

Modulation of the Action Control System by Social Intention: Unexpected Social Requests Override Preplanned Action

Luisa Sartori
Università di Padova

Cristina Becchio
Università di Torino

Maria Bulgheroni
Università di Padova

Umberto Castiello
Università di Padova

Four experiments investigated the influence of a sudden social request on the kinematics of a preplanned action. In Experiment 1, participants were requested to grasp an object and then locate it within a container (unperturbed trials). On 20% of trials, a human agent seated nearby the participant unexpectedly stretched out her arm and unfolded her hand as if to ask for the object (perturbed trials). In the remaining 3 experiments, similar procedures were adopted except that (a) the human was replaced by a robotic agent, (b) the gesture performed by the human agent did not imply a social request, and (c) the gaze of the human agent was not available. Only when the perturbation was characterized by a social request involving a human agent were there kinematic changes to the action directed toward the target. Conversely, no effects on kinematics were evident when the perturbation was caused by the robotic agent or by a human agent performing a nonsocial gesture. These findings are discussed in the light of current theories proposed to explain the effects of social context on the control of action.

Keywords: kinematics, biological movement, social cognition, reach to grasp, motor control

In everyday life, people are often confronted with situations in which unexpected changes occur while they are acting. Situations of this kind can be recreated in a laboratory setting in which an unexpected event, or *perturbation*, occurs during the performance of the task being studied (Haggard, 1994). Perturbation experiments have been influential in motor control research as they elucidate how preplanned actions are adjusted in response to sudden changes of an object's intrinsic (e.g., size) or extrinsic (e.g., location) properties. For example, Paulignan, MacKenzie, Marteniuk, and Jeannerod (1991) studied the ability of the motor system to accommodate a change in object location that coincided with movement initiation. These authors placed three cylinders on a table in front of the participant. The usual target to reach and grasp was the central cylinder. By unexpectedly shifting illumination (on 20% of the trials) from the central cylinder to one of the laterally placed cylinders at the onset of the reaching movement, Paulignan et al. created the impression that the target had changed location. This apparent change in object location perturbed the prehensile movement. They found that participants took no more

than 100 ms to initiate a corrective arm movement in response to the displacement of the target, with the earliest behavioral change manifesting in the parameter of arm acceleration (see also Castiello, Paulignan, & Jeannerod, 1991). A similar paradigm was used by Paulignan, Jeannerod, MacKenzie, and Marteniuk (1991; see also Castiello, Bennett, & Stelmach, 1993) to study the corrective responses to a sudden visual change in object size without alteration of object position. Participants were presented with two targets: a small-diameter cylinder, vertically inserted into the center of a large-diameter cylinder. Perturbations could be achieved by interchanging illumination of the two, as for the perturbation of object location. Changes were evident in the timing and amplitude of maximum hand aperture, as well as in the reaching component of the movement.

Subsequent studies have demonstrated rapid online adjustments for reactions to sudden changes in the orientation (Desmurget & Prablanc, 1997; Desmurget et al., 1996, 1995), speed (Brenner, Smeets, & de Lussanet, 1998), and weight (Brouwer, Georgiou, Glover, & Castiello, 2006) of target objects. The logic of the experiments was the same in each case. A perceptual change in the environment of the movement was unexpectedly produced at the time the hand started to move. Typically, the response to the perturbation occurred within a 100- to 300-ms time window after the change, depending on the perturbed object feature.

In all of these studies, changes were restricted to the physical environment within which the movement occurred. A challenging, unexplored question is whether such rapid online adjustments can also be noticed when sudden changes are applied to the social environment in which the action takes place.

Previous studies on the possible influence of social context on motor processes have largely focused on the planning phase, that

Luisa Sartori, Maria Bulgheroni, and Umberto Castiello, Dipartimento di Psicologia Generale, Università di Padova, Padova, Italy; Cristina Becchio, Centro di Scienza Cognitiva, Dipartimento di Psicologia, Università di Torino, Torino, Italy.

