16 Observing a human or a robotic hand grasping an object: differential motor priming effects

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Abstract. The present paper aims to investigate how functional connections between action and perception may contribute to our imitation of motor acts of other beings. Four experiments examined motor priming effects on imitation from biological and nonbiological effector systems. In Experiment 1 we asked subjects first to observe grasping movements performed by a human actor and by a robotic hand, and subsequently to perform the same movement. For 80% of the cases the movement performed by the primer and that performed by the subjects were directed to the same object (valid trials). For the remaining 20% of cases the subjects were required to perform an action towards an object that differed in size from the object grasped by the primer (invalid trials). Experiment 2 was similar to Experiment 1 except that the ratio between valid and invalid trials was 50%. We found priming effects confined to when a human actor served as the primer. In Experiment 3 we showed that the selective effects found for the human primer in Experiment 1 were unrelated to the fact that, in the robot condition, only an arm/hand system was visible while for the human actor both the face and the upper body were visible. Experiment 4 demonstrated some differences between the robot and a human primer even when the kinematics of the human primer did not change as a function of object size. The results demonstrate that motor priming can occur from the observation of biological action. The implications for understanding imitative behaviour are discussed in terms of differential levels of priming: some degree of unspecific priming (first level) seems to occur whenever the observer is exposed to a human versus a robot arm. There appears to be some conspecific advantage, which is completely unrelated to things like object size, trial type, or kinematics. More specific forms of priming (levels 2 and 3) appear to be fully dependent on model kinematics. Priming is only seen for the human hand when it operates naturally. It is not seen for the robot and it is not seen for the human hand when its kinematics do not differentiate between conditions.

16.1 Introduction

The ability to imitate movements is of fundamental survival value for intelligent organisms, providing an important means of learning as well as a mechanism by which an individual may be accommodated within a group (for a review, see Bekkering and Wohlschläger, this volume, Chapter 15). The role of imitation in the development of human and other animals has long been documented, Darwin (Romanes and Darwin 1884), Thorndike (1898), and Piaget (1951) being three notable contributors to the literature. In recent years interest in the topic has been rekindled by new evidence emerging on the behavioural (for a review, see Prinz, in press) and physiological underpinnings of imitative behaviour (di Pellegrino, Fadiga, Fogassi, Gallese, and Rizzolatti 1992; Gallese, Fadiga, Fogassi, and Rizzolatti 1996; Rizzolatti and Arbib 1998).

In the following sections of this introduction we will briefly review experimental paradigms applied to humans and primates to investigate the various aspects of imitative behaviour, which have led to the present series of experiments.

16.1.1 Behavioural experimental studies

A number of paradigms have been implemented and a number of studies have been performed to investigate the mechanisms underlying imitation task performance (for a review, see Prinz, in press; Vogt, in press). For example, Kerzel, Bekkering, Wohlschläger, and Prinz (2000) developed the 'movement reproduction' paradigm to investigate the perception and reproduction of intentional actions. In particular, they asked participants to observe two consecutive object movements and then reproduce the first of them as precisely as possible while ignoring the second. The basic paradigms consisted of two disks moving on a display. Participants were required to observe them and reproduce the velocity of the first disk with a stylus movement on a graphic tablet. The results indicated that participants were able to reproduce velocity on the basis of the velocity of the first disk, but, interestingly, the velocity of the second disk also influenced the reproduction pattern. Velocity reproduction for the first disk tended to be faster if the velocity of the second disk was higher. While these results suggest a sharing of representational resources between movement perception and movement production, it is with the 'movement selection' paradigm that the issues about proper imitation may be better investigated. Stürmer, Aschersleben, and Prinz (2000) developed a paradigm based on gesture selection. This paradigm considered two gestures: hand spreading and hand grasping. In the first case fingers were extended, and in the second case fingers were flexed. Participants were required to perform one of these two hand movements as performed by an actor. An important feature for this task was that the identity of the stimulus gesture was irrelevant for the selection of the response gesture (to be performed by the subject). Instead, the relevant cue for the type of movement to be performed was the color of the stimulus hand i.e. red signified finger extension; blue signified finger flexion). Similar to evidence on Stroop- and Simon-type compatibility effects, the authors found that the speed of responding was faster when there was correspondence between the stimulus and response gestures than when there was no correspondence. From this the authors argued that similar representational structures are involved in the perception and execution of actions (Prinz 1990, in press). Along the same lines, Brass, Bekkering, Wohlschläger, and Prinz (2000) developed the 'effector selection paradigm', where the gesture to be performed was fixed (lifting of the finger) but there was a choice between two effectors to perform the gesture (index or middle finger). Two kinds of instructions were utilized, an imitative instruction where participants were required to lift the same finger as that lifted by a hand on a display and a symbolic instruction where participants were required to lift the same finger as indicated by a cross on the display. It was found that when the finger to imitate was the same as the finger to be lifted, as in the imitative cueing condition, response times were shorter than when actions were cued symbolically.

The aforementioned studies suggest that there is a supramodal representational system, which matches the perceptual information of a seen act with proprioceptive information concerning an executable act. Bekkering, Gattis, and Wohlschläger (2000), however, have recently challenged this idea. In their experiments, preschool children were asked to imitate a set of hand gestures made by an actor positioned in front of them. The gestures varied in complexity. For example, a model touched the left and/or right ear(s) with one or both of the ipsilateral and/or contralateral hand(s). There were three ipsilateral hand movements (left hand to left ear, right hand to right ear, both hands

to ipsilateral ears) and three contralateral hand movements (left hand to right ear, right hand to left ear, and both hands to contralateral ears). The results suggested that the children preferred to use the ipsilateral hand. However, when hand movements were made to only one ear this ipsilateral preference was not observed. Similarly, the ipsilateral preference was not evident when movements were directed at a space rather than a physical object. Their results supported a goal-directed imitation hypothesis where it is advanced that the desired goal of an imitative act is what is extracted from a model's movement (Bekkering *et al*. 2000), not a specific priming of the effector corresponding to that used by the actor being observed.

16.1.2 Neurophysiological studies

A number of physiological studies have also supported the notion that motor structures are involved in action perception as well as production—particularly those concerned with the so-called 'mirror neurons'(e.g. Rizzolatti and Arbib 1998) in area F5 of the pre-frontal cortex of the macaque monkey (see Gallese *et al*., this volume, Chapter 17). These neurons are active not only when a monkey grasps and manipulates objects, but also when a monkey observes an experimenter performing a similar gesture. Moreover the cells do not discharge merely in response to object presentation, but rather they require a specific observed action in order to be triggered. The tuning of the neurons can also be quite specific, coding not only the action but also how it is executed. For example, a neuron might fire during observation of grasp movements but only when the grasping action is performed with the index finger and thumb. Also, if the same grasp is performed using a tool, the neuron may no longer fire.

