ELSEVIER

Neuropsychologia 46 (2008) 448–454

NEUROPSYCHOLOGIA

www.elsevier.com/locate/neuropsychologia

Robotic movement elicits visuomotor priming in children with autism

Andrea C. Pierno[a], Morena Mari[a],
Dean Lusher[b], Umberto Castiello[a,c,*]

[a] Department of General Psychology, University of Padua, Italy
[b] Department of Psychology, University of Melbourne, Australia
[c] Department of Psychology, Royal Holloway-University of London, UK

Received 26 April 2007; received in revised form 12 August 2007; accepted 24 August 2007
Available online 1 September 2007

Abstract

The ability to understand another person's action and, if needed, to imitate that action, is a core component of human social behaviour. Imitation skills have attracted particular attention in the search for the underlying causes of the social difficulties that characterize autism. In recent years, it has been reported that people with autism can bypass some of their social deficits by interacting with robots. However, the robot preference in terms of imitation has yet to be proved. Here we provide empirical evidence that interaction with robots can trigger imitative behaviour in children with autism. We compared a group of high functioning children with autism with a group of typically developing children in a visuomotor priming experiment. Participants were requested to observe either a human or a robotic arm model performing a reach-to-grasp action towards a spherical object. Subsequently, the observers were asked to perform the same action towards the same object. Two 'control' conditions in which participants performed the movement in the presence of either the static human or robot model were also included. Kinematic analysis was conducted on the reach-to-grasp action performed by the observer. Our results show that children with autism were facilitated – as revealed by a faster movement duration and an anticipated peak velocity – when primed by a robotic but not by a human arm movement. The opposite pattern was found for normal children. The present results show that interaction with robots has an effect on visuomotor priming processes. These findings suggest that in children with autism the neural mechanism underlying the coding of observed actions might be tailored to process socially simpler stimuli.

Keywords: Autism; Visuomotor priming; Kinematics; Action observation; Social cognition

1. Introduction

Interactive robots are used increasingly not only in entertainment and service robotics, but also in rehabilitation, therapy, and education (Robins, Dautenhahn, Dickerson, & Stribling, 2004; Werry, Dautenhahn, Ogden, & Harwin, 2001). The aim of the work presented in this paper is to study the potential contribution of robots to research into the nature of autism (Frith, 1989). Specifically, we focus our analysis on imitation which plays a fundamental role in human development and social understanding. Imitation skills of children with autism have been studied extensively in autism research and therefore this behaviour provides a relevant focus for our study.

As reported in several reviews of the imitation literature in autism, persons with autism typically demonstrate impaired performance compared to controls (Rogers & Bennetto, 2000; Rogers & Pennington, 1991; Smith & Bryson, 1994). So far 'imitation' studies in autism have been confined to the explicit request to imitate (e.g., Rogers, Hepburn, Stackhouse, & Wehner, 2003) whereas automatic imitation has been much less investigated (Pierno, Mari, Georgiou, Glover, & Castiello, 2006). Here we focus on automatic imitation which is usually revealed through the administration of visuomotor priming paradigms (Castiello, Lusher, Mari, Edwards, & Humphreys, 2002; Craighero, Fadiga, Umiltà, & Rizzolatti, 1998; Edwards, Humphreys, & Castiello, 2003; Heyes, Bird, Johnson, & Haggard, 2005). In the absence of instruction to imitate, move-

---

[*] Corresponding author at: Department of General Psychology, University of Padova, Via Venezia 8, 35131 Padova, Italy. Tel.: +39 049 827 6659.
E-mail address: umberto.castiello@unipd.it (U. Castiello).

0028-3932/$ – see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.neuropsychologia.2007.08.020

ment observation facilitates execution of the observed action. Such facilitation effects have been described in both neurophysiological and behavioural terms. In first instance, a pattern of muscle facilitation was revealed during the observation of an action strictly resembling that occurring during the actual execution of the observed movement (Fadiga, Fogassi, Pavesi, & Rizzolatti, 1995). In second instance, reaction times and movement duration decrease when an observed and a subsequently executed hand action matched (Castiello et al., 2002; Craighero et al., 1998; Edwards et al., 2003; Heyes et al., 2005). Furthermore, facilitation effects in reach-to-grasp tasks have been described as an anticipation in time of key kinematic parameters following the observation of a human model performing a similar action (Castiello et al., 2002; Edwards et al., 2003). Importantly, in children with autism such facilitation effects were absent when the model is human (Pierno et al., 2006; Theoret et al., 2005). In the present study, we compared a group of high functioning children with autism with a group of typically developing children in a visuomotor paradigm which has been previously used to reveal visuomotor priming deficits in autism (Pierno et al., 2006). In our test, participants were requested to observe either a human or a robotic arm model performing a reach-to-grasp action towards a spherical object. Subsequently, the observer was asked to perform (but not to imitate) the same action towards the same object. Two 'control' conditions in which participants performed the movement in the presence of either the static human or the robot model (therefore in the absence of any motor priming) were also included.

