Anticipatory gaze in human-robot interactions

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ABSTRACT

Our interactions with the world and with other individuals are strongly dependent on the way we move our eyes. A particular phenomenon occurring during action observation is proactive gaze behavior: the observer's gaze anticipates the forthcoming goal of the observed movement rather than reactively tracking the demonstrator's motion. Interestingly, the appearance of anticipatory saccades during action observation seems to be tightly connected to a motor resonance mechanism, that is to a direct mapping between the observed action and the motor repertoire of the observer. In other words, gaze predictivity would indicate that we have recognized the agent as conspecific, or at least as an interaction partner who could share our same goals and same actions. With the aim of evaluating the naturalness of human-robot interactions and to test if a robotic model is able to induce motor resonance as a human demonstrator, we compared gaze behavior when participants observed a human and the humanoid robot iCub performing a simple object - transport task. Since participants showed a very similar anticipatory gazing pattern when observing the human and the robotic stimuli, we concluded that proactivity in gazing is a very robust mechanism in our brain, which can be evoked also by a robotic model. Moreover, this kind of study introduces the measure of proactive gaze behavior as a powerful tool to understand which elements in the robotic implementation let the robot be perceived as an interactive agent rather than a mechanical tool.

Keywords

Proactive Gaze, Anticipation, Motor Resonance

1. INTRODUCTION

It is generally said that "Eyes are the mirror of the soul", as a person's thoughts can be ascertained by looking in his eyes. Recent researches have shown that this proverb could carry a deeper meaning than it is usually thought. In fact, observing how a person's gaze moves can actually give insights not only about his conscious thinking or his feelings, but also on the mechanisms at the basis of his understanding of the world. Indeed, several authors have demonstrated that during the observation of a goal-directed action the gaze reaches the action target well ahead than the actor's hand [4, 3]. This predictivity, however, occurs only when the interaction between human and object is visible, and disappears when the object moves by itself. The authors explained these findings in the framework of the direct matching hypothesis [16], suggesting that action observers implement covert action plans that correspond to those executed by the actor. Proactive gaze behavior would therefore represent a sign of the activation of the mirror neuron system, a set of cortical networks that serves fundamental functions, as understanding others' intentions or learning by imitation [15]. This finding would imply that the appearance of proactive gaze is associated to our mapping on our motor repertoire the action of someone we are observing. This link between perception and action is known as motor resonance and it has been suggested to be the behavioral expression of mirror neuron system activity [14]. Thus, this automatic gaze-driving mechanism would indicate that we have recognized the agent as conspecific, or at least as an interaction partner who could share our same goals and same actions - and not as an object. If this can appear trivial in the case of human-human interactions, it becomes interesting when human-robot interactions are taken into account. The phenomenon of motor resonance - which is thought to be at the basis of gaze proactivity - in the last decade has been investigated also in presence of humanoid robots (see for instance [1, 18] for reviews). Behavioral, neuroimaging and neurophysiological experiments have addressed the question whether mirror neurons could be activated by the observation of a robotic agent (e.g., [12, 5, 9, 19]) with contrasting results. The analysis of gaze patterns during the observation of a robot performing simple actions could shed some further light on how humanoid robots are perceived by the human brain. In this work we evaluated whether the observation of a robotic actor might evoke proactive gaze behavior in the observer. In particular, we considered a simple "object - transport" task, usually adopted in gaze studies (e.g. [3]) and we replaced the human action demonstrator with the iCub robotic platform [11]. This study could represent a fundamental basis to understand the plausible requisites of robot appearance and motion type to allow for human-humanoid motor resonance to occur.