Neurons showing quite similar properties to those in area F5 have also been reported within the superior temporal sulcus (STS) by Perrett and colleagues (Oram and Perrett 1996; Perrett, Rolls, and Caan 1982; Perrett, Harris, Bevan, and Thomas 1989). For instance, in the lower bank of the STS, cells sensitive to actions of the hand were found. One apparent difference between the neurons in F5 and the STS is that neurons in the STS do not respond to executed motor acts but rather only to perceived ones.

Evidence that a similar mirror system exists in humans comes from studies using transcranial magnetic stimulation (TMS) and functional brain imaging. Using TMS, Fadiga, Fogassi, Pavesi, and Rizzolatti (1995) demonstrated a selective increase in motor-evoked potentials when subjects observed various actions. This increase occurred in the muscles that the subjects would usually use for producing the actions they observed. In addition, two PET studies (Grafton, Arbib, Fadiga, and Rizzolatti 1996; Rizzolatti *et al*. 1996) have shown selective activation in the superior temporal sulcus, the inferior parietal lobule, and the inferior frontal gyrus of the left hemisphere when subjects observe a grasping action performed by an experimenter. Along these lines a recent study conducted using functional magnetic resonance techniques (fMRI; Iacoboni *et al*. 1999) confirmed the activation of frontal and parietal areas during an imitation task.

These results suggest that the brain may employ specialized circuitry to code stimuli for imitative actions. Furthermore, this circuitry seems responsive to immediate observation of biologically appropriate actions for the organism (e.g. a grasping movement performed by a member of the same species (a conspec)), but not to similar actions that are not biologically appropriate for the organism (e.g. grasping by a tool; Gallese *et al*. 1996). Whether the same mechanisms are used for longer-term recall and reproduction of action outside of the immediately observed context is less clear, though there is some suggestive evidence from functional brain imaging that similar brain areas

may be activated in action imitation after immediate observation and in longer-term recall (Decety and Grèzes 1999).

16.1.3 The present study

The present study provides a novel and integral contribution to the already existing body of evidence regarding imitation. The issues we tackle in the present paper have never been considered in the previous literature on imitation. For example: does the observed action have to be part of the already existing behavioural repertoire of the observer in order to trigger mechanisms for imitation? We know from the neurophysiology of imitation (Gallese *et al*. 1996) and from developmental studies (Woodward 1998, 1999) that monkeys and children code and attend to grasping actions performed by a person but not necessarily to those performed by a mechanical device. In the first case, a monkey's mirror neurons are silent when the object is grasped with forceps or pliers (Gallese *et al*. 1996). In the second case, findings indicate that six-month-old children selectively attend to an object grasped when a person, but not a mechanical claw, grasps the object (Woodward 1998, 1999).

On the basis of these studies, we may expect that observation of an action performed by a conspec should have consequences on subsequent motor behaviour by a human subject. For example, detailed information about the kinematics of the observed action may be used to prime an action made at a later time by the observer, so that, for example, the action is parameterized on the basis of the previously observed action. Moreover, priming an action should occur over and above effects due to recall of the behaviour as previously performed by the observer (at least to the extent that recall might only partially engage the same specialized imitative circuitry). The detailed behavioural consequences of action observation on the kinematics of subsequent actions have not been examined hitherto. This was the aim of the present study. We examined whether there are priming effects produced by observing grasping by a human actor on the execution of a similar action by an observer. If this were the case, then the kinematics of actions to a target would vary according to whether the human model had grasped an object of the same or a different size. In addition, we contrasted the observation of an action performed by a conspec (another human) with the observation of an action performed by a non-conspec, a robot arm. Observation of a robot arm performing the reaching action allows us to investigate three relevant issues: (1) it provides a baseline for assessing whether either mere sight of a prime object of a particular size, or observation of a nonbiological grasping action, was sufficient to generate action priming; (2) the use of a robotic arm allows also for a comparison between imitation for an action performed within the supposed behavioural repertoire of a normal person (performed by a conspec), and an action outside the normal behavioural repertoire (an action performed by the robot); (3) the study of priming from the robotic arm should match and extend the work with monkeys on neuronal activation associated with actions performed with hands and tools, and also the human developmental work on the same topic.

16.2 The experiments

16.2.1 Experiment 1: visuomotor priming: robotic versus human primer

In this initial experiment we used an experimental paradigm based on visuomotor priming (Craighero, Fadiga, Rizzolatti, and Umiltà 1998). Subjects were asked to observe grasping movements performed by a human model or by a robotic hand to a target of one of two sizes. Immediately after this, the

subjects had to grasp a target object that could be the same size as the prime object, or a different (unprimed) size. In Experiment 1, the prime and target were likely to be the same size (on 80% of the trials), so that both the size of the prime and the movement made by the human model were informative of the probable action to the subsequent target. Kinematics of the reach-to-grasp action were recorded. The question addressed was whether effects of the movement performed by the human model or the robotic hand could be observed on the actions performed by the participants. Further, we asked whether such effects, if any, occurred over and above effects due to recall and/or prediction of the action from either the size of the primed object or the type of primer (human or robot).

16.2.1.1 Methods

Participants. Eight subjects (4 women and 4 men, aged 20–25 years) volunteered to participate. All were right-handed, all reported normal or corrected-to-normal vision, and all were naive as to the purpose of the experiment. They attended two experimental sessions of 4 hours duration in total.

Robot. The arm looked like an average human forearm with a gloved hand. It was mounted on a metal frame with a single motor that moves the arm from a vertical position to a horizontal position. The 4 fingers and 1 thumb had a common movement so as to mimic the closing of a human hand. The construction was electro-mechanical and was controlled by an 87c751 micro-controller. The hand was constructed from nylon cords for tendons, silicon rubber for joints, and wooden dowels for bones. The 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 was approximately 0.1 kg. A feature of the robot is that it does not differentiate kinematics between large and small objects as humans do. This problem will be tackled in Experiment 4 where it is demonstrated that this difference is not relevant for interpretation of the data from the previous three experiments.

Type of stimuli. The stimuli consisted of 2 spherical white foam objects (diameter: ~8 cm and ~2 cm) positioned at 30 cm distance along the mid-sagittal plane.

Type of trials. There were two trial types. (1) A 'valid' trial, where a robotic arm *or* a human experimenter performed a reach-to-grasp action towards either the small or the large object and subsequently the subject grasped the same object. This occurred on 80% of the trials. (2) An 'invalid' trial, where the robotic arm or the human experimenter performed an action towards the *small* object and the subject grasped the *large* object or vice versa. This occurred on 20% of the trials.