2. Methods

2.1. Participants

Twelve high-functioning children with autism (6 males and 6 females, 10–13 years old, mean 11.1 years; see Table 1) and 12 sex and age-matched $[F(1,11) = 0.32, p > 0.05]$ normally developing controls (6 males and 6 females, 10–13 years old, mean 11.2 years; see Table 1) with no reported neurological or academic problems participated in the study. A normally developing 12-year-old child acted as a model. All children were right-handed, reported normal or corrected-to-normal vision, no-hearing impairments, and were naive as to the purpose of the experiment. None were on medication or exhibited praxis problems as assessed by an occupational therapist. They attended one experimental session of $\sim$1 h duration. The children with autism were diagnosed according to the Diagnostic and Statistical Manual of Mental Disorders-IV (DSM-IV) criteria for autism. IQ was measured with the Wechsler Intelligence Scale for Children (WISC-R; see Table 1). The normally developing and children with autism were IQ matched $[F(1,11) = 0.12, p > 0.05]$. The Childhood Autism Rating Scale (Schopler, Reichler, & Rochen Renner, 1993) had been administered at the ages of 4–8 years by an experienced clinical psychologist. Further tools for diagnosis were the Autism Diagnostic Interview—Revised (ADI-R; Lord et al., 2000; see Table 1) and the Autism Diagnostic Observation Schedule (ADOS; Lord, Rutter, & Le Couteur, 1994). At the time of the experiment all of the children with autism were attending special education classes for autism. The study was approved by the local Ethical Committee.

2.2. Experimental conditions

Participants performed a block of 20 trials for each of the following experimental conditions: (i) *Human–human condition*. Two participants, a model and an observer, were seated facing each other at a table (Fig. 1A). Prior to each trial both the model and the observer put their right hand on a starting switch located 10 cm in front of their mid-line. A 'go' signal given by the experimenter indicated to the human model to perform a reach-to-grasp action towards the target stimulus. The stimulus was a plastic sphere (diameter: 5 cm) positioned at a distance of 20 cm from the hand starting position along the subjects' mid-sagittal plane. As soon as the action was completed and the hand of the model returned to the starting switch a sound was presented (880 Hz; 200 ms). The sound indicated to the observer, either a normally developing or autistic child, to perform a reach-to-grasp action towards the target stimulus. Participants were not explicitly instructed to imitate the previously observed action but were simply asked to perform a reach-to-grasp action towards the target stimulus when the sound was presented. (ii) *Robot–human condition*. The procedure was exactly the same as for the 'human–human' condition except that a robot replaced the human model and the start of the robot's action was controlled by the experimenter via software procedures (Fig. 1B). The robotic arm was custom-designed and built by in-house technicians. It looked like an average human forearm with a gloved hand and was mounted on a metal frame and used a single motor to move the arm from a vertical to a horizontal position. The four fingers and thumb had a common movement so as to mimic the closing of a human hand. The construction was electro-mechanical and controlled by an 87c751 micro-controller. The hand was constructed of nylon cords for the tendons, silicon rubber for the joints, and wooden dowels for the bones. Movement was provided by a dc electric motor that tensed the tendons to close the hand. Springs were used to store energy and thus reduce the required power and size of the dc motors. Limit sensors on the arm and hand were used by the micro-controller to control movement. The arm length was approximately 0.5 m. The maximum pickup weight

Table 1
Participant demographics for children with autism and for the normally developing children participating in the study

SS	Children with autism								Normally developing	
	Diagnosis	Age	Sex	IQ	CARS[a]	ADI-R			Age	Sex
						Social (cutoff = 10)	Communication (cutoff = 8)	Stereotypy (cutoff = 3)		
S1	Asperger's	10.2	F	105	35	30	22	7	10	F
S2	Autism	10	F	98	36	27	22	12	10	F
S3	Asperger's	13	M	109	33	26	19	6	12.7	M
S4	Autism	10.5	M	96	35	22	22	8	10	M
S5	Asperger's	10	M	102	33.5	21	20	7	12.8	M
S6	Asperger's	13.1	F	94	37	22	19	6	13	F
S7	Asperger's	11.2	M	102	32.5	26	20	6	11	M
S8	Autism	10.6	M	108	34	23	21	7	11	M
S9	Asperger's	11	F	108	36	27	19	10	11	F
S10	Asperger's	13	F	97	34	26	15	8	12.8	F
S11	Autism	10	F	100	33	24	18	8	10	F
S12	Autism	11	M	103	34.5	22	20	7	11	M

[a] CARS: Childhood Autism Rating Scale. Total score of 30–37: mild autism.

