HUMAN-HUMANOID INTERACTION:
IS A HUMANOID ROBOT PERCEIVED AS A HUMAN?

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As humanoid robots become more commonplace in our society, it is important to understand the relation between humans and humanoid robots. In human face-to-face interaction, the observation of another individual performing an action facilitates the execution of a similar action, and interferes with the execution of different action. This phenomenon has been explained by the existence of shared internal representations for the execution and perception of actions, which would be automatically activated by the perception of another individual's action. In one interference experiment, null interference was reported when subjects observed a robotic arm perform the incongruent task, suggesting that this effect may be specific to interacting with other humans. This experimental paradigm, designed to investigate motor interference in human interactions, was adapted to investigate how similar the implicit perception of a humanoid robot is to a human agent. Subjects performed rhythmic arm movements while observing either a human agent or humanoid robot performing either congruent or incongruent movements. The variance of the executed movements was used as a measure of the amount of interference in the movements. Both the human and humanoid agents produced significant interference effect. These results suggest that observing the action of humanoid robots and human agents may rely on similar perceptual processes. Furthermore, the ratio of the variance in incongruent to congruent conditions varied between the human agent and humanoid robot. We speculate this ratio describes how the implicit perception of a robot is similar to that of a human, so that this paradigm could provide an objective measure of the reaction to different types of robots and be used to guide the design of humanoid robots interacting with humans.

Keywords: Social Robotics; Perception of Action; Motor Interference; Uncanny Valley

1. Introduction

Recent advances in humanoid robotics[1-3] brought certain social issues into consideration. It is generally accepted that humanoids will become part of our daily lives, as have computers, the internet and email. Therefore the study of how humanoids are perceived by human peers becomes an important issue if we expect them to interact with humans in human fashion[4]. There are some studies addressing the question of what kind of form[5] and functionality[6-8] a human-like robot should have in order to be socially accepted. The former relies on the introspective judgments of humans to decide how human-like the robots are perceived. The latter approach relies on the implicit assumption that if the robot has similar cognitive mechanisms as humans (e.g. gaze following) then they must be readily accepted as humanly, and mainly focus on building such robotic systems.

Here we propose a different approach, to test whether a humanoid could be treated as a human by the *perceptual system* of a human observer. We deliberately use the term 'perceptual system of human' rather than simply 'human'. This is because our paradigm uses the *implicit* behavioral *effect* caused by the observation of others' behavior. In this way, we avoid invoking higher level cognitive systems that are involved in answering introspective questions (e.g. do you think that it is a human-like movement?). In order to determine a suitable task that would enable us to tap into the implicit processing of human subjects' perception of humanoid robots, we first need to examine how human perceive others' actions.

1.1 The hypothesis of shared representations

A number of recent studies have demonstrated that the perception of another's action and the actions executed by the self are mediated by common brain areas. Experimental psychology experiments have demonstrated that perceiving a simple action, such as a finger tapping[9], grasping[10], or arm movements[11] facilitates the concomitant execution of the same action and curbs the execution of a different one. This implies that observing the actions of other individuals and executing actions are not entirely distinct processes. These results led to the hypothesis that some cognitive representations are used both in the observation and in the execution of actions. These are termed shared representations.

Similar conclusions were drawn from the study of human brain functions. 'Mirror neurons' were found in reciprocally connected ventral premotor and parietal cortices using monkey electrophysiology. These neurons are activated both when monkeys perform a goal-directed action and when they see the same action performed by an experimenter[12,13]. In humans, neuroimaging has shown that action-related cortices in the premotor and parietal cortices are activated during observation of actions[14] (see [15] for a computational model).

In addition, ventral premotor and parietal cortices are involved in imitation: In the left hemisphere the premotor cortex appears to be more involved in the goal related aspects of the action[16] whereas the parietal cortex is more involved in body movement[16,17]. Finally, one study showed that cortices involved in producing a specific action, pointing or writing, are specifically recruited when understanding the goal of another individual's pointing or writing actions[18].