Apparatus. Reflective passive markers (0.25 cm diameter) were attached to (a) the wrist, (b) the index finger, and (c) the thumb. Movements were recorded with the ELITE motion-analysis system. This consisted of two infrared cameras (sampling rate 100 Hz) inclined at an angle of 30° to the vertical and placed 2 m on the side of the table and 2 m apart. The spatial error measured from stationary and moving stimuli was 0.4 mm. Coordinates of the markers were reconstructed with an accuracy of 1/3000 of the field of view and sent to a host computer. Visual availability of the stimuli was controlled with Plato spectacles (Plato Technologies Inc.). These were lightweight and were fitted with liquid crystal lenses. The robotic arm or the experimenter was positioned at 90°, in front of the subject. The starting position of the robotic arm and the starting position of the experimenter's arm were the same (see Fig. 16.1). The distance from the hand of the subject, the hand of the robot, and

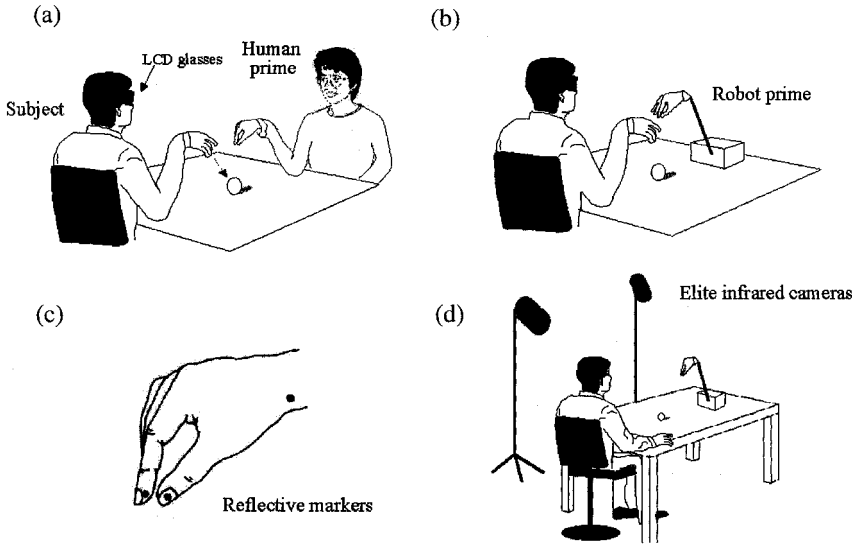

Fig. 16.1 In panel (a) and panel (b) the position of the subject (wearing LCD glasses) and the position of the experimenter or the robot are represented. Panel (c) shows the position of the markers. Panel (d) represents the position of the infrared cameras.

the hand of the experimenter to the target was kept constant (~30 cm). The type of movement performed by the robotic arm and the experimenter differed in that, for the robot, the programmed accelerative and decelerative phases of the movement were similar for small and large objects alike. For humans, these phases differ (as demonstrated by our baseline data where kinematics for the human prime were measured). Both the opacity of the lenses and the initiation of movement by the robotic arm were controlled by the computer. At the beginning of each trial involving the use of the robotic arm, the experimenter at the computer console pressed the data acquisition button, the spectacles cleared, and the robotic arm started to move at a delay of 0.5 s from the opening of the glasses. When the experimenter performed the reach-to-grasp action, he/she started the movement as soon as he/she detected the clearance of the spectacles. Subjects wore earplugs to avoid noise produced by the experimenter during the re-positioning of the object after each trial. It was felt that such noise could provide information regarding the type of trial to be performed (valid or invalid).

Procedure. Subjects were asked to perform the task as indicated by a tape-recorded set of instructions. The sequence of events was as follows: after the first opening of the spectacles the subject had to observe the robotic arm or the human grasping the small or the large object. Then the spectacles were shut and when they re-opened the subject had to perform the grasping action towards the same object in the case of 'valid' trials or towards a different object in the case of 'invalid' trials. The target stayed on throughout the duration of the trial. The participants performed 400 randomized trials (100 per block) over which all possible types of trial/target-size/human–robot combinations occurred. Twenty trials for each combination were subsequently analysed.

Data processing. The ELIGRASP (B|T|S|, 1997) software package was used to analyse the data. This provided a three-dimensional reconstruction of the marker positions. The data were then filtered using a finite impulse response (FIR) linear filter-transition band of 1 Hz (sharpening variable = 2; cut-off frequency = 10 Hz). The reaching component was assessed by analysing the acceleration and the velocity profile of the wrist marker. The grasp component was assessed by analysing the distance between the two hand markers. Movement duration was taken as the time between movement onset and the end of the action (when the target was touched). The period following this, in which the target was lifted, was not assessed. Analysis of the reaching component of the action was based on the time of peak acceleration, velocity, and acceleration and the time from peak velocity to the end of the movement (the deceleration time). For the grasp component, the time to reach maximum peak grip aperture, the amplitude of the peak grip aperture, the peak velocity for the opening phase of the finger movements, and the time from maximum grip aperture to the end of the movement (the closing time) were analysed. Measurements were also taken for the opening phase of the hand movement in relation to the maximum velocity of the movement and the time at which each occurred. The measurement of the maximum grip aperture was based on the greatest distance reached between the thumb and the index finger, and the time of its occurrence. A prolonged deceleration time, and a lower amplitude of peak velocity for the reaching component of a grasp action, for smaller relative to larger stimuli are consistently reported in the reach-to-grasp literature (Castiello 1996; Gentilucci *et al*. 1991; Jakobson and Goodale 1992; Marteniuk, Leavitt, MacKenzie, and Athenes 1990). Differences in deceleration time and peak velocity should therefore be expected here as a function of the size of the target objects, and these differences are a necessary precondition for tests of priming. For the grasp component, we expect there to be a reduced maximum grip aperture for the smaller of the two stimuli, and the maximum grip aperture to be formed earlier in time (Castiello 1996; Gentilucci *et al*. 1991; Jakobson and Goodale 1992; Marteniuk *et al*. 1990). In addition we analysed the peak velocity of the fingers as they opened for the grip and the time taken to close the grip on the object, because (a) previous results have demonstrated differences in the rate of finger opening as a function of target size (Bonfiglioli and Castiello 1998), and (b) closing time provides an index that is sensitive to reach-to-grasp strategies (Hoff and Arbib 1993). For each dependent variable an analysis of variance (ANOVA) was performed with type of primer (human, robot), type of trial (valid, invalid), and object size (small, large) as the within-subjects factors. *Post-hoc* comparisons were conducted on the means of interest using the Newman–Keuls procedure (alpha level: .05).

16.2.1.2 Results

In this and the following experiments priming can be observed at three levels of specificity:

- First level: by effector. In the Results sections this refers to the main effect of robotic versus human primer.
- Second level: by effector and object size (small vs. large object). In the Results sections this refers to the two-way interaction between target size and type of primer (robotic vs. human primer).
- Third level: by effector and trial type. This refers to the two-way interaction between type of primer and trial type and the three-way interaction between type of prime, type of trial, and size.