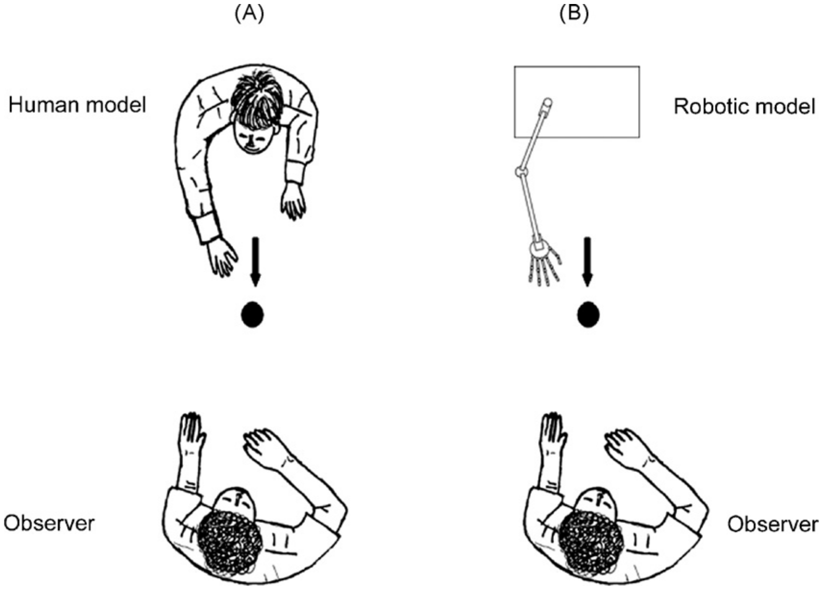

Fig. 1. Experimental set up. Panel A represents the ‘human–human’ condition in which two participants, a model and an observer, were seated facing each other at a table. Panel B represents the ‘human–robot’ condition in which a participant was facing the robotic arm.

was approximately 0.1 kg. The movement of the robot was quite smooth and the folding of the hand was comparable to a ‘human’ grasping action. The robot was programmed to simultaneously move its arm and open its fingers when the experimenter pressed a button. Movement duration, arm velocity and the maximum aperture of the fingers in time and amplitude were programmed (on the basis of the average data acquired from the child who acted as a model in a preliminary session; ±5 ms). After reaching the maximum aperture the fingers started to close upon the to-be-grasped object. The kinematic values obtained during the preliminary session were compared with those obtained during the *human–human* condition. The breakdown of kinematics for the robot and the human model (preliminary and experimental sessions) are presented in Table 2. (iii) *Human control condition.* The subjects/observers performed the action in the presence of the static human model. A sound indicated to the observer, either a typically developing or autistic child, to perform a reach-to-grasp action towards the target stimulus. (iv) *Robot control condition.* The subjects/observers performed the action in the presence of the static robotic model. A sound indicated to the observer, either a typically developing or autistic child, to perform a reach-to-grasp action towards the target stimulus. The order of conditions was counterbalanced within and between participants. On-line examination of trials indicated that the children with autism were not less likely to comply to the task demands. In this respect they did not require a greater number of repetitions of the model in order to attempt the task. Thus, it appeared that the administrative procedures motivated all children similarly, and there was no indication of more refusal or less attention on the part of the children with autism.

2.3. Kinematic recordings

The ELITE motion analysis system (Bioengineering Technology & Systems [BTS]) was used to record movements. Reflective passive markers (0.2 cm diameter) were attached on the (a) wrist-radial aspect of the distal styloid process of the radius; (b) index finger-radial side of the nail; (c) thumb-ulnar side of the nail. The wrist marker was used to measure the reaching component of the action (velocity profiles). Tangential speed data were used to determine the onset and offset of the movement using a standard algorithm (threshold for movement onset and offset was ~5 cm/s). The markers positioned on the finger and thumb were used to measure the grasp component of the action (time of maximum grip aperture). Four infrared cameras (sampling rate 100 Hz) captured the movement of the markers in 3D space. Movement duration was calculated as the time between the release of the starting switch and the time at which the participant’s fingers closed upon the object. The onset was taken as the earliest time at which movement of the wrist occurred. The offset was taken at the latest time at which the movement of the thumb and index finger occurred. Initiation time was calculated as the time between a starting tone (880 Hz; 200 ms) and the release of the starting switch.

2.4. Eye movement video recording

Eye movements were recorded by means of a videocamera pointed at an angle which allowed the head and upper body of both the model (from the back) and the observer (from the front) to be visible. The observers’ eye movements were monitored on-line and subsequently evaluated by an independent rater. This procedure was adopted to ensure that during the trial the observer was gazing at the scene including the model and the object. Trials in which the observer’s gaze moved away from the area including the model and the object during the observation phase of the trial were discarded (but stored) and subsequently repeated. The independent rater evaluation served to double check that the trials discarded on-line had been correctly evaluated. The criteria for evaluation included the direction of gaze towards the face, the trunk and the moving arm of the human model and the area encompassed by the robot model (which was similar to the area encompassed by the child model). The area encompass-

Table 2
Mean values for movement duration, time to peak velocity and the time of maximum grip aperture for the human model for the preliminary and experimental sessions and for the robot model

	Human model preliminary session	Human model experimental session	Robot model	Statistical values
Movement duration (ms)	804 (86)	797 (83)	800	$F(2,19) = 0.31$, $p > 0.05$
Time to peak velocity (ms)	291 (32)	286 (20)	286	$F(2,19) = 1.06$, $p > 0.05$
Time to maximum grip aperture (ms)	342 (28)	337 (31)	347	$F(2,19) = 0.76$, $p > 0.05$

S.D. in parentheses.

ing the eyes was also magnified on a different window on the screen in order to perform a more precise evaluation and correlation with the image including the whole upper body of the observer and the back view of the model. We attempted to use more advanced eye monitoring techniques but calibration and infrared markers positioning were unsustainable for the children (in particular for the children with autism).