2. BACKGROUND

Flanagan and Johansson [4] demonstrated that when subjects observe an object manipulation task, their gaze predicts forthcoming events rather than reactively tracking actor's motion. They asked subjects to perform or observe a block-stacking task and found out that the coordination between observer's gaze and actor's hand was very similar to the visuo-manual coordination adopted during action execution. In fact, in both cases gaze was directed to subsequent action goals, represented, in this task, by the places where blocks were grasped or released. Interestingly, however, when the hands moving the object could not be seen, the observer's gaze did not anticipate objects behavior anymore, but started tracking the moving blocks and being reactive rather than predictive. The authors explain these findings in terms of a motor resonance mechanism, suggesting that action observation activates in the observer the same action plans he would have adopted in action execution. A further study brought evidence in favor of this hypothesis investigating gaze behavior in infants ranging from 6 months to 12 months of age [3]. The choice of this particular age range was made to confront subjects who have already mastered a grasp and transport action (12-months-olds) with a control group who did not (6-months-olds), though being able to show predictive behaviors (6-months-olds can anticipate the reappearance of temporary occluded objects [17]). According to the mirror system hypothesis, proactive gaze reflects the mapping of observed actions onto one's own representation of the same actions. Thus, the development of gaze predictivity should follow action development. The authors found that during the observation of a grasp and transport action the 12-months-olds focused on goals as the adults did, while 6 months olds did not. These results and the fact that predictivity appeared only when the agent moving the object was visible (and not when objects moved alone), provided further support to the hypothesis of a role of the mirror system in the emergence of proactive gaze.

The explanation of gaze proactivity in terms of mirror system activation has been challenged by Eshuis et al. [2], who suggested that the tendency to anticipate others' goals might not be mediated by a direct matching process, but rather would depend on a general expectation that humans behave in a goal-directed and rational manner (teleological processing). Actually, infants show both teleological and direct matching processing, but goal anticipation with gaze has been proved to depend only on the latter [8]. Indeed, Gredebaeck and colleagues demonstrated that when 6- and 12-months-olds are presented with feeding actions performed in non-rational manner, only twelve-months-olds, who had a longer experience in being fed, anticipate with their eyes the action goal. Nevertheless, both groups react with surprise to the irrationality of the behavior, suggesting the existence of dissociation between teleological processing and the direct matching mechanism. Interestingly, the degree of gaze anticipation correlated significantly with the experience in being fed. A similar correlation has also been found between manual ability and the ability to anticipate the goal of others' actions [7]. Toddlers (between 18 and 25 months of age) who were good at solving a puzzle were also more proficient at anticipating the goal of similar actions performed by others. These findings are in favor of the theory that goal anticipation is facilitated by a matching process that maps the observed action onto one's own motor representation of that action. It emerges therefore that proactive gaze behavior is tightly connected to the activation of the mirror neurons system. Thus, measuring the appearance of an anticipatory gazing pattern can be considered a sign of the occurrence of the motor resonance mechanism, which mirror neurons subserve [1]. In our experiment, we replicated a protocol similar to the one adopted by Falk-Ytter et al. [3] to study gaze proactivity in young infants. In the task subjects' gaze was monitored during the observation of an agent performing transport-and-release-into-target movements. In this and in a previous study [4] gaze has been shown to arrive on target in advance of demonstrator's hand when the object is transported by a human actor. On the contrary, the observer's eyes follow the object when it moves by itself, as if it were self propelled. Here we assessed how gazing behavior changed when the actor was a human and when he was replaced by a humanoid robot moving with a biological motion. If no motor resonance is evoked by robot observation, we might expect subjects to follow with their eyes the robot hand transporting the object. Otherwise, we should observe an anticipatory pattern of eyes movements. Each of these results can give us insights about the role of agents' appearance in eliciting mirror neuron system activation and, in turn, gaze proactivity.

3. METHODS

3.1 Subjects

Ten right-handed subjects (2 women and 8 men, M=31 years, SD=13) took part in the experiment. All subjects were healthy, with normal or corrected to normal vision, and did not present any neurological, muscular or cognitive disorder. The participants gave informed consent prior to testing. All experiments were conducted in accordance with legal requirements and international norms (Declaration of Helsinki, 1964).