16.2.1.3 Effects of size

Consistent with previous results within the reach-to-grasp literature, we found a longer movement duration [873 vs. 845 ms; $F(1,7)=14.67$, $p=0.001$], a prolonged deceleration time [457 vs. 433 ms; $F(1,7)=4.94$, $p=0.05$], and a lower peak velocity amplitude [$F(1,7)=8.10$, $p=0.01$] for smaller than for larger stimuli (Castiello 1996; Gentilucci *et al*. 1991; Jakobson and Goodale 1992; Marteniuk *et al*. 1990). For the grasp component the maximum grip aperture occurred earlier in time [525 vs. 548 ms; $F(1,7)=9.36$, $p=0.01$] and it was reduced in size for smaller relative to larger stimuli [70 vs. 84 mm; $F(1,7)=17.32$, $p=0.001$] (Castiello, 1996; Gentilucci *et al*. 1991; Jakobson and Goodale 1992; Marteniuk *et al*. 1990).

16.2.1.4 First-level priming effects

This section refers to the main effect of the type of primer (robot vs. human). Several parameters of the movements differed if the primer was the robot arm rather than the human model. In essence this was because subjects tended to adopt the parameters for responding to the large object when the primer was the robot, irrespective of the actual size of the prime. Thus, for the reaching component, the time to reach peak acceleration [236 vs. 257 ms; $F(1,7)=28.16$, $p=0.001$], peak velocity [403 vs. 430 ms; $F(1,7)=11.11$, $p=0.01$], and peak deceleration [570 vs. 587 ms; $F(1,7)=8.44$, $p=0.01$] were decreased for trials where the robot arm was the primer rather than the human. For the grasp component there were differences in the accelerative phase as the fingers moved to their maximum aperture. The time to maximum acceleration of the fingers occurred earlier [83 vs. 97 ms; $F(1,7)=9.76$, $p=0.01$] and the maximum acceleration was greater [2159 vs. 2063 mm/s^2; $F(1,7)=17.21$, $p=0.001$] following robotic rather than human primers.

16.2.1.5 Second-level priming effects

This section considers the interaction between target size and type of primer. We found differences in the movement parameters between human and robot primers as a function of the size of the target object. In each case, the parameters were close to those found for the large target object, on trials where the primer was a robot (for an example, see Fig. 16.2(a)). In contrast, on human primer trials, there was an effect of the size of the target object. For small relative to large stimuli there was a longer movement duration [$F(1,7)=20.13$, $p=0.001$], a prolonged deceleration time [$F(1,7)=27.02$, $p=0.0001$], a shorter time to achieve the maximum grip aperture [$F(1,7)=7.47$, $p=0.05$], and a lowered size of maximum grip aperture [$F(1,7)=11.06$, $p=0.001$]. The results for this section are rather important because they demonstrate that primed movement kinematics can influence the execution of grasping movements. This is clearly shown by the contrasting data for the robot condition, where no effects of size were found (though remember that the movement of the robot was similar for different target sizes).

16.2.1.6 Third-level priming effects

Priming effects were apparent in two-way interactions involving type of primer (robot, human) and type of trial (valid, invalid), and one 3-way interaction for deceleration time, involving type of primer (robot, human), type of trial (valid, invalid), and target size (small, large). Let us consider the two-way interactions first.

Reaching component. There was a (type of prime) × (type of trial) interaction for: the time to reach peak acceleration [$F(1,7)=7.34$, $p=0.01$], the time to obtain peak velocity [$F(1,7)=8.53$, $p<0.01$], the time to reach peak deceleration [$F(1,7)=9.12$, $p=0.01$], and the deceleration time

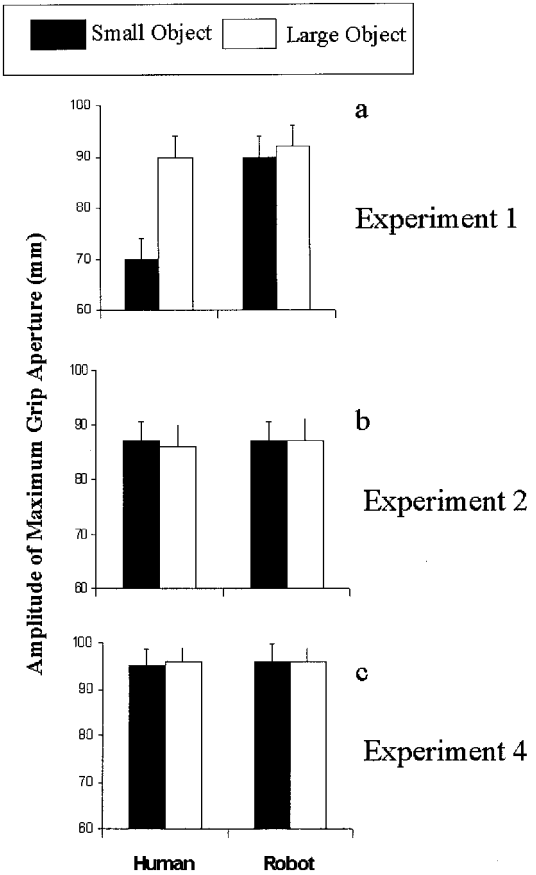

Fig. 16.2 The two-way interaction (Type of Primer by Size) obtained for Expts. 1, 2, and 4 for the measure amplitude of maximum grip aperture.

itself [$F(1,7)=6.53$, $p=0.01$]. For each of these parameters, the values for valid and invalid did not differ if the robot appeared on the priming trials. However, when the primer was human, then in all cases differences emerged between valid trials on the one hand, and invalid trials on the other (all $p<0.05$, Newman–Keuls tests). Figure 16.3(a) represents an example of this patterning for the parameter deceleration time. With the human primer, deceleration time was reduced for valid but not for invalid trials.

Grasp component. For the grasp component, the interaction between the type of primer and type of trial was significant for the following parameters: time to maximum grip aperture [$F(1,7)=10.21$, $p=0.001$], maximum grip aperture [$F(1,7)=20.11$, $p=0.001$], time to peak acceleration of finger opening for grip [$F(1,7)=8.82$, $p=0.01$], and closing time [$F(1,7)=10.44$, $p=0.001$]. As for reaching, there were no differences between valid and invalid trials when the primer was the robot arm. With the human primer, the time to peak acceleration of the opening grip and the time to obtain

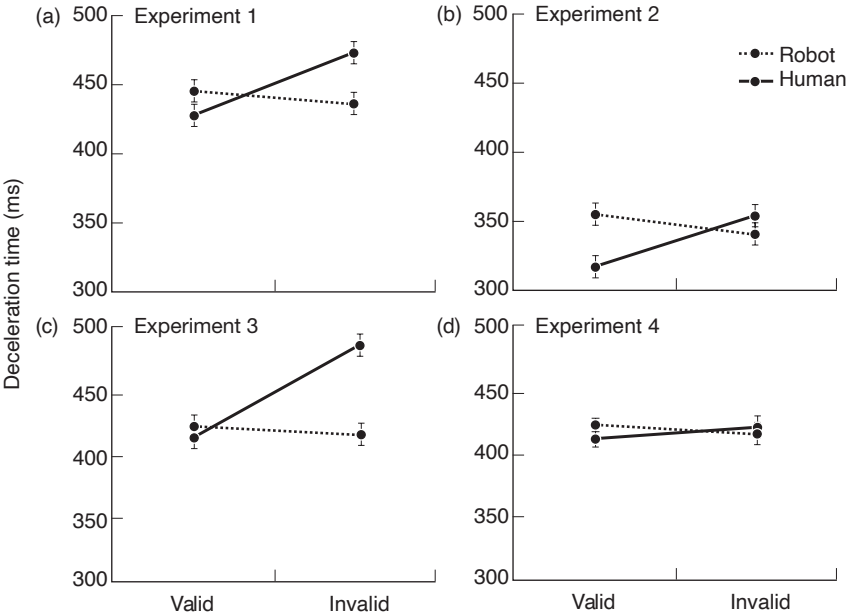

Fig. 16.3 The two-way interaction (Type of Primer by Type of Trial) obtained for deceleration time for the four experiments.