2.5. Data analysis

As for other visuomotor priming experiments the analyzed kinematic dependent variables were movement duration, time to peak velocity, and the time of maximum grip aperture (Edwards et al., 2003). A repeated-measures analysis of variance (ANOVA) for each of the considered dependent measures was performed. The between-subjects factor was group (children with autism, controls) and the within-subjects factor was experimental condition (control human, control robot, robot prime, and human prime). Bonferroni corrections were applied for the contrasts of interest. For the eye movement data a two-tailed *t*-test for independent samples analysis was performed comparing the percentage of discarded trials (over the total number of acquired data) for each group for both the robot and the human conditions. Although for the human condition we considered direction of gaze towards different body parts (i.e., face, trunk/moving arm) these data were collapsed as to make the comparison with the robot consistent (i.e., the robot did not have a face, but roughly encompassed a similar volume as the human model). In this respect, preliminary analyses showed that both autistic and normally developing children showed a similar percentage of trials in which gaze was directed towards either the face [$t_{(22)} = 0.372$, $p > 0.05$] or the trunk/moving arm [$t_{(22)} = 0.187$, $p > 0.05$] of the human model during the observation phase.

3. Results

Statistical analyses revealed that facilitation effects were evident only in the ‘human’ condition for the normally developing children and only in the ‘robot’ condition for the children with autism. The group by experimental condition interaction was significant for movement duration [$F(1,11) = 56.32$, $p < 0.0001$; $\eta^2 = 0.832$; Fig. 2A], time to peak velocity [$F(1,11) = 33.02$, $p < 0.0001$; $\eta^2 = 0.786$; Fig. 2B] and the time of maximum grip aperture [$F(1,11) = 18.43$, $p < 0.0001$; $\eta^2 = 0.941$; Fig. 2C]. Post hoc contrasts revealed that for the normally developing children movement duration was shorter and both the time to peak velocity and the time to maximum grip aperture were reached earlier for the ‘human’ than for the ‘robot’ and the two ‘control’ conditions (*p*s < 0.001). Crucially, for the children with autism movement duration were shorter and both time to peak velocity and time to maximum grip aperture were earlier for the ‘robot’ than for the ‘human’ and the two ‘control’ conditions (*p*s < 0.001; Fig. 1A–C). No differences were found between the autistic and the normally developing children for the control conditions for all dependent measures. Further, there was no effect of the type of prime for both the autistic and the normally developing children on movement initiation time [interaction group × experimental condition; $F(1,11) = 0.0306$, $\eta^2 = 0.009$]. Thus, the facilitation effects found for the children with autism in the robot condition and for the normally developing children in the human condition arose from a more efficient programming of the action, rather than speeding at the start of the movement.

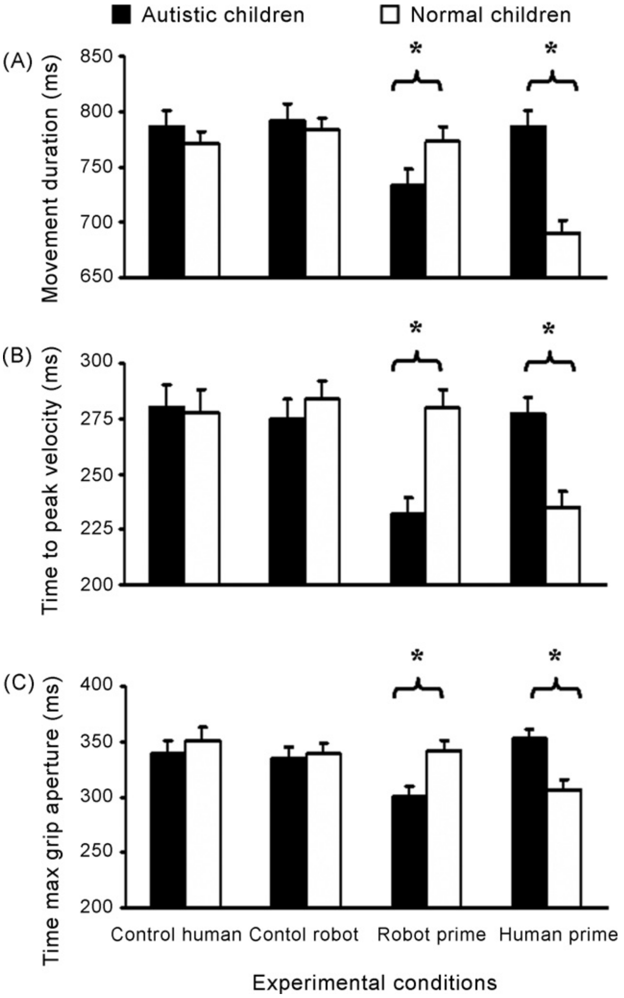

Fig. 2. Graphical representation of the significant interaction between group (autistic children, normal children) and condition (control human, control robot, robot prime, and human prime) for movement duration (panel A), time to peak velocity (panel B) and time to maximum grip aperture (panel C). Bars represent the standard errors of the means. ms: milliseconds. Asterisks indicate significance for the main contrasts of interest.