3.2 The humanoid robot

We used the humanoid robot iCub [10] as demonstrator and we made him repeatedly perform grasp-transport and release actions in front of the observer. iCub is a humanoid robot developed as part of the EU project RobotCub and subsequently adopted by more than 20 laboratories worldwide. It is approximately 1m tall with the appearance of a 3.5 years old child. The upper body has in total 38 degrees of freedom: 7 for each arm, 9 for each hand, and 6 for the head. Each hand has three independent fingers while the fourth and fifth are driven by a single motor and are mainly used for additional stability and support. The hand is fully tendon-driven. Seven motors are placed remotely in the forearm and all tendons are routed through the wrist mechanism (a 2 DOF differential joint). The thumb, index, and middle finger are driven by a looped tendon in the proximal joint. Each joint is instrumented with positional sensors, in most cases using absolute position encoders. A set of DSP-based custom designed control cards takes care of the low-level control loop in real-time. The DSPs communicate with each other via a CAN bus. Four CAN bus lines connect the various segments of the robot. All sensory and motor-state information is transferred to an embedded Pentium based PC104 card that handles synchronization and reformatting of the various data streams. Time consuming computation is typically carried out externally on a cluster of machines. The communication with the robot occurs via a Gbit Ethernet connection. As we wanted to use the robot's right arm and hand to produce grasping, release and transport movements, we commanded only the right arm and the torso joints to generate the movement. To avoid any balancing issue, the robot was mounted from the back. To generate the transport movement the robot had to track the end point Cartesian trajectories captured from human motion. The grasp and release actions were instead realized with a fast, position controlled, stereotyped closing and opening of the fingers. To produce robot's hand trajectories, we collected at 250 Hz the human transport movement by means of an infrared marker positioned on the hand of a human actor (Optotrak Certus System, NDI). Then, we downsampled the data of a factor of 5 and we roto-translated them to match the coordinate system of the iCub hand, so that the points in the trajectory belonged to the workspace of the robot. The end effector coordinates were then transformed into torso and arm joint angles solving the inverse kinematics by means of nonlinear constrained optimization [13]. A velocity-based controller was used to track the transformed trajectories. Tracking achieved was satisfactory for our purposes as the robot movements were human-like for a human observer (see Fig.1C).

3.3 Experimental paradigm

Subjects sat comfortably on a chair at about 75 cm from the action plane, with their chin positioned on a chin rest. They wore an Eyelink helmet, provided of a scene camera located in correspondence to the center of their forehead. The scene was a table top on which an object (little octopus pelouche) and a vase (the target) were placed at a distance of about 40 cm. The work area was individuated by two vertical bars, which also held the four infrared markers needed by the Eyelink to compensate for head movements. At the beginning of each trial the object was set into a predefined starting position on the right side of the scene. Then the demonstrator, either a human actor or the robot iCub, grasped the object with his right hand and transported and released it into the target (Fig.1).

During the whole movement the eyes of the demonstrator were hidden from view, to avoid the presence of any cue except object motion. A screen behind the demonstrator provided a uniform background. To replicate the setup described in Falck-Ytter et al. [3] and maximize the probability to obtain gaze proactivity (as suggested by the results by Eshuis et al. [2]) we attached to the vase a little toy which produced a sound at object arrival. The Eyelink system recorded binocularly at 250 Hz gaze motion and projected in real time gaze position on the video recorded by the scene camera. The camera was arranged in order to

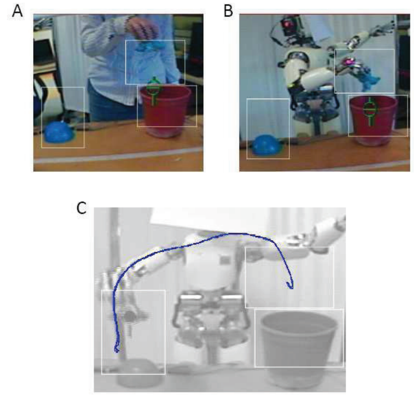

Figure 1: Sample action presentations in the human (A) and the robotic (B) conditions. The rectangular zones indicate Areas of interest (AOI). C: Sample trajectories of the robotic hand.