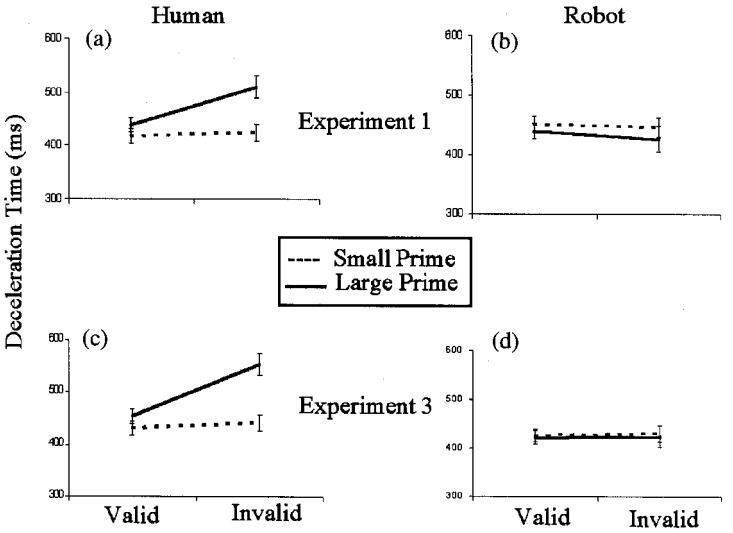

Fig. 16.4 The three-way interaction (Type of Primer by Type of Trial by Size) obtained for Expts. 1 and 3 for deceleration time.

maximum grip aperture were longer on valid trials; in addition, the maximum grip aperture was smaller and the closing time shorter for valid trials.

The three-way interaction between type of primer, type of trial, and object size was significant for deceleration time [$F(1, 7) = 13.12$, $p = 0.001$]. As before, deceleration times did not vary as a function of trial type following robot primers. However, following human primers, deceleration times were slower for invalid relative to valid trials, but this only occurred when the target was large. The three-way interaction is illustrated in Fig. 16.4.

16.2.1.7 Discussion

These results demonstrate that third-level priming effects occurred on trials with human primers but not on trials with robot primers. When the primer was a robot, we failed to find any changes in movement kinematics as a function of whether trials were valid or invalid. There were also few differences between the kinematics of the responses to large and small targets, with the movement kinematics being set towards large targets (see Fig. 16.2(a)). These responses following robot primers can be understood if subjects adopted a relatively conservative response strategy on these trials, initiating their movement with parameters set for large targets. The data from trials with human primers indicate that, on invalid trials, it was easier to adapt an action parameterized for a large object (from a large prime to a small target) than an action parameterized for a small object (from a small prime to a large target). Thus, following human primers there were few costs on invalid trials for small targets, whilst there were reliable costs for large targets. When subjects make a grasp response to a target, any adjustment from a large to a smaller grasp response will match the natural pattern of action in which the finger and thumb reach a maximum grasp aperture that is wider than the target to be grasped and then close around the target under guidance from visual feedback. In contrast, adaptation of a grasp from small to large will operate against the usual patterns of adjustment during reaching for grasping, generating asymmetric costs on performance. With the robot primer, subjects seem to adopt a strategy of minimal adjustment, and so move in all cases (irrespective of the size of the prime object) from an initial parameterization favouring a large grasp.

As we have noted, quite different results occurred on trials following observation of the robot and of a human movement. This is interesting because the effects of the prime were mostly to disrupt action. For example, on invalid trials deceleration times were slowed when the prime was small and the target large (Fig. 16.4(a)). It would appear that subjects adapted their behaviour to match the observed primer action even though this was not necessarily beneficial to their performance. The degree to which this imitation effect is under strategic control was tested in Experiment 2 when we reduced the informativeness of the priming event by only having prime and target actions valid on half the trials. Strategic use of the priming event should be lessened under these conditions.

The fact that we found third-level priming effects only with human and not robot primers indicates that priming was not due to subjects' preprogramming actions based on (a) the size of the priming object (note that this was predictive of the size of the target), and (b) a memory of the action parameters used for the predicted target. If priming were due to either of these factors, then differences between valid and invalid trials should have occurred for robot primers as well as for human primers.

16.2.2 Experiment 2: testing the automaticity of the priming effects

Consider a trial where the subject observes a primer action made to the small object. This event may lead subjects to set parameters for small grasp actions, even though a large target may subsequently

be presented. As a consequence of this, subjects show a cost effect when reaching to a subsequent target. This kind of adjustment could itself operate in one of two ways. One could be strategic, with subjects taking account of the transitionary changes in validity rather than the overall information carried by prime events. The other could be more automatic, based on some form of reinforcement learning operating on a trial-by-trial basis. Whichever is the case, the important point to stress is that similar effects were not found unless subjects observed another human performing the priming action, though they could have used the size of the prime object in a similar way.

This raises the question of how strategic preprogramming is. To investigate this preprogramming issue we ran a further study with 50–50 valid to invalid contingencies. Under these conditions it should not be strategically beneficial for subjects to preprogram the movement.

16.2.2.1 Methods

Participants. Eight subjects (4 women and 4 men, aged 20–25 years) with the same characteristics as those in the previous experiment volunteered to participate. None of them had participated in the previous experiment. They attended one experimental session of 1 hour duration in total.

Apparatus, materials, procedure and data processing. These were the same as for Experiment 1, except that the ratio between valid and invalid trials was 50%, and the number of performed trials was reduced from an overall value of 400 to 160.

16.2.2.2 Results

Data were analysed as for Experiment 1.

Effects of size. In contrast to the findings for Experiment 1 we found that deceleration time and the amplitude of peak velocity were similar for smaller and larger stimuli. For the grasp component we found no differences for the time of maximum grip aperture and the amplitude of grip aperture between smaller and larger stimuli, and, for both stimuli, movement parameters seemed to be set for the larger object (cf. Table 16.1 and Fig. 16.2(b)). This suggests that a conservative response strategy was adopted when primes were not valid on a majority of trials.