To investigate for possible differences across conditions on a trial-by-trial basis for each group, we performed a post hoc analysis for each of the considered dependent measures with group (children with autism, controls) as a between-subject factor and trial (1–20) and experimental condition (control robot, control human, robot prime, human prime) as within-subjects factors. The main factor ‘trial’ did not interact significantly with any of the other factors for all dependent measures. As shown in Fig. 3 for the dependent measure ‘time to peak velocity’, children with autism showed a consistent lack of facilitation for the ‘human’ condition and a consistent facilitation effect for the ‘robot’ condition across all trials. The opposite pattern of results was found for the normally developing children. Further, we also performed a qualitative profile analysis looking for possible differences across trials for each participant of the two groups. For each subject the above-mentioned patterns of results was confirmed, except that 4 out of the 12 children with autism showed facilitation (decrease in movement duration and anticipation of peak velocity) following the observation of the ‘human’ model on the first trial. However, for the same four children with autism, such facilitation effects faded away by the second trial.

Analyses concerned with eye movements performed on the percentage of discarded trials did not reveal any group differ-

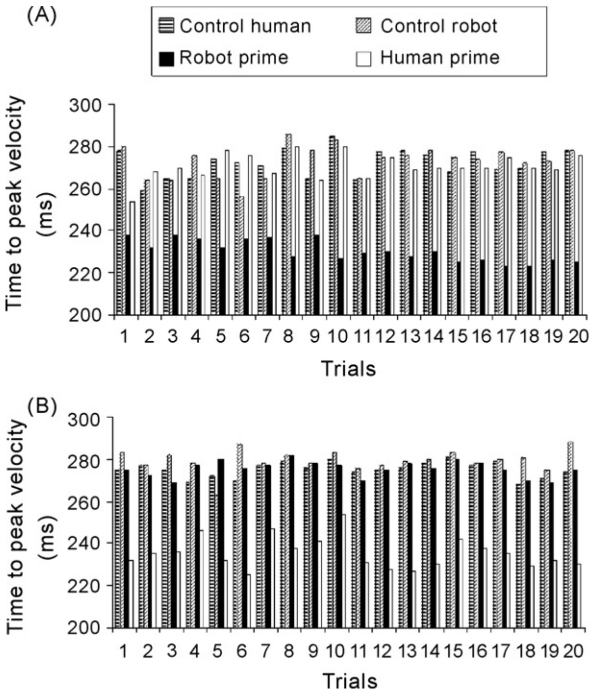

Fig. 3. Graphical representation of the group means for time to peak velocity across the 20 trials for each of the experimental conditions. Panel A represents the group means for the children with autism. Panel B represents the group means for the typically developing children.

ence. This indicated that gaze did not veer away more often for one or the other type of model. Specifically, no statistical differences were revealed when comparing the robot and the human model for both the autistic [$t_{(22)} = 0.267$, $p = 0.792$; 3.3% vs. 2.7%] and the normally developing children [$t_{(22)} = 0.393$, $p = 0.698$; 2.9% vs. 3.1%].

4. Discussion

The result that arm movements of normally developing children were facilitated when primed by a human rather than a robotic model is consistent with those obtained in previous visuomotor priming experiments both in children and adults (Castiello et al., 2002; Craighero et al., 1998; Edwards et al., 2003; Heyes et al., 2005; Pierno et al., 2006). The novel aspect of the present results is concerned with the demonstration that visuomotor priming proceeds normally in children with autism when primed by a robotic model. This finding is generally consistent with other results demonstrating that people with autism perform at normal to superior levels at tasks presented in repeatable and predictable formats established by a robot or a computer (Robins et al., 2004; Werry et al., 2001). Crucially the present findings extend the evidence of such facilitation in terms of visuomotor priming.

The natural question is why would children with autism be facilitated by a robot prime? We suggest that a possible explanation might be found in the way children with autism represent and understand other people actions and intentions. That is, at an automatic unconscious level which is independent from the participants' preference.

Human actions are characterized by high degree of variability. Performing the same action 20 times would produce 20 different movements' trajectories and kinematics. In this respect, it is plausible that such variability does not create particular problems to a neurologically healthy observer, given that possibly he/she does not 'see' 20 different actions, but simply recognizes and 'sees' the motor intentions which makes those 20 movements 20 repetitions of the same action. However, it might well be that for the children with autism human actions contain far more variance than robotic actions. Therefore, children with autism might (presumably because of better attention to small details) notice the variance more than controls, and accordingly they would be more sensitive to it. In other words, children with autism might not cope with as much variance as typical children, and thus they respond better to highly repetitive predictable stimuli such as the robot's actions. Support to this view comes from a recent proposal by Baron-Cohen (2006). His suggestion is that children with autism are mainly attracted to systems of low or minimal variance (such as machines) and less sensitive to systems (such as people behaviour) where there is maximal variance.