frame the working plane. An alignment procedure assured that gaze and camera images were correctly superimposed. Before each recording session a standard 9 points calibration procedure was performed on the movement plane. The calibration was then validated and replicated, in case the average error for the worst eye was over 0.8 visual degrees. In addition, a depth correction procedure was realized to map eye motion on the camera scene also in presence of fixations outside the calibration plane. All these procedures were performed through the SceneLink application (SR Research) provided with the Eyelink system. The experiment was composed by two sessions. During the first session the demonstrator was the robot iCub who repeated for 8 times the grasp-transport and release action, from the same starting position to the vase, with a biological motion (see Sec. 3.2). During the second session the robotic demonstrator was replaced by the experimenter, who replicated the task. The choice to have always the robotic demonstrator first was taken to avoid people being forced to perceive the robot as human due to a pre-exposure to the human actions. The robotic movement was recorded on the video, while, at the same time, the coordinates of the end effector were saved on a file. At the beginning of each movement part (grasp/start movement/ object release) a change in color of a small image in the periphery of the image occurred to allow for an easier movement segmentation during data analysis.

3.4 Data analysis

The analysis was mainly based on videos which recorded both actors' movements and observers' gaze position. Each video (720x480 pixel size, 29.97 fps) was manually segmented into different parts (one for each transport movement) in Adobe Premiere 6.5. The Eyelink Data Viewer software was adopted to analyze gaze movements in detail and to define Areas of Interests (AOI), which were afterward overlaid on the video. We individuated three AOIs (90 x 126 pixel each, corresponding to about 9.3 x 13 °); one covering the objects starting position (*hand start*), one covering the end position of the hand before leaving the object (*hand stop*) and one covering the vase (*goal area*). Gaze was measured during each movement of an object to the target. Data were included in the analysis if subjects fixated at least once the *goal area* up to 1000 ms after the object disappeared into the vase. Two subjects never looked at the *goal area*, either keeping an almost stable fixation during the whole experiment or continuously tracking the demonstrator's hand without ever looking at the object. Their data were therefore discarded from all subsequent analysis, which were conducted on a total of 8 subjects. To compute gaze anticipation or delay, the timing of subjects' fixation shift to the *goal area* was compared to the arrival time of the object. If gaze arrived at the *goal area* before the object, the trial was considered predictive (positive values). To evaluate the amount of anticipation, for each trial we computed the proportion of anticipation, that is the difference between the time of object and gaze arrival on target, divided by movement duration. Movement duration was computed as the time after the object left the area *hand start* and the time the object entered the *goal area*. To statistically compare the degree of anticipation during human and robot observation, the proportion of anticipation and the percentage of anticipatory trials in the two conditions were subjected to t-test analysis. To compensate for the difference in the timing of the release action between human and robot hand (the opening of the robotic hand lasted longer than the opening of the human hand), in the robotic condition the arrival time of the object into the *goal area* was replaced by the time when the hand stopped over the vase.

4. RESULTS AND DISCUSSION

As a first measure we wanted to verify which kind of gaze behavior is associated to the observation of goal directed actions performed by a humanoid robot. Falk-Ytter et al. [3] demonstrated that self propelled objects do not elicit proactive gaze, even when they move with a biological kinematics and are directed toward a target. Human action, on the opposite, evokes a significant anticipatory gaze behavior. We then looked at the proportion of trials in which observer's gaze was anticipatory and we quantified anticipation as the ratio of the time passed between observer's gaze arrival into the *goal area* and the end of the movement of the robotic arm over movement duration. The robotic movement lasted around 3 s (M=2.8, SD=0.09). On average subjects showed an anticipatory behavior, with a mean percentage of 70% (M=70, SD=33) of anticipatory trials and with gaze anticipating actor's hand on average the 30% of trial duration (M=27, SD=25, see Fig.2 A).

If the robot had been perceived as an inanimate device, we would have expected a tracking behavior, with the eyes of the observer following the movement of the hand [4]. This would have been translated into negative or near zero values of the measured anticipation (see sec.3.4). Instead, average anticipation (normalized by movement duration) was significantly greater than 0 (one tailed one sample *ttest*, $t(7)=3.05$, $p<0.01$), indicating the presence of proactive gaze behavior, at least in the majority of subjects.