Table 16.1 Movement duration and kinematic parameters of the subjects' movements for Small and Large conditions for Exp. 2. SEM in parenthesis

	Small	*Large*	*F*	*Sig.*
Reaching component				
Deceleration time (ms)	339 (16)	353 (13)	2.15	ns
Amplitude peak velocity (mm/s)	696 (31)	707 (36)	2.24	ns
Grasp component				
Time to maximum grip aperture (ms)	495 (32)	515 (29)	3.53	ns
Maximum grip aperture (mm)	91 (3)	88 (3)	3.12	ns

First-level priming effects. As for Experiment 1, several parameters of the movements were accelerated after seeing the robotic rather than the human arm as the primer.

Reaching component. For the reaching component, anticipation was evident for the time to peak acceleration [247 vs. 263 ms; $F(1,7)=28.14$, $p=0.0001$], the time to peak velocity [398 vs. 416 ms; $F(1,7)=20.16$, $p=0.001$], and the time to peak deceleration [536 vs. 559 ms; $F(1,7)=10.08$, $p=0.02$].

Grasp component. For the grasp component it was the accelerative opening phase of the finger to a maximum that differed between the robotic and the human conditions. The time to peak grip-opening acceleration was earlier [139 vs. 150 ms; $F(1,7)=6.16$, $p=0.05$] and greater (2576 vs. 2342 mm/s^2; $F(1,7)=11.65$, $p=0.001$) for the robotic than for the human condition.

Second-level priming effects. The interaction between type of primer (human, robot) and target size was not significant for any of the dependent measures analysed. For example, as represented in Fig. 16.2(b), for both the human and robot primers no differences for the small and the large objects were found for the amplitude of maximum grip aperture. For both human and robot primers, subjects adopted movement parameters for a large object at the start of each trial, leading to a reduction in the overall effects of object size on reaching and grasping.

Third-level priming effects. Despite the overall effects of object size being the same on target actions following both human and robot primers, there remained a differential priming effect. The two-way interaction between type of primer and type of trial was significant for both reaching and grasping components measures. An example of this effect for deceleration time is shown in Fig. 16.3(b).

Reaching component. For the reaching component the time to attain peak velocity occurred at the same time for valid and invalid trials when the robot was the primer. However, with a human primer, the peak velocity was attained earlier in time on invalid trials relative to valid trials [$F(1,7)=7.05$, $p<0.01$]. The same held for the time to peak deceleration [$F(1,7)=6.20$, $p=0.05$].

Grasp component. For the grasp component, the interaction between the type of primer and type of trial was significant for the following parameters: time to maximum grip aperture [$F(1,7)=10.48$, $p=0.01$] and the amplitude of maximum grip aperture [$F(1,7)=6.66$, $p=0.01$]. When the robot was the primer, the time to maximum grip aperture, and the maximum aperture obtained, did not differ for valid and invalid trials. However, with a human primer the maximum grip aperture took place earlier in time on invalid trials than on valid trials. *Post-hoc* comparisons revealed that the differences between valid trials and invalid trials were significant $p_s<0.05$.

16.2.2.3 Discussion

When primes were not generally valid, subjects tended to adopt a conservative response strategy with human and robot primers alike, with responses tending to be set for the larger of the two target objects. Nevertheless, some third-level priming effects were apparent when the primer was human, whilst there was little differential effect of the robot primer. In particular, maximum grip aperture tended to be reduced, the time taken to reach this point was delayed, and the time to attain peak velocity for the reach component of the movement was more prolonged on valid relative to invalid trials. These results mimic the data from Experiment 1 and suggest some adjustment of the parameters of the movement on valid trials, particularly when the prime was small (with the conservative, 'wide grip' parameters being set less often).

16.2.3 Experiment 3: testing differences between robot and human primes: is how much of a body you can see important?

The results from the previous two experiments suggest that there are differences in the different levels of movement priming between a robotic and a human hand. In the third experiment we investigated whether the priming effects found with the human primer in Experiments 1 and 2 were due to the fact that, in the robot condition, only a forearm/hand was visible while, for the human actor, many other cues were available (i.e. the face, the upper body). The motivation for these experiments comes from possible functional differences between, on the one hand, neurons within STS showing selective neuronal responses to the sight of actions of the hand (Perrett *et al*. 1989) and, on the other hand, neurons found in area F5 (Rizzolatti and Arbib 1998). This difference is that neurons in STS do not respond (as neurons in area F5 do) to executed motor acts, but rather only to perceived ones. Also, in studies of STS and mirror neurons by Perrett and colleagues and Rizzolatti and colleagues, similar to those of Experiments 1 and 2 of the present study, the entire body and face of the experimenter performing the action was visible. Thus it may be possible that our forearm/hand robot did not activate the neural system concerned with movement execution in order to generate motor priming effects in Experiments 1 and 2. To clarify this question we performed an experiment where only the forearm and the hand of the human actor were visible.

16.2.3.1 Methods

Participants. Eight subjects (4 women, 4 men, aged 20–25 years), with the same characteristics as those who took part in the previous experiments, volunteered to participate. None of them had participated in the previous experiments. They attended two experimental sessions of 4 hours duration in total.

Apparatus, materials, procedure, and data processing. These were the same as for Experiment 1, except that the experimenter was hidden behind a thick black net curtain and only the arm was visible to the subjects. Prime actions were valid on 80% of the trials.

16.2.3.2 Results

Data were analysed as a means of comparison between Experiment 1 and Experiment 3. Experiment (1 vs. 3) was the between-subjects factor. Type of primer (human, robot), type of trial (valid, invalid), and object size (small, large) were the within-subjects factors. The four-way interaction between experiment, type of primer, type of trial, and object size was significant for deceleration time [$F(1, 7) = 8.54$, $p = 0.01$] and the amplitude of peak velocity [$F(1, 7) = 11{,}23$, $p = 0.001$]. Deceleration time and the amplitude of peak velocity did not vary as a function of trial type and size following robot primes. However, following human primes, deceleration time was shorter and the amplitude of peak velocity was lower for invalid trials relative to valid trials. Further, deceleration time was shorter and the amplitude of peak velocity was lower for small invalid trials (see Fig. 16.4).

16.2.3.3 Discussion

The present experiment was performed mainly because the STS region is activated by movements of various body parts (Perrett *et al*. 1989). In the earlier experiments here, more body information was visible for the human primer than for the robot primer, and this may have influenced the subjects' performance. However, the data from Experiment 3 confirm the reliability of the present

effects, and confirm that the effects are not dependent on subjects seeing more than the arm of the human primer. Priming effects at all levels were obtained from the sight of a human arm reaching and grasping an object. With a robot primer, subjects again tended to adopt a conservative response strategy suitable for the larger object, irrespective of whether the target was large or small, and irrespective of the size of the prime object. Sight of the human model body is not necessary for priming to occur.

16.2.4 Experiment 4: testing the differences in kinematics between robot and human primers

The contrasting results from the human and robot primers in the earlier experiments could be due to the differences between a conspec and a robot as a primer, or to the fact that the kinematics for the robot did not differentiate between large and small objects. In Experiment 4 we clarify this point, normalizing the kinematics for a human prime with respect to object size. We asked a naïve human primer to perform the movement blindfolded within an allotted time. These constraints were felt sufficient to normalize the movement of the human primer with respect to object size. We evaluated whether this normalized movement, made by a human primer, was now equivalent to the robot primer.