Movement imitation requires various complex mechanisms for mapping an observed movement onto one's own motor planning. From a robotics point of view imitation requires the solution of several hard sub-problems including action recognition, pose estimation and tracking, body correspondence, coordinate transformation from external to egocentric space, matching of observed movement to a previously learned one, suitable movement representations for imitation, modular motor control[19]. Although the exact nature of biological motor primitives are not known, in robotic imitation usually hand tuned (perceptuo-)motor primitives are used as a means of shared representations, which form a basis set of motion serving as a vocabulary for imitating (and observing) movements[19,20].

1.2 Perception of action and motor interference

Perceiving an action interferes with the action you are executing, a phenomenon that could explain a number of social behaviors such as contagion of behaviors and synchronicity within a group. An experimental paradigm was recently introduced to investigate sensory-motor interference in face-to-face behaviors, thus reproducing a socially valid interaction[11]. It taps into implicit perceptual processing[21], which therefore can be used to assess without introspection how humanly a robot is perceived by humans. In this paradigm, subjects and the experimenter were face to face, and both produced arm movements that were either horizontal or vertical. Experimental conditions were defined by the compatibility between the two movements. Variance in the movement was increased when subjects visually follow incompatible movements of human demonstration. However, this effect was specific to watching human actions, and could not be reproduced by the observation of robot actions. We were surprised that the results were negative, i.e. the robot movement did not have similar affect as the human movement. We hypothesized that the results could be due to the robot's form (i.e. not a humanoid) and movement generation capability (i.e. not biologically realistic motion). Thus we recreated the experimental setup using human subjects and our humanoid robot that could perform human like movements. Our experiment, when contrasted with [11] can uncover whether this interference is due to the knowledge of the human nature of the other agent, or due to an automatic processing of certain features of the stimuli – (human-like) form and (biological) motion.

2. Hypotheses

2.1 Interference between perceiving and executing actions

Under the hypothesis that there is a shared substrate between perceiving and executing actions, it is predicted that observing an action should facilitate the execution of the same action, and curb the execution of a different action; results reported in the literature[11] are equivocal. Though a strong interference effect is found when subjects perform an arm movement incompatible to the one they are producing (e.g. vertical versus horizontal) defined by the increase of variance of the movement, no facilitation effect is associated with compatible movements. Kilner and colleagues found increased variance from interference during the performing of arm movements in the vertical and horizontal axes[11]. However, in the vertical movements, gravity is parallel to the axis of the movement whereas in the horizontal movements it is oriented perpendicular to the axis of movement. This could provide additional sensory information to the subjects about the accuracy of their movements which may limit their variability. In order to reduce this possible effect we reproduced the experiment with movements that were rotated by 45 degrees to the left and right, where similar forces due to gravity are present during both movements. We then test if increased variance in these movements is produced by the incongruency between the executed and observed movements, confirming that the shared substrate between perception and action is responsible for the interference effect.

2.2 Influence of the interacting agent on the interference

Interestingly, Kilner et al.'s study did not find any interference effect using a robot. They concluded that the visuomotor interference is specific to interactions between humans[11]. We aimed at testing this claim with two improvements: we used a humanoid robot, that is, its general shape is similar to the shape of a human; and the movements of the robot were reproductions of the movements of one of the experimenters. The form and motion of the robot and experimenter are similar. Therefore if human-humanoid interactions produces comparable interference effects to human-human interactions we can conclude that the effect is explained by an implicit perceptual mechanism sensitive to the general humanoid form and biological motion of the other agent. In this case the interference effect can be used to evaluate the quality of the human-humanoid interaction. In contrast, if the interference effect is absent when subjects interact with the humanoid robot then this effect must be explained by the contextual knowledge of the human nature of the agent.

3. Methods

3.1 The humanoid robot

We used the humanoid robot *DB*[3] to produce diagonal reaching movements. *DB* is a hydraulic anthropomorphic robot with legs, arms (with hands without fingers), a jointed torso, and a head (Fig. 1).