Some individuals, however, showed a tracking behavior. To understand whether this absence of anticipation was due to the presence of the robot as actor or rather to different causes, we analyzed the proportion of anticipation and the percentage of anticipatory trials during the observation of human executing actions similar to the ones previously performed by the robotic demonstrator. In Fig.2 B are shown the percentage of anticipatory trials and the amount of anticipation (in proportion to movement duration) for each subject in this "human" condition. The pattern was similar to the one measured for the observation of robotic actions: those few subjects who assumed a tracking behavior during robot observation did the same also during human observation. This suggests that the disappearance of anticipation was not due to the presence of a robotic artifact as demonstrator, but rather to other factors which modulate gazing behavior also during human action observation. This finding replicates the results by Gesierich et al. [6], which showed that half of their sample presented in tendency a tracking behavior during action observation (moving virtual blocks on a computer screen). The authors suggest that this could occur as some subjects, when they realize that the study will depend on their gaze analysis because of the calibration procedures, become convinced of the necessity of tracking the moving agent, as if it were a non-said task constraint.

To assess whether the presence of a robotic demonstrator causes a quantitative difference in gazing strategy we compared the percentage of anticipation trials in the "human" and the "robotic" condition. Though a tendency to increase prediction appears for the human condition, no significant difference is present (paired sample *ttest*, $t(7)$=1.43,p>0.05). The timing of the human action was more variable than the robotic one and in general shorter: average human movement duration was around 2.5 s (M=2.4, SD=0.4), while average robot movement duration lasted a little less than 3 s (M=2.8, SD=0.09). To compensate for a possible subjective effect of this difference on the amount of anticipation between human and robotic action observation, we fitted linearly the proportion of anticipation over movement duration for all trials in the human condition, for each subject. Then, we extrapolated the proportion of anticipation in the human condition for a trial duration corresponding to the average robotic movement duration for that subject. Lastly, we replaced the anticipation measured in the "human" condition with this corrected estimate. The results are plotted in Fig.3. As it emerges clearly from the figure, no difference in gazing behavior appears when the actor is a human or a humanoid robot (paired sample *ttest*, $t(7)$=1.15,p>0.05).

Thus, our results suggest that motor resonance, in the form of anticipatory gaze behavior, occurs during humanoid robot observation as much as during human agents observation.

5. CONCLUSIONS

In our series of experiments we investigated how a humanoid robot performing an action is perceived by the human brain. The question was whether a robotic model is able to induce motor resonance as a human actor would or, on the contrary, it is perceived as a self moving object, which does not evoke mirror activation and proactive gaze. To address this interrogative we replicated an experiment originally performed with a human demonstrator, replacing him with the humanoid robot iCub [11]. The results showed an anticipatory behavior completely similar to the one measured during the observation of human actions. In sum, proactivity in gazing is a very robust mechanism in our brain, which is evoked even in presence of differences between the observed action and the motor program available to the observer, as large as a change of the actor appearance from human to robotic. Probably this robustness is due to the great relevance of anticipatory mechanisms in our every-