In neural terms a mechanism which might be suited to explain the effects reported here is the so-called 'mirror system'. It has been suggested that the penetration of visual information into the motor knowledge of an observer is underpinned by the 'mirror system' (Gallese & Goldman, 1998; Gallese, Keysers, & Rizzolatti, 2004; Rizzolatti, Fogassi, & Gallese, 2001). This system responds both when a human performs a certain motor act such as grasping an object, and also when a person observes another human performing the same motor act. Each time an individual sees an action performed by another individual, the activation of mirror neurons transforms visual information about a physical movement, into knowledge about an intentional action. This implicit knowledge, which Pacherie and Dokic (2006) call 'motor understanding' (to differentiate it from a purely 'visual understanding'), is what allows us to penetrate the motor intention of another individual's actions, without the need for conscious/deliberate inferences.

Crucially, in children with autism, bilateral anatomical abnormalities localized in 'mirror' areas (ventral premotor, posterior parietal, and superior temporal sulcus cortices) have been reported (Boddaert et al., 2004; Hadjikhani, Joseph, Snyder, & Tager-Flusberg, 2006; William, Whiten, Suddendorf, & Perrett, 2001). This possible neural dysfunction finds support by the results obtained in a series of studies which have used different techniques, i.e. electroencephalography (Oberman et al., 2005), transcranial magnetic stimulation (Theoret et al., 2005), and kinematics (Pierno et al., 2006). These studies have revealed that during hand action observation autistic individuals did not show 'mu' frequency suppression over the sensory-motor cortex, muscle facilitation and visuomotor priming, respectively.

Assuming that children with autism have a dysfunctional 'mirror' system it may allow the speculation that they lack an intentional filter which normally developing children may utilize to code for another person's behaviour. In other words, children with autism may be unable to, or impaired in building a motor representation. Without an intentional understanding of another person's action, the variability which characterizes biological movement represents a disturbance (which may account for the lack of visuomotor priming effects for the 'human–human' condition). Conversely, the robotic movement, which does not carry such elements of variability, facilitates the recognition of the action goal and allows for the visuomotor priming effects to emerge. In this connection a well-known finding is that children with autism are better at reproducing observed actions on the basis of a strategy which considers action goals rather than the action itself (Hamilton, Brindley, & Frith, 2007; Hobson & Lee, 1999; Wants & Harris, 2002). However, further studies are needed to confirm this. For instance an aspect to be clarified is whether the robotic invariability will lead to increased priming for someone without a fully functioning mirror system, regardless of whether the mirror system registers a goal.

Before the above hypotheses can be fully accepted a number of issues need some clarification. First, it might be said that on the initial viewing, the human's movement is perceived as neither more nor less variable than a robot movement. Hence, for the children with autism equal amounts of facilitation should be found for the human and robot movement on the initial trial, with facilitation becoming more evident on successive trials for the robot but not for the human model. In this respect, the analysis performed to explore facilitation effects on a trial-by-trial basis seems to rule out this possibility. However, as shown in Fig. 3A, autistic children seem to show a non-significant trend indicating facilitation effects for the 'human prime' condition on the initial trial. Though, as outlined within Section 3, this trend might have been driven by a small proportion of participants.

Second, two alternative explanations would be that children with autism were simply more interested in the robot (than the controls, or the human prime) and that the normally developing children were under an 'audience' effect and therefore performed faster in the mere presence of a conspecific (Zajonc, 1965; Zajonc, Heingartner, & Herman, 1969). However, our skepticism with respect to these possible explanations derives from the analysis performed on the participants' specific points of gaze within the scene and the results obtained for the control conditions. In first instance, only trials in which both normal and children with autism were gazing within the area including the moving arm of either the human or the robotic model and the target object were considered for analysis. Further, when considering the percentage of discarded trials it does not emerge any group difference suggesting that gaze did not veer away more often for one or the other type of model. Additionally, when debriefed, all normally developing children at the end of the experimental session reported that they found the 'robot' more interesting than the 'human' condition. Furthermore, if differences between the human and the robot model were simply due to a different degree of attention paid to the type of model then they should also be evident for the control conditions in which both models were stationary. However, as shown in Fig. 2 results for these conditions were similar for both groups. Therefore, we are inclined to believe that the hypotheses that the robot triggered in the children with autism a greater level of interest and/or attention and that the mere presence of another person elicited faster action in normally developing children can be ruled out.