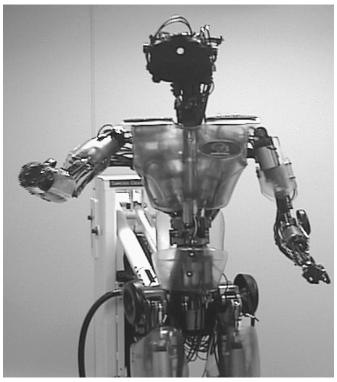
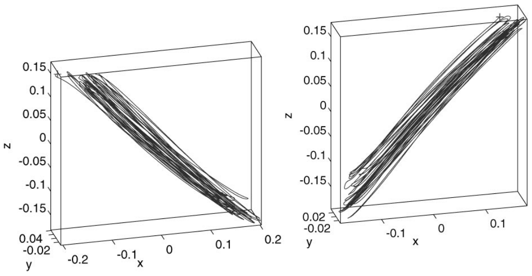


Fig. 1. DB, the humanoid robot used in our experiment

DB was designed by the Sarcos company and the Kawato Dynamic Brain Project, and built by Sarcos to be 1.85 meters tall with a human-like appearance. The robot contains 25 linear hydraulic actuators and five rotary hydraulic actuators having 30 degrees of freedom: three in the neck, two in each eye, seven in each arm, three in each leg, and three in the trunk (Fig. 1).

Our interest was to use the robot's right arm to produce diagonal movements, thus we commanded only the right arm and the torso joints to generate the movement. The robot was mounted from the back eliminating the need to deal with balancing issues. The task of the robot was to replicate the end point Cartesian trajectories recorded from human demonstrators (see next section for the data collection details) which were periodic top-left to bottom-right (L) and top-right to bottom-left (R) reaching movements involving elbow, shoulder and some torso movements.). The controller is implemented on the real-time operating system VxWorks using several parallel Motorola PowerPC processors in a VME rack within the environment provided by SL Simulation and Real-Time Control Software Package (http://www-clmc.usc.edu/publications/S/schaal-TRSL.pdf.



Top-Right to Bottom Left

Top-Left to Bottom Right

Fig. 2. The transformed human movement trajectories for each of the two movements studied. The robot was located behind the boxes enclosing the trajectories.

To produce trajectories for the robot, we first extracted the main direction of human trajectories using PCA and applied a linear transformation such that the points in the trajectory lie within the workspace of the robot as much as possible. Not all the points were reachable, so the extent of the movements was scaled by 0.95 in each direction of the robot coordinate frame allowing the robot to move without hitting its joint limits.

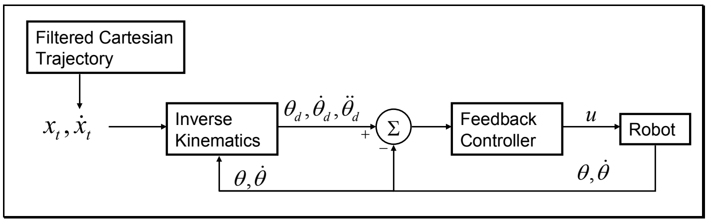


Fig. 3. Cartesian tracker used in generating the arm movements of the humanoid robot.

A velocity-based Cartesian controller was used to track the transformed trajectories shown in Fig. 2. The control scheme we used is shown in Fig. 3, where the inverse kinematics is solved using Jacobian pseudo-inverse with null space optimization[22]. We considered the tracking achieved satisfactory for our purposes as the robot movements were smooth and human-like for a human observer. Figure 4 shows the tracking in x, y and z coordinates for the two trajectories used in the experiments. Note that the plane of interest was the one spanned by x and z axes.

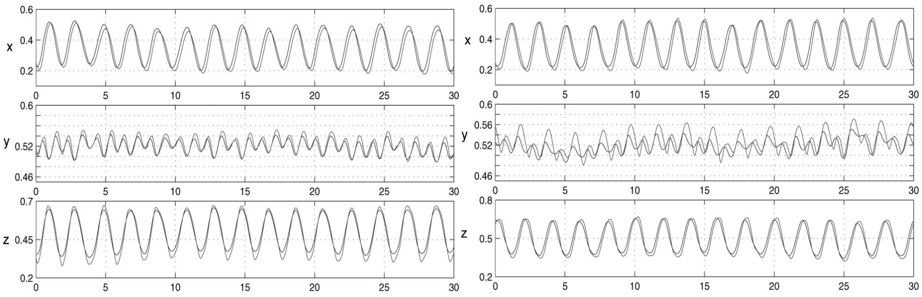


Fig. 4. Left: top-right to bottom-left movement tracking (R); Right: top-left to bottom-right tracking (L); Horizontal axis is the time, the vertical axes are x, y, and z of the robot coordinate frame (z pointing up, x pointing right, y pointing away in front of the robot; the origin is at the waist.)