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Correspondence concerning this article should be addressed to Umberto Castiello, Dipartimento di Psicologia Generale, Università di Padova, 35131 Padova, Italy. E-mail: umberto.castiello@unipd.it

is, the phase operating before movement execution. In this respect, evidence that planning an action is influenced not solely by the physical environment but also by the social environment has been provided, recording kinematics of actions directed toward conspecifics (Becchio, Sartori, Bulgheroni, & Castiello, 2008b). In this study, participants were requested to reach toward and grasp an object and either put it in a concave base (single-agent condition) or pass it to another agent (social condition). The agent was instructed to replace the object in the initial position. The results revealed specific patterns of spatial trajectories for single intended actions and social intended actions, suggesting that planning incorporates overarching social goals into the action plan. For instance, the length of wrist trajectory was longer and the amplitude of wrist trajectory height was higher for the social than for the single-agent condition.

Meulenbroek, Bosga, Hulstijn, and Miedl (2007) further demonstrated that in a sequential motor task, a transfer of performance parameters takes place between coactors involved in transferring objects. First, one of the two actors was asked to pick up a cylinder from a nearby location on the table and put it in the middle of the table. Subsequently, the other actor was asked to fetch the cylinder and to reposition it in a nearby target area. The authors varied both the size and the weight of the transferred cylinder. Time series analysis of the lifting heights indicated that the actor who fetched the cylinder second benefited from movement observation. Specifically, the actor who fetched the object first showed a systematically larger surprise effect when the size and the weight of the cylinder were incongruent compared with the actor who was asked to transport the object after the first actor had done so.

Surprisingly, the influence of other people's actions is also evident even when it would be more effective for task performance if the other's actions were ignored. For instance, Kilner, Paulignan, and Blakemore (2003) found that observing continuous human arm movements by another person significantly interferes with ongoing executed movements if the observed movements are qualitatively different from the movements being made. Sebanz, Knoblich, and Prinz (2003, 2005) demonstrated that for an interference effect to take place, it is not even necessary that the action of another person be observed. Simply knowing that another person is performing a similar task may be sufficient to produce an action selection conflict.

Altogether, these studies have suggested that during action planning and execution, people integrate information about the social environment. The question addressed in this study is whether information about the social environment also affects the online control phase of action, that is, during the execution of a movement involved in the action.

It has been proposed that planning and online control of action each serve a specialized purpose, different from the other, and that each uses a distinct visual representation (Glover, 2004). Online control can assume two different forms. A usual "feedback control" form would take place when a target object shifts its position slightly during movement execution. Alternatively, if some stimulus event signaled that the person should change the target of the action from one object to another, then it is likely that an online reprogramming of the movement would be required. Here, we conducted a series of experiments to investigate whether online control of the latter type is influenced by the social dimension of the observed change. In Experiment 1, we investigated whether

exposure to an unexpected social interactive gesture by another agent would affect the participants' kinematics. Three subsequent experiments were specifically designed to disentangle the contribution of the social factor from the contribution of biological factors in determining the perturbation effect. In particular, in Experiment 2 the human agent was replaced by a robotic agent; in Experiment 3, the gesture performed by the human agent did not imply a social request; and in Experiment 4, the gaze of the human agent was not available.

Experiment 1: Human Social Cue

In this experiment, participants were requested to reach for, grasp, and lift a target object and put it in a container. On 20% of the trials, a perturbation occurred. This perturbation consisted of the sudden request by a human agent to hand her the target object in the participant's hand. Specifically, at the moment at which the participant started the action toward the target object, the agent stretched out her right arm and unfolded her hand to ask for the object. We reasoned that if the online control system is sensitive to sudden social changes in the environment, then exposure to an unexpected social request should perturb the execution of the preplanned action. Specific predictions concerning the sort of readjustments that may occur, and the dependent measures that should be sensitive to the social manipulation, are reported in the *Data analysis* section.

Method

Participants. Fifteen students (10 women and 5 men, ages 20–31 years) took part in the experiment. All participants were right handed, had normal or corrected-to-normal vision, and were naïve as to the purpose of the experiment. Participants gave their written consent before the experiment.

Type of stimulus. The stimulus was an egg-shaped object (long axis = 5.7 cm) positioned on a black table in front of the participant at a distance of 25 cm from the hand starting position along the midsagittal plane (see Figure 1A).