A further element which may explain the facilitation effects found for children with autism in the 'robot–human' condition may be represented by the absence of complex social/emotional markers. It has been proposed that in typically developing children imitative processes begin with imitation of facial movements, available at birth, and develops to include related body movements seen in emotional contagion and mirroring of facial expressions, body posture and gestures. Thus, an affective mechanism modulating social exchanges may be involved in imitation (Nielsen, 2006; Rogers et al., 2003; Uzgiris, 1981). An assumption underlying this interpretation, is that the problems experienced by children with autism in imitative behaviours may be determined not only by the incapacity to establish a motor equivalence between demonstrator and imitator, but also by disrupted emotional/affective regulation (Gallese, 2006). This view is consistent with recent neuroimaging evidence concerning the imitation of the facial expressions of basic emotions in high functioning children with autism. Using functional magnetic resonance imaging, it has been revealed that during both observation and imitation, children with autism did not show activation of the mirror neuron system (Dapretto et al., 2006; Iacoboni & Dapretto, 2006). However, a point to consider in terms of 'emotional' markers is that children with autism find social interaction aversive and that this view has led to a reluctance among researchers to insist that children with autism respond to social initiatives (Sigman, Dissanayake, Corona, & Espinosa, 2003). It is therefore important to detail and consider how the human model acted. In this respect video analyses revealed that the human model (in terms of facial expression and eye gaze) behaved quite similarly for both the human priming and the control conditions. Although this is a very indirect indicator of the autistic children's attitude (the model may have felt sympathy and interest for the autistic children but they did not respond to this offer), it is unlikely that the presence of such social cues have prohibited appropriate responding from the children with autism.

As a final point, a possible limitation of the present study might be concerned with the fact that we tested only one specific action (i.e., reach-to-grasp). Therefore, at this stage we cannot ascertain whether any priming effect of observing this action was specific to performance of the same action, or whether facilitation would have occurred if the executed action had been quite different from the observed action. However, the fact that previous authors have found greater visuomotor priming effects when there was correspondence between the effector used by both the model and the observer (Heyes et al., 2005) may suggest that the choice of using effector correspondence provides the ideal method for revealing visuomotor priming effects.

In conclusion the present study identifies new conditions for the study of the dysfunctional imitative processes in autism by looking at automatic 'implicit' imitation rather than explicit imitation. Importantly, it reveals that the use of robots may trigger in children with autism automatic imitative mechanisms. This may prove to be important for the rehabilitation of the imitative functions in children with autism.

Acknowledgments

Support for this work was provided by a grant from the Italian Ministry of Research (MUR) and the Wellcome Trust to UC. Our sincere thanks to the children and parents who participated in the study. We also thank Dr. Cristina Becchio and Prof. Chris Frith for their comments on previous versions of this manuscript.

References

Baron-Cohen, S. (2006). The hyper-systemizing, assortative mating theory of autism. *Progress in Neuro-Psychopharmacology & Biolological Psychiatric*, *30*, 865–872.

Boddaert, N., Chabane, N., Gervais, H., Good, C. D., Bourgeois, M., Plumet, M. H., et al. (2004). Superior temporal sulcus anatomical abnormalities in childhood autism: A voxel-based morphometry MRI study. *NeuroImage*, *23*, 364–369.

Castiello, U., Lusher, D., Mari, M., Edwards, M. G., & Humphreys, G. W. (2002). Observing a human or a robotic hand grasping an object: Differential motor priming effects. In W. Prinz & B. Hommel (Eds.), *Common mechanisms in perception and action*. Cambridge: MIT.

Craighero, L., Fadiga, L., Umiltà, C., & Rizzolatti, G. (1998). Evidence for visuomotor priming effect. *NeuroReport*, *20*, 347–349.

Dapretto, L., Davies, M. S., Pfeifer, J. H., Scott, A. A., Sigman, M., Bookheimer, S. Y., et al. (2006). Understanding emotions in others: Mirror neuron dysfunction in children with autism spectrum disorders. *Nature Neuroscience*, *9*, 28–30.

Edwards, M. G., Humphreys, G. W., & Castiello, U. (2003). Motor facilitation following action observation: A behavioural study in prehensile action. *Brain & Cognition*, *53*, 495–502.

Fadiga, L., Fogassi, L., Pavesi, G., & Rizzolatti, G. (1995). Motor facilitation during action observation: A magnetic stimulation study. *Journal of Neurophysiology*, *73*, 2608–2611.

Frith, U. (1989). *Autism: Explaining the Enigma*. Oxford: Basil Blackwell.

Gallese, V. (2006). Intentional attunement: A neurophysiological perspective on social cognition and its disruption in autism. *Brain Research Reviews*, *1079*, 15–24.

Gallese, V., & Goldman, A. (1998). Mirror neurons and the simulation theory of mind-reading. *Trends in Cognitive Science*, *2*, 493–501.

Gallese, V., Keysers, C., & Rizzolatti, G. (2004). A unifying view of the basis of social cognition. *Trends in Cognitive Science*, *8*, 396–403.

Hadjikhani, N., Joseph, R. M., Snyder, J., & Tager-Flusberg, H. (2006). Anatomical differences in the mirror neuron system and social cognition network in autism. *Cerebral Cortex*, *16*, 1276–1282.