3.2 Experimental paradigm

Eight naïve subjects (6 right handed; 2 left handed) (6 males; 2 females) ranging from 20-35 years of age performed rhythmic arm motions with their right arms in front of their bodies while standing. Subjects were instructed to make rhythmic arm movements across their bodies from either the top-right to the bottom-left (R) or from the top-left to the bottom-right (L) with respect to their own torso at 0.5 Hz.

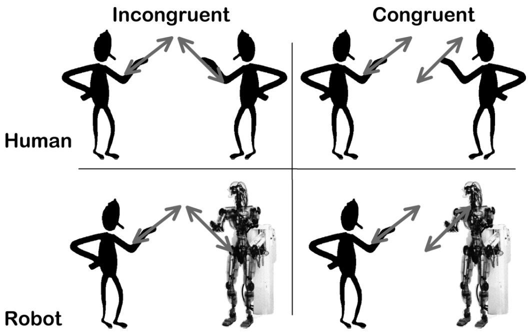


Fig. 5. The Experimental paradigm: subjects performed diagonal rhythmic movements starting either from top-left (L) or top-right (R) while tracking the hand of either a human agent or a humanoid robot performing either congruent or incongruent movements

Subjects performed these movements while standing approximately 2 meters away from either a humanoid robot or another human that was performing similar arm movements (Fig. 5). During each trial, the subjects were instructed to produce one of the two movements (R) or (L) and track the other agent's hand movement. The movements produced by the two agents were either spatially congruent (C; same direction) or incongruent (I; ninety degrees to the subject's motion). The subjects were also instructed to be in phase with the other agent's movements. For each 30 second trial, the kinematics of the endpoint of the subject's right index finger was recorded at 250 Hz using OPTOTRAK 3020 (Northern Digital, Waterloo).

The experimenters made movements at 0.5 Hz while listening to a 1 Hz beep on headphones. They kept their eyes closed to avoid reciprocal interference form the observation of the subjects' movements. Each subject performed movements in front of the robot and two experimenters, where the order of experimenter presentation was randomized across subjects. A session of the experiment, containing four conditions (R/L) x (C/I) was performed in a random order of presentation with the first experimenter, and in a reversed order with the second experimenter. The robot's arm movements were based on data recorded from one of the experimenters which were collected in the same way as for the subjects and were digitally low-pass filtered using a zero-lag, fifth-order Butterworth filter with a cut-off frequency of 25 Hz. The humanoid robot has a pair of cameras mounted at the top of the head that could be perceived as human eyes. It is not possible to close them to reproduce the closed eyes of the experimenter in the human-human interaction conditions. In order to avoid a confounding factor a black cloth was used to cover the robot¹s cameras.

3.3 Analysis

The three dimensional trajectories of each marker were digitally low-pass filtered using a zero-lag, fifth-order Butterworth filter with a cut-off frequency of 25 Hz. Each movement was segmented from the surrounding movements using the 3D curvature[23] (c(t)) where:

$$c(t) = \frac{\sqrt{\|\dot{x}(t)\|^2 \|\ddot{x}(t)\|^2 - \left(\dot{x}(t)^T \ddot{x}(t)\right)^2}}{\|\dot{x}(t)\|^3} \qquad (1)$$

This measure of curvature is very low when the velocity of the movement is high, but becomes very high as velocity slows and the movement changes direction. By using the measure of curvature, each upward or downward movement could be segmented from the surrounding movements for further analysis. The beginning and end of each movement was removed if the curvature was above 100 [1/m] preventing small drifts in the hand location at the extremes of movement from influencing the results. For analysis, the three dimensional kinematic data of the finger was projected onto a vertical plane containing the main axis of the movement (Vertical) and an orthogonal plane containing the main axis of the movement (Horizontal).

In order to quantify the effects of the conditions on the behavior of the subjects, we calculated the signed area of each movement defining the deviation from the straight-line joining the start and end of each segmented movement[24]. This area was calculated separately in the vertical and horizontal planes. To estimate the variability of the behavior within each 30-second trial, the variance of the signed area of movement segments was calculated. An ANOVA examined the main effect of movement (R/L) and congruency (C/I) with random effects of subjects on the variability in each of the two planes. The ANOVA considered first and second level interaction effects, significant at the alpha 0.05 level.