16.2.4.1 Methods

Participants. Six subjects (4 women, 2 men, aged 25–30 years) with the same characteristics as those who took part in the previous experiments volunteered to participate. None of them had participated in the previous experiments. They attended one experimental session of 2 hours duration in total.

Apparatus, materials, procedure, and data processing. These were the same as for Experiment 1, except that for this experiment the naïve subject was asked to be the human primer. The human primer was trained to reach for the small and the large object within an interval corresponding to the time employed by the robotic hand to complete the movement (800 ms; ± 25 ms). The interval was defined by two sounds (200 ms sound duration; 880 Hz). This interval was the same for the small and the large object. Further, the human primer was blindfolded so he could not see his arm while reaching for the object. In other words, he did not know the size of the object he was grasping. This led to the primer using a movement patterning that was very similar to that for the robot. That is, the hand opened widely and closed on the object only after having touched it with the palm. During the experimental session the subject wore earphones so as not to hear the two sounds when the 'instructed' primer was demonstrating the movement. Prime actions were valid on 80% of the trials.

16.2.4.2 Results

Of relevance for the present study is that the normalization procedure was successful. Kinematics analyses showed that there were *no differences for movements directed to the small and the large object for the 'instructed' primer* (see Table 16.2, where the values are presented as a percentage of movement duration). Thus, in this study, the human primer acted similarly to the robot primer. As found for Experiment 2 there was a tendency for the subject to program movement in terms of the larger object (see Fig. 16.2(c)).

Data were analysed as for Experiment 1 and are summarized as follows. Several parameters of the movements differed if the primer was the robot arm relative to the human model (first-level priming effects). Thus, for the reaching component, the times to reach peak acceleration [242 vs. 265 ms;

Table 16.2 Kinematic parameters of the subjects' and the human primer's movements for Small and Large conditions for Exp. 4. Temporal measures are expressed as a percentage of movement duration. SEM in parenthesis

	Subjects		*Human primer*		*Statistics*	
	Small	*Large*	*Small*	*Large*	*F*	*Sig.*
Reaching component						
Deceleration time	57	56	56	56	0.21	ns
(%)	(7)	(7)	(6)	(5)		
Amplitude peak velocity	549	544	552	550	1.04	ns
(mm/s)	(6)	(9)	(7)	(6)		
Grasp component						
Time to maximum grip	48	48	48	49	2.12	ns
aperture (%)	(3)	(3)	(4)	(5)		
Maximum grip aperture	96	97	97	97	1.43	ns
(mm)	(3)	(4)	(4)	(4)		

$F(1,5)=17.16$, $p=0.001$] and peak velocity [421 vs. 446 ms; $F(1,5)=5.01$, $p=0.05$] were decreased for trials where the robot arm was the primer rather than the human. For the grasp component there were differences in the accelerative phase as the fingers moved to their maximum aperture. The time to maximum acceleration of the fingers occurred earlier [100 vs. 115 ms; $F(1,5)=4.86$, $p=0.05$] following robotic rather than human primers. In contrast to Experiment 1, second-level priming effects were not found (the interaction between type of primer and size was not significant for any of the dependent measures). These results further suggest that the actions of the 'normalized' human primer were interpreted independently of the size of the object. Priming effects were not apparent in the two-way interactions involving type of primer and type of trial (second-level priming effects). Further, no third-level priming effects were found. The interaction type of primer × type of trial was not significant for any of the dependent measures (e.g. Fig. 16.3(d)). The values for valid and invalid trials did not differ for both the robot and the human primes.

The data from Experiment 4 confirm the reliability of the differences between the robot and the human primer for the reach component of performance. We also failed to find evidence of the size of the prime object on movements to the target. This is not surprising, however, given that the kinematics of the human primer did not differ to large and small objects. Despite this, kinematics were delayed following the human primer relative to the robotic primer, as we found in the earlier studies.

16.3 General discussion

We have reported four experiments showing that priming effects at all levels seem to occur whenever the observer is exposed to a human versus a robot arm. First, there appears to be some conspec advantage, which is completely unrelated to things like object size, trial type, or kinematics. Second, the more specific forms of priming (level 2 and 3) appear to be fully dependent on model kinematics. In Experiments 1 and 4, specific priming is only seen for the human hand when it operates naturally.

It is not seen for the robot and it is not seen for the human hand when its kinematics do not differentiate between the two conditions.

At first glance it may be argued that the different results obtained for the human model and the robot hand are present because the robot's hand kinematics do not differentiate between large and small objects. In other words, the whole pattern of results can be interpreted in such a way that the kinematics of the movement prime the action irrespective of whether the kinematics are shown by a human or a robot. However, we clarified this issue in Experiment 4, where a human model was constrained to perform the same kinematics for both the large and the small objects. The results for this experiment confirm those of the other experiments, suggesting that a robot arm is perceived in a way that is different from a human arm (since the reach components of action remained selectively accelerated for robot primers). Consistent with this, studies of functional imaging in humans have found no evidence for either premotor or frontal activation when movements of a hand have been observed in a virtual reality system (Decety *et al*. 1994). The robot hand here, and the virtual hand in Decety *et al*. (1994) seem not to engage cells which mediate immediate visually guided action (see also Gallese *et al*., this volume, Chapter 17).

This lack of engagement with a robot arm is particularly evident when looking at the relationship between the type of primer and the type of trials. In the human condition, subjects appeared to preprogram a response based on the prime, and then use this to guide action. As a consequence, on invalid trials they had to amend their motor program to respond to the properties of the stimulus. This leads to acceleration of the action, that is, the accelerative part of both the reaching and the grasp components is anticipated.

The effect of the human primer action on deceleration time was longer for 'invalid' than for 'valid' trials when a large stimulus was presented (third-level priming effects). In contrast, for the robot trials subjects appeared not to preprogram the movement for the 'valid' condition, so that no 'invalid' effect is noticed. Again, a possible explanation is that the robot's kinematics are similar for both the small and the large objects, thus the priming effect is not evident because subjects are coding for similar types of actions rather than for different types of objects.

Another possible explanation for the present results is to consider the robot as a control condition with kinematics held constant. If viewed in this way, the results from Experiment 1 could be taken to show that kinematics matter. This point is also confirmed on the basis of the results of Experiment 4 where the kinematics of the human primer did not differ for large and small objects. The conclusion that kinematics is relevant (at least as regards level-2 and level-3 priming) is not only supported by comparing the natural human arm (Experiment 1) with the robot arm (Experiments 1 and 4), but also by comparing it with a nonnaturally moving human arm (Experiment 4). This indicates, in line with the results obtained by Kerzel *et al*. (2000) and Stürmer *et al*. (2000), not only that participants were able to reproduce the actor's pattern, showing correspondence between the stimulus (actor's movement) and response (observer's movement) gestures, but also that this similar representational system not only matches the perceptual information of a seen act with proprioceptive information concerning an executable act but also takes movement kinematics into account.