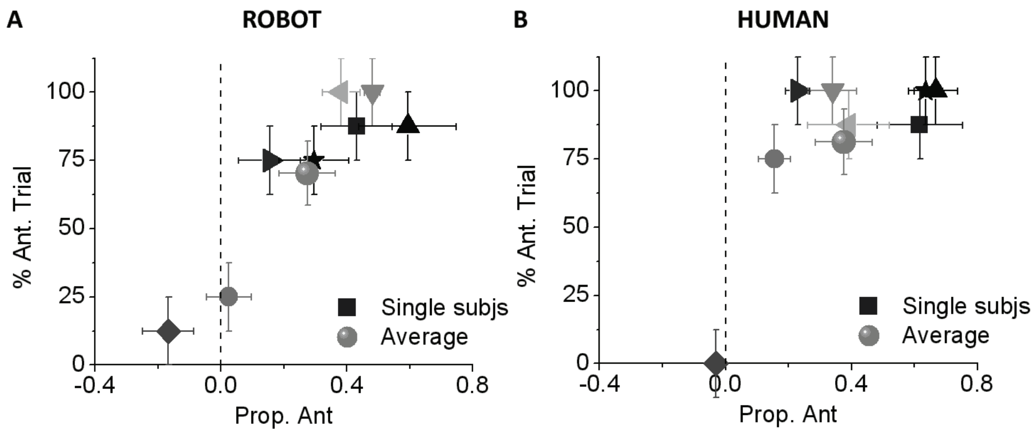

Figure 2: Gaze behavior during the observation of robotic (A) and human (B) actions. Percentage of anticipation (percentage of trials in which gaze is arrived to target before actor's hand) plotted against anticipation measured as proportion of movement duration. Different small symbols represent different subjects. The larger sphere indicates the population average. Error bars correspond to standard errors. The dashed line indicates 0 anticipation, approximately corresponding to a tracking gaze behavior.

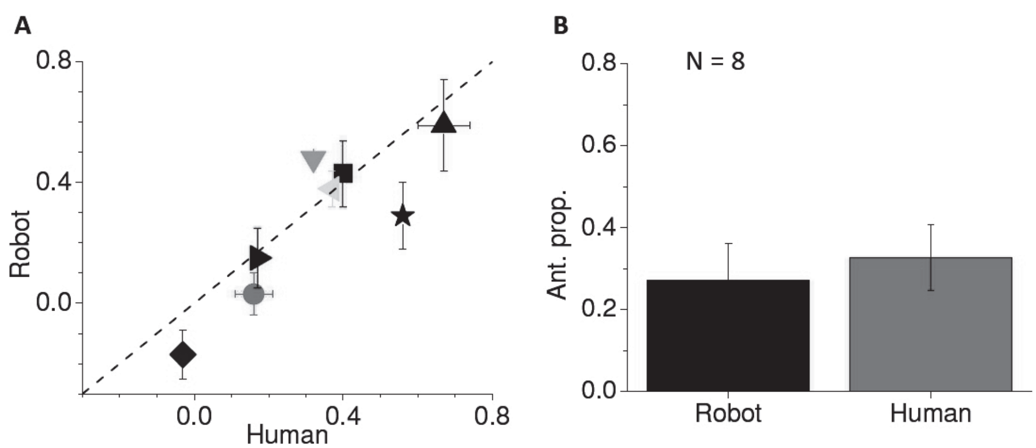

Figure 3: Human - Robot comparison. Amount of Anticipation (measured as proportion of movement duration). A: Single subjects' proportion of anticipation during the observation of robotic actions plotted against the corresponding proportion of anticipation during the observation of human actions. "Human" values have been corrected for movement duration differences between robotic and human conditions (see text for details). Error bars represent within subject standard error. Different symbols represent different subjects. The dashed line individuates the identity line: if a data point lies under this line, the proportion of anticipation for that subject is higher in the "human" condition than in the "robot" one. B: Average anticipation proportion across subjects, in the "robot" and the "human" actor conditions. Error bars represent standard error of the mean of the population.

day life. Indeed, in absence of such a predictive system, we would be unable to proficiently interact with other people, due to the intrinsic neuro-muscular delays of our body.

This work describes the first attempt to assess HRI by monitoring subjects' gaze anticipatory patterns during robot observation. Indeed, this kind of study introduces the measure of proactive gaze behavior as a powerful tool to understand which elements in the robotic implementation let the robot be perceived as an interactive agent rather than a mechanical tool. The need of naturally interacting robots is becoming always more urgent with the progressive development of humanoid robotic platforms. This requirement implies the necessity of designing not only new controls for robot behavior, but also new evaluation methods to assess quantitavely how the robot is perceived by the human counterpart. The measure of motor resonance, either by means of neuroimaging or by behavioral studies, could represent a very good candidate validation procedure [1]. Indeed, it does not require a cognitive evaluation of the shape or of the behavior of the robot, but directly measures the natural, unconscious effects of the observation of robotic actions. We suggest the monitoring of gaze behavior as an innovative and convenient behavioral measure of motor resonance. The advent of newer and more comfortable head mounted tracking systems will in the future make this procedure an even more convenient and versatile validation tool of human-robot interactions.