4. Results

In accordance with Kilner et al.'s[11] study, subjects' movements were projected on the vertical and horizontal planes. The rationale is that the main direction of the movement is comprised in the vertical plane, in which instructions require subjects to perform top-left to bottom-right and top-right to bottom-left movements, while no instruction specifies the direction of the movement in the horizontal plane. In addition, the curvature of the movements' projection on the horizontal plane reflects biomechanical constraints, and since subjects and the experimenter or humanoid robot are facing each other, the movements are similarly incongruent in all conditions in the horizontal plane.

In the vertical plane, the ANOVA on the variability of the behavior (variance of the signed area for each trial) showed a significant effect of the congruency for both interaction with the human agent and the humanoid robot (Table 1). There was no effect of the movement or of the interaction between congruency and movement for either the human agent or the humanoid robot. In contrast with the vertical plane, there was no significant effect for congruency or the interaction in the horizontal plane for both agents. This indicates that the effect of congruency on the variability of the behavior is specific to the vertical plane.We have no satisfactory explanation for the significant effect of the movement direction on the variance when subjects interacted with the robot.

Table 1. Results from the ANOVA examining the variability of the signed area in the vertical plane

Effect	**Human**		**Robot**	
	F	***p***	**F**	***p***
Congruency	4.31	0.04	4.89	0.03
Movement	2.12	0.15	0.49	0.49
Congruency x Movement	0.43	0.52	2.64	0.11

Table 2. Results from the ANOVA examining the variability of the signed area in the horizontal plane

Effect	**Human**		**Robot**	
	F	***p***	**F**	***P***
Congruency	0.36	0.55	3.14	0.08
Movement	2.66	0.11	5.49	0.02
Congruency x Movement	0.22	0.64	0.91	0.34

The averages of variability for Congruent and Incongruent movements are shown on Fig. 6 for interaction with human (A) and robot (B). The scale in graphs A and B of figure 6 reveals an increase of the variance during interaction with human agents in comparison to the humanoid robot. Since subjects' instructions were similar in both conditions, a possible explanation should involve the other agent's movement. For instance a reduced variability of the robot's movements in comparison to humans' would be a possible candidate. Yet for mechanical reasons the robot movement span was smaller than the human's, which could also explain the reduction of the subject's movement variance. Thus we cannot satisfactorily conclude on the difference of the subject's variance scale visible on Figure 6.

There is an increase of the variability in the incongruent conditions for both human agent and humanoid robot. The ratio between the incongruent and congruent conditions was higher when subjects interacted with the human agent (2.1:1) than with the humanoid robot (1.4:1).

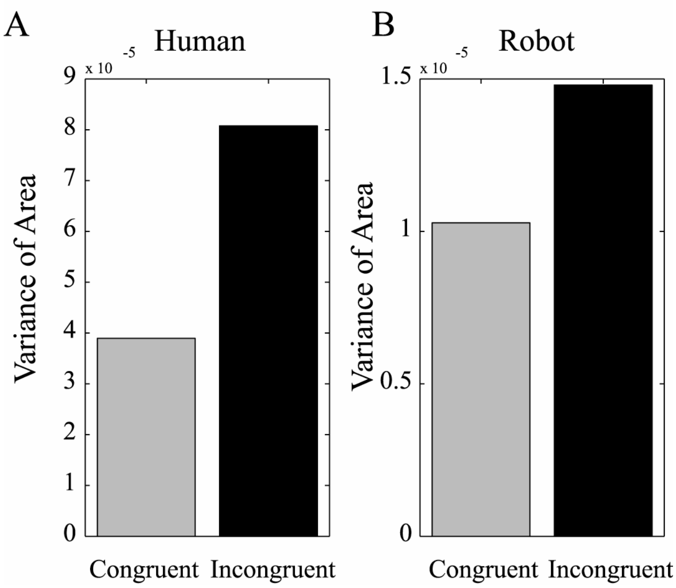


Fig. 6. The average variance of the deviation area for human (left panel) and robot (right panel) is shown. Note that the scales of the plots are different. This effect could be due to the decrease in the average extent of the movement between the human (0.63 m) and the robot (0.47 m) agents.