Hamilton, A., Brindley, M. R., & Frith, U. (2007). Imitation and action understanding in autism spectrum disorders: How valid is the hypothesis of a deficit in the mirror neurons system. *Neuropsichologia* (E-pub ahead of print).

Heyes, C. M., Bird, G., Johnson, H., & Haggard, P. (2005). Robotic movement elicits automatic imitation. *Cognitive Brain Research*, *22*, 233–240.

Hobson, R. P., & Lee, A. (1999). Imitation and identification in autism. *Journal of Child Psychology and Psychiatry*, *40*, 649–659.

Iacoboni, M., & Dapretto, M. (2006). The mirror neurons system and the consequences of its dysfunction. *Nature Reviews Neuroscience*, *7*, 942–951.

Lord, C., Risi, S., Lambrecht, L., DiLavore, P. C., Pickles, A., & 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*, 205–223.

Lord, C., Rutter, M., & Le Couteur, A. (1994). Autism Diagnostic Interview—revised: A revised version of a diagnostic interview for caregivers of individuals with possible pervasive developmental disorders. *Journal of Autism and Developmental Disorders*, *24*, 659–685.

Nielsen, M. (2006). Copying actions and copying outcomes: Social learning through the second year. *Developmental Psychology*, *42*, 555–565.

Oberman, L. M., Hubbard, E. M., McCleery, J. P., Altshuler, E. L., Ramachandran, V. S., & Pineda, J. A. (2005). EEG evidence for mirror neuron dysfunction in autism spectrum disorders. *Cognitive Brain Research*, *24*, 190–198.

Pacherie, E., & Dokic, J. (2006). From mirror neurons to joint actions. *Journal of Cognitive Systems Research*, *7*, 101–112.

Pierno, A., Mari, M., Georgiou, I., Glover, S., & Castiello, U. (2006). Failure to read motor intentions from gaze in children with autism. *Neuropsychologia*, *44*, 1483–1488.

Rizzolatti, G., Fogassi, L., & Gallese, V. (2001). Neurophysiological mechanisms underlying the understanding and imitation of action. *Nature Reviews Neuroscience*, *2*, 661–670.

Robins, B., Dautenhahn, K., Dickerson, P., & Stribling, P. (2004). Robot-mediated joint attention in children with autism. *Interaction Studies*, *5*, 161–198.

Rogers, S. J., & Bennetto, L. (2000). Intersubjectivity in autism: Roles of imitation and executive function. In A. M. Wetherby & B. M. Prizant (Eds.), *Autism Spectrum Disorders; A transactional developmental perspective* (pp. 79–108). Baltimore: Brookes.

Rogers, S. J., Hepburn, S. L., Stackhouse, T., & Wehner, E. (2003). Imitation performance in toddlers with autism and those with other developmental disorders. *Journal of Child Psychology and Psychiatry*, *44*, 763–781.

Rogers, S. J., & Pennington, B. F. (1991). A theoretical approach to the deficits in infantile autism. *Developmental Psychopathology*, *3*, 137–162.

Schopler, E., Reichler, R., & Rochen Renner, B. (1993). *Childhood Autism Rating Scale*. Los Angeles: Western Psychological Services.

Sigman, M., Dissanayake, C., Corona, R., & Espinosa, M. (2003). Social and cardiac responses of young children with autism. *Autism*, *7*, 205–216.

Smith, I. M., & Bryson, S. E. (1994). Imitation and action in autism: a critical review. *Psychological Bulletin*, *116*, 259–273.

Theoret, H., Halligan, E., Kobayashi, M., Fregni, F., Tager-Flusberg, H., & Pascual-Leone, A. (2005). Impaired motor facilitation during action observation in individuals with autism spectrum disorder. *Current Biology*, *15*, 84–85.

Uzgiris, I. (1981). Two functions of imitation during infancy. *International Journal of Behavioural Development*, *4*, 1–12.

Wants, S. C., & Harris, P. L. (2002). How do children ape? Applying concepts from the study of non-human primates to the developmental study of 'imitation' in children. *Developmental Science*, *5*, 1–13.

Werry, I., Dautenhahn, K., Ogden, B., & Harwin, W. (2001). Can social interaction skills be taught by a social agent? The role of a robotic mediator in autism therapy. In M. Beynon, C. L. Nehaniv, & K. Dautenhahn (Eds.), *Cognitive Technology: Instruments of Mind: 4th International Conference, CI 2001*, Warwick, UK, August 6–9, 2001, Proceedings//(pp57–74). Berlin,//Springer.

William, J. H. G., Whiten, A., Suddendorf, T., & Perrett, D. I. (2001). Imitation, mirror neurons, and autism. *Neuroscience and Biobehavioural Reviews*, *25*, 287–295.

Zajonc, R. B. (1965). Social facilitation. *Science*, *149*, 269–274.

Zajonc, R. B., Heingartner, A., & Herman, E. M. (1969). Social enhancement and impairment of performance in cockroach. *Journal of Personality and Social Psychology*, *13*, 83–92.