Recently, Bekkering and colleagues (2000) postulated a new view on the representations that mediate perception and action in imitation. They suggest a motor-pattern process that is guided by an interpretation of the motor pattern as a goal-directed behaviour. The present results do indicate that the desired goal of the action—for instance, grasping an object—can be preprogrammed from observation of a prior action. Further, it is shown that this computation is chiefly driven by primed movement kinematics rather than by object size. We believe that this is one of the most interesting

of the present results. It shows that not only target size, as has been shown many times in the literature, but also primed movement kinematics can influence the execution of grasping movements. Also, since both the robot and the constrained human primer did not elicit priming effects, it appears that the source of priming was not the perceived size of the prime (from which the predicted size, and associated movement patterns for the target, could be generated).

In conclusion, we have demonstrated motor priming effects when human subjects see an action to an object by a human primer. There are also general differences in reach kinematics after observing a human relative to a robotic primer, even when the specific grasp components are not primed. We speculate that the neural basis for these priming effects may reside in the specialized circuitry revealed by physiological and functional imaging studies in the superior temporal, inferior parietal, and inferior frontal lobes.

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References

Bekkering, H., Gattis, M., and Wohlschläger, A. (2000). Imitation of gestures in children is goal-directed. *Quarterly Journal of Experimental Psychology*, *53A*, 153–164.

Bonfiglioli, C. and Castiello, U. (1998). Dissociation of covert and overt spatial attention during prehension movements: Selective interference effects. *Perception and Psychophysics*, *60*, 1426–1440.

Brass, M., Bekkering, H., Wohlschläger, A., and Prinz, W. (2000). Compatibility between observed and executed finger movements: Comparing symbolic, spatial, and imitative cues. *Brain and Cognition*, *44*, 124–143.

Castiello, U. (1996). Grasping a fruit: Selection for action. *Journal of Experimental Psychology: Human Perception and Performance*, *22*(*3*), 582–603.

Craighero, L., Fadiga, L., Rizzolatti, G., and Umiltà, C. (1998). Visuomotor priming. *Visual Cognition*, *5*, 109–125.

Decety, J. and Grèzes, J. (1999). Neural mechanisms subserving the perception of human actions. *Trends in Cognitive Sciences*, *3*, 172–178.

Decety, J., Perani, D., Jeannerod, M., Bettinardi, V., Tadary, B., Woods, R., Mazziotta, J.C., and Fazio, F. (1994). Mapping motor representations with positron emission tomography. *Nature*, *371*, 600–602.

di Pellegrino, G., Fadiga, L., Fogassi, L., Gallese, V., and Rizzolatti, G. (1992). Understanding motor events: A neurophysiological study. *Experimental Brain Research*, *91*, 176–180.

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

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

Gentilucci, M., Castiello, U., Corradini, M.L., Scarpa, M., Umiltà, C., and Rizzolatti, G. (1991). Influence of different types of grasping on the transport component of prehension movements. *Neuropsychologia*, *29*, 361–378.

Grafton, S.T., Arbib, M.A., Fadiga, L., and Rizzolatti, G. (1996). Localisation of grasp representations in humans by PET: 2. Observation versus imagination. *Experimental Brain Research*, *111*, 103–111.

Hoff, B. and Arbib, M.A. (1993). Models of trajectory formation and temporal interaction of reach to grasp. *Journal of Motor Behavior*, *25*, 175–192.

Iacoboni, M., Woods, R.P., Brass, M., Bekkering, H., Mazziotta, J., and Rizzolatti, G. (1999). Cortical mechanisms of human imitation. *Science*, *286*, 2526–2528.

Jakobson, L.S. and Goodale, M.A. (1992). Factors affecting higher-order movement planning: A kinematic analysis of human prehension. *Experimental Brain Research*, *86*, 199–208.

Kerzel, D., Bekkering, H., Wohlschläger, A., and Prinz, W. (2000). Launching the effect: Representations of causal movements are influenced by what they lead to. *Quarterly Journal of Experimental Psychology, Section A: Human Psychology*, *53*, 1163–1185.

Marteniuk, R.G., Leavitt, J.L., MacKenzie, C.L., and Athenes, S. (1990). Functional relationships between the grasp and transport components in a prehension task. *Human Movement Science*, *9*, 149–176.

Oram, M.W. and Perrett, D.I. (1996). Integration of form and motion in the anterior superior polysensory area (STPa) of the macaque monkey. *Journal of Neurophysiology*, *76*, 109–129.

Perrett, D.I., Rolls, E.T., and Caan, W. (1982). Visual neurones responsive to faces in the monkey temporal cortex. *Experimental Brain Research*, *47*, 329–342.

Perrett, D.I., Harris, M.H., Bevan, R., and Thomas, S. (1989). Framework of analysis for the neural representation of animate objects and actions. *Journal of Experimental Biology*, *146*, 87–113.

Piaget, J. (1951). *Play, dreams, and imitation in childhood*. W.W. Norton.

Prinz, W. (1990). A common-coding approach to perception and action. In O. Neumann and W. Prinz (Eds.), *Relationships between perception and action: Current approaches*, pp. 167–201. Berlin, New York: Springer-Verlag.

Prinz, W. (in press). Experimental approaches to imitation. In A. Meltzoff and W. Prinz (Eds.), *The imitative mind: Development, evolution, and brain bases*. Cambridge: Cambridge University Press.

Rizzolatti, G. and Arbib, M. (1998). Language within our grasp. *Trends in Neurosciences*, *21*, 188–194.

Rizzolatti, G., Fadiga, L., Matelli, M., Bettinardi, V., Perani, D., and Fazio, F. (1996). Localization of cortical areas responsive to the observation of hand grasping movements in humans: a PET study. *Experimental Brain Research*, *111*, 246–256.

Romanes, G.J. and Darwin, C. (1884). *Mental evolution in animals*. Appleton and Co.

Stürmer, B., Aschersleben, G., and Prinz, W. (2000). Correspondence effects with manual gestures and postures: A study of imitation. *Journal of Experimental Psychology: Human Perception and Performance*, *26*, 1746–1759.

Thorndike, E.L. (1898). Animal intelligence: An experimental study of the associative process in animals. *Psychological Review Monograph*, *2*, 551–553.

Vogt, S. (in press). Visuomotor couplings in object-oriented and imitative actions. In A. Meltzoff and W. Prinz (Eds.), *The imitative mind: Development, evolution and brain bases*. Cambridge: Cambridge University Press.

Woodward, A.L. (1998). Infants selectively encode the goal object of an actor's reach. *Cognition, 69*, 1–34.

Woodward, A.L. (1999). Infants' ability to distinguish between purposeful and nonpurposeful behaviors. *Infant Behavior and Development*, *22*(*2*), 145–160.