5. Discussion

5.1. An objective tool to assess human perception of robots

Robots designers currently rely on the assumption that anthropomorphic robots would be more competent in social interactions because humans would interact intuitively with them[4]. However this assumption is widely unexplored, especially considering the conflicting hypothesis called the 'uncanny valley' introduced by Masahiro Mori[4]. For this roboticist, the relation between human empathic reaction and anthropomorphism of the robot does not show a monotonic increasing curve, but presents a sharp chasm, indicating a strong negative reaction, before reaching the exact human-likeness. Robots imperfectly attempting to reproduce humans would cause a negative reaction leading to the rejection of the robot as an interacting partner.

Despite the consequences this 'uncanny valley' hypothesis could have in the design of interacting robots, it has not been investigated scientifically, perhaps due to a lack of an objective tool to test the human reaction. Instead, designers usually rely on intuition or surveys, which can suffer from subjective biases. It is thus desirable to create a paradigm in order to assess the human reaction to the perception of robots without conscious introspection.

We contend that the experimental framework and tools developed in behavioral sciences to investigate social interactions among humans[21] could be adapted to test human interactions with robots. One prominent hypothesis in cognitive neuroscience is the existence of a common framework for execution and perception of action. A paradigm developed to investigate this common mechanism measures how an observed action interferes with the production of an action. Within this framework, we adapted a motor interference study[11], which is well suited for examining full body interactions.

5.2 Validation of the interference effect

Interference was measured as the variability of the subjects' arm movements while observing congruent and incongruent movements made by either a human agent or a humanoid robot. Movements were projected onto horizontal and vertical planes under the hypothesis that interference would only be found on the vertical plane, on which congruency was controlled. Indeed, there was a significant effect of congruency on the subjects' variability of behavior when projected on the vertical but not on the horizontal plane. For both human agent and humanoid robot, we found an increase of the variability in the incongruent conditions on the vertical plane (Fig. 6).

For human-human interactions, our results reproduce previously published data[11]. Although the paradigm was modified, our results are highly similar to this previous report, and it is remarkable that the ratio of 2.1:1 that we found between the variance of the incongruent and congruent conditions of human-human interactions is similar to the two-fold increase in variability inferred from their results[11].

In Kilner et al.'s study[11] no increase in variability was found when subjects were observing a robot performing the actions. In sharp contrast to the abovementioned study, we observe a significant effect of the incongruency for human-robot interactions. Similar to human-human interactions, the observation of incongruent movements increases the variability of the subjects' behaviors. This discrepancy could be explained by the differences between the humanoid robot used in our study, which has a human-like appearance and produced human-like movements, in contrast to the industrial robot used in Kilner et al.'s study[11] which consisted of metal shafts which moved linearly with constant velocity (personal communication).

In both studies, the value of the ratio is approximately 2:1 when interacting with the human. In contrast, the ratio is 1.4:1 when interacting with the humanoid robot, and approximately 1:1 when interacting with an industrial robot. Combining these studies, we propose that the ratio between variability in incongruent and congruent conditions could be used as an index of human-likeness perception. Further studies controlling the form of the robot, for instance using more human-like robots (influence of the face appearance), and its motion, using a gradient of movements ranging from least human-like to human-like, are needed to verify this suggestion. Yet it is striking that in these two studies, an unconscious motor effect could be explained by the human-likeness of the interfering agent.

6. Conclusion

The motor interference which is explained by the shared representation hypothesis is not specific to human-human interactions but can also be observed in human-humanoid interactions. Collectively these studies suggest that combination of the form and the motion of an agent is an important factor for the social competence of the interaction. Our next step should be to separate the relative contribution of form and motion to this interference. This study validates an effective experimental paradigm to assess a human's implicit reaction to a humanoid robot. It should now be extended to investigate and guide the design of socially competent humanoid robots.

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References

1. Adams, B., Breazeal, C., Brooks, R. A. & Scassellati, B. Humanoid Robots: A New Kind of Tool. *IEEE Intelligent Systems* **15**, 25-31 (2000).

2. Cheng, G., Nagakubo, A. & Kuniyoshi, Y. Continuous Humanoid Interaction: An Integrated Perspective - Gaining Adaptivity, Redundancy, Flexibility - In One. *Robotics and Autonomous Systems* **37**, 161-183 (2001).