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7. REFERENCES

[1] T. Chaminade and G. Cheng. Social cognitive neuroscience and humanoid robotics. *J Physiol Paris*, 103(3-5):286–295, 2009.

[2] R. Eshuis, K. R. Coventry, and M. Vulchanova. Predictive eye movements are driven by goals, not by the mirror neuron system. *Psychol Sci*, 20(4):438–440, Apr 2009.

[3] T. Falck-Ytter, G. Gredebäck, and C. von Hofsten. Infants predict other people's action goals. *Nat Neurosci*, 9(7):878–879, Jul 2006.

[4] J. R. Flanagan and R. S. Johansson. Action plans used in action observation. *Nature*, 424(6950):769–771, Aug 2003.

[5] V. Gazzola, G. Rizzolatti, B. Wicker, and C. Keysers. The anthropomorphic brain: the mirror neuron system responds to human and robotic actions. *Neuroimage*, 35(4):1674–1684, May 2007.

[6] B. Gesierich, A. Bruzzo, G. Ottoboni, and L. Finos. Human gaze behaviour during action execution and observation. *Acta Psychol (Amst)*, 128(2):324–330, Jun 2008.

[7] G. Gredebäck and O. Kochukhova. Goal anticipation during action observation is influenced by synonymous action capabilities, a puzzling developmental study. *Exp Brain Res*, 202(2):493–497, Apr 2010.

[8] G. Gredebäck and A. Melinder. Infants' understanding of everyday social interactions: a dual process account. *Cognition*, 114(2):197–206, Feb 2010.

[9] J. M. Kilner, Y. Paulignan, and S. J. Blakemore. An interference effect of observed biological movement on action. *Curr Biol*, 13(6):522–525, Mar 2003.

[10] G. Metta, L. Natale, F. Nori, G. Sandini, D. Vernon, L. Fadiga, C. von Hofsten, K. Rosander, M. Lopes, J. Santos-Victor, A. Bernardino, and L. Montesano. The icub humanoid robot: an open-systems platform for research in cognitive development. *Neural Netw*, 23(8-9):1125–1134, 2010.

[11] G. Metta, G. Sandini, D. Vernon, L. Natale, and F. Nori. The icub humanoid robot: an open platform for research in embodied cognition. In *PerMIS: Performance Metrics for Intelligent Systems Workshop*, 2008.

[12] E. Oztop, D. Franklin, T. Chaminade, and G. Cheng. Human-humanoid interaction: is a humanoid robot perceived as a human? *Int. J. Humanoid Robot*, 2:537–559, 2005.

[13] U. Pattacini, F. Nori, L. Natale, G. Metta, and G. Sandini. An experimental evaluation of a novel minimum-jerk cartesian controller for humanoid robots. In *IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2010.

[14] G. Rizzolatti, L. Fadiga, L. Fogassi, and V. Gallese. Resonance behaviors and mirror neurons. *Arch Ital Biol*, 137(2-3):85–100, May 1999.

[15] G. Rizzolatti, L. Fadiga, V. Gallese, and L. Fogassi. Premotor cortex and the recognition of motor actions. *Brain Res Cogn Brain Res*, 3(2):131–141, Mar 1996.

[16] G. Rizzolatti, L. Fogassi, and V. Gallese. Neurophysiological mechanisms underlying the understanding and imitation of action. *Nat Rev Neurosci*, 2(9):661–670, Sep 2001.

[17] K. Rosander and C. von Hofsten. Infants' emerging ability to represent occluded object motion. *Cognition*, 91(1):1–22, Feb 2004.

[18] A. Sciutti*, A. Bisio*, F. Nori, G. Metta, L. Fadiga, T. Pozzo, and G. Sandini. Measuring human-robot interaction through motor resonance. *International Journal of Social Robotics*, in press, 2012.

[19] Y. F. Tai, C. Scherfler, D. J. Brooks, N. Sawamoto, and U. Castiello. The human premotor cortex is 'mirror' only for biological actions. *Curr Biol*, 14(2):117–120, Jan 2004.