Apparatus. The work surface was a rectangular table (150 cm × 100 cm). The participant was seated on a height-adjustable chair so that the thorax pressed gently against the front edge of the table and the feet were supported. Before each trial, each participant's right hand rested on a starting pad (a 7 cm × 6 cm brown velvet cloth). The starting pad was attached 3 cm from the edge of the table on the midsagittal axis 15 cm anterior to the participant's midline (see Figure 1A). The starting position involved the ulnar side of the hand placed on the starting pad, the shoulder slightly flexed, a semipronation of the forearm, a 5°–10° wrist extension, and opposition between the pads of the index finger and thumb. Infrared reflective markers (0.25-mm diameter) were taped to the following points on the participant's right upper limb: (a) wrist, dorsodistal aspect of the radial styloid process; (b) thumb, ulnar side of the nail; and (c) index finger, radial side of the nail. Markers were fastened using double-sided tape. Movements were recorded using an ELITE motion analysis system (Bioengineering Technology & Systems [BTS], Milan, Italy). Four infrared cameras (sampling rate 100 Hz) placed 120 cm away from each of the four corners of the table (see Figure 1A) captured the movement of the markers in three-dimensional space. Coordinates of the mark-

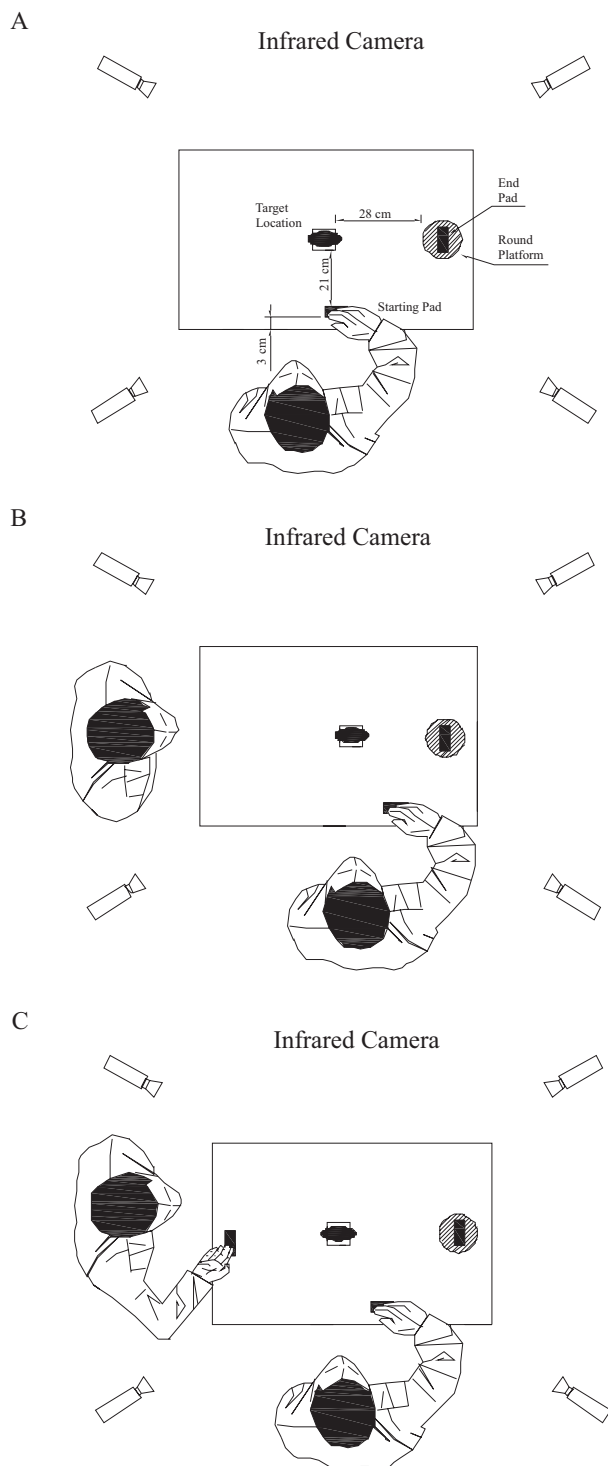


Figure 1. Experiment 1. A: Experimental set-up. B: Graphical representation of the experimental setting for the unperturbed trials. In these trials, the participant's task is to reach toward and grasp the object and locate it within a container in the presence of a passive coexperimenter