used online to give an upcoming action outcome accurate coordinates in space and time (for a useful illustration see Aglioti et al. 2008). It is worth noting, however, that even if the link between predictive eye movements and the MNS is theoretically appealing (Miall 2003; Csibra 2007; Gallese et al. 2009), and has support from behavioural experiments (Flanagan & Johansson 2003; Cannon & Woodward 2008), more study is needed.

In summary, the present study shows that young children with ASD predict other people’s action goals. Given that the predictive eye movements observed here are likely to reflect a matching process mediated by the MNS, the present result does not support a global ‘broken mirror’ theory of ASD, an interpretation also supported by preliminary MEG and fMRI data (Avikainen et al. 1999; Saron et al. 2009). Whether the capacity to predict the goal of manual actions shows delayed development in ASD during infancy is an interesting question for further research.

Parents of all participants provided written consent according to the guidelines specified by the Ethical Committee at Uppsala University (the study was conducted in accordance with the standards specified in the 1964 Declaration of Helsinki).

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Figure 1. Static representation from the video shown in the human agent condition. See the electronic supplementary material for areas of interest and time window definitions.

3. RESULTS
Eye movements were strikingly similar across groups (figure 2). All groups predicted upcoming goal sites with their gaze for both reach-to-grasp and placement actions, and there were no significant differences between the groups (table 1). No participant showed exclusively reactive gaze performance when seeing human actions. Similar to neurotypical individuals (Flanagan & Johansson 2003; Falck-Ytter et al. 2006; Eshuis et al. 2009), children with ASD tracked the moving targets reactively in the self-propelled condition (table 1).

To investigate the role of repetition, the first trial was analysed separately (combining both action types to increase power). One-sample t-tests (one-tailed) confirmed that all groups predicted the goal of the actions in the first trial (ASD: mean/s.d. = 178/253 ms, t(17) = 2.986, p = 0.004; typically developing five-year-olds: mean/s.d. = 184/285 ms, t(11) = 2.245, p = 0.023; typically developing adults: mean/s.d. = 156/102, t(8) = 4.600, p = 0.001).

There were no significant differences in terms of prediction when comparing children diagnosed with autistic syndrome with children diagnosed with PDD-NOS. Within-subject variation in timing performance was greater in ASD than in the typically developing groups (see the electronic supplementary material for further details).

4. DISCUSSION
This study shows that young children with ASD use predictive eye movements in action observation. Both for reach-to-grasp and placement actions, eye movements were strikingly similar across groups. Gaze was anticipatory already in the first trial, showing that extensive repetition is not necessary for prediction. Furthermore, gaze was anticipatory even without ‘artificial’ end effects (a sound was accompanying the placement but not the reach-to-grasp action in this study; Eshuis et al. 2009). Importantly, it was demonstrated that the mechanism underlying predictive eye movements in children with ASD requires seeing a hand–object interaction; gaze tracked the targets reactively when the objects moved by themselves. Thus,
Figure 2. Graphs show hand (index finger) position of the actor as well as gaze position for the three groups as a function of time (ASD, autism spectrum disorder; TD, typically developing). Data represent mean performance for each group. The stimulus video included three reach-to-grasp actions (goals 1, 3, 5) and three placement actions (goals 2, 4, 6). Gaze performance was strikingly similar across groups, and gaze arrived at the goals before the arrival of the hand. As can be seen (e.g. bottom graph), no group tended to track the moving hand. Pictures to the right show a static representation of the video stimulus (oriented according to each graph). Black line, actor's index finger; gaze: dark blue line, ASD preschoolers; gaze: light blue line, TD preschoolers; gaze: pink line, TD adults.

Table 1. Mean prediction times for children with ASD, typically developing five-year-olds and typically developing adults.

<table>
<thead>
<tr>
<th>action type</th>
<th>group (n)</th>
<th>mean (s.d.)</th>
<th>t-, p-values</th>
<th>F, p-values</th>
</tr>
</thead>
<tbody>
<tr>
<td>reach-to-grasp</td>
<td>ASD (18)</td>
<td>102 (181)</td>
<td>2.407 = 0.028</td>
<td>1.094, n.s.</td>
</tr>
<tr>
<td></td>
<td>Typ-5y (13)</td>
<td>207 (247)</td>
<td>3.029 = 0.010</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Typ-adult (10)</td>
<td>165 (154)</td>
<td>3.535 = 0.006</td>
<td></td>
</tr>
<tr>
<td>placement</td>
<td>ASD (18)</td>
<td>179 (221)</td>
<td>3.428 = 0.006</td>
<td>1.245, n.s.</td>
</tr>
<tr>
<td></td>
<td>Typ-5y (12)</td>
<td>106 (186)</td>
<td>1.987 = 0.036</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Typ-adult (8)</td>
<td>245 (168)</td>
<td>4.347 = 0.004</td>
<td></td>
</tr>
<tr>
<td>self-propelled objects</td>
<td>ASD(15)</td>
<td>-58 (61)</td>
<td>-0.948, n.s.</td>
<td></td>
</tr>
</tbody>
</table>

*aGaze arrival at goal relative to arrival of the hand. Note that while figure 1 is based on all data points, the gaze arrival data presented here are based on the criteria specified in the electronic supplementary material, §2d.

*bOne-sample t-tests (one-tailed) against t-value = 0 ms (i.e. arrival of the hand).

*cOne-way ANOVAs comparing the three groups (for each action type separately).

Table 1 includes data for reach-to-grasp and placement actions. For self-propelled objects, the data are not presented due to the limited sample size. Theoretical and experimental underpinnings of the results are discussed in the context of action prediction in autism and its possible role in intention understanding. Proc Natl Acad Sci USA 104, 17 825–17 830. (doi:10.1073/pnas.0706273104)