3. Atkeson, C. G. et al. Using Humanoid Robots to Study Human Behavior. *IEEE Intelligent Systems* **15**, 46-56 (2000).

4. Fong, T., Nourbakhsh, I. & Dautenhahn, K. A survey of socially interactive robots. *Robotics and Autonomous Systems* **42** (2002).

5. DiSalvo, C., Gemperle, F., Forlizzi, J. & Kiesler, S. All robots are not created equal: the design and perception of humanoid robot heads. *Proceedings of the conference on Designing interactive systems: processes, practices, methods, and techniques* http://doi.acm.org/10.1145/778712.778756 (2002).

6. Scassellati, B. Foundations for a theory of mind for a humanoid robot. *B. Scassellati, Foundations for a theory of mind for a humanoid robot, Ph.D. Thesis, Dept. Elec. Eng. Comp. Sci., MIT, 2001.* (2001).

7. Kozima, H. & Yano, H. A robot that learns to communicate with human caregivers. *H. Kozima and H. Yano, A robot that learns to communicate with human caregivers, in: Proc. Intl. Wksp. Epigenetic Rob., 2001.* (2001).

8. Breazeal, C. & Scassellati, B. Infant-like Social Interactions between a Robot and a Human Caretaker. *CaretakerAdaptive Behavior* **8**, 49-74 (2000).

9. Brass, M., Bekkering, H., Wohlschlager, A. & Prinz, W. Compatibility between observed and executed finger movements: comparing symbolic, spatial, and imitative cues. *Brain Cogn* **44**, 124-43. (2000).

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

11. Kilner, J. M., Paulignan, Y. & Blakemore, S. J. An interference effect of observed biological movement on action. *Current Biology* **13**, 522-525 (2003).

12. Gallese, V., Fadiga, L., Fogassi, L. & Rizzolatti, G. Action recognition in the premotor cortex. *Brain* **119**, 593-609 (1996).

13. Rizzolatti, G., Fadiga, L., Gallese, V. & Fogassi, L. Premotor cortex and the recognition of motor actions. *Cognitive Brain Research* **3**, 131-141 (1996).

14. Grezes, J. & Decety, J. Functional anatomy of execution, mental simulation, observation, and verb generation of actions: a meta-analysis. *Hum Brain Mapp* **12**, 1-19. (2001).

15. Oztop E., Wolpert D., Kawato M. Mirror neurons: key for mental simulation? *Proceedings of Computational Neuroscience Meeting* (2003).

16. Chaminade, T., Meltzoff, A. N. & Decety, J. An fMRI study of imitation: Action representation and body schema. *Neuropsychologia* **In press** (2004).

17. Arbib, M. A., Billard, A., Iacoboni, M. & Oztop, E. Synthetic brain imaging: grasping, mirror neurons and imitation. *Neural Networks* **13**, 975-997 (2000).

18. Chaminade, T., Meary, D., Orliaguet, J. P. & Decety, J. Is perceptual anticipation a motor simulation? A PET study. *Neuroreport* **12**, 3669-3674. (2001).

19. Schaal, S., Ijspeert, A., Billard, A. Computational approaches to motor learning by imitation, Philosophical Transaction of the Royal Society of London: Series B, Biological Sciences, 358, 1431, pp.537-547 (2003).

20. Mataric, M. J., "Getting Humanoids to Move and Imitate", IEEE Intelligent Systems, 18-24 (2000).

21. Blakemore, S.-J., Winston, J. & Frith, U. Social cognitive neuroscience: where are we heading? *Trends in Cognitive Sciences* **8**, 216-222 (2004).

22. Sciavicco, L. & Siciliano, B. *Modelling and control of robot manipulators* (Springer, London ; New York, 2000).

23. Schaal, S. & Sternad, D. Origins and violations of the 2/3 power law in rhythmic three-dimensional arm movements. *Exp Brain Res* **136**, 60-72 (2001).

24. Franklin, D. W., Osu, R., Burdet, E., Kawato, M. & Milner, T. E. Adaptation to stable and unstable dynamics achieved by combined impedance control and inverse dynamics model. *J Neurophysiol* **90**, 3270-82 (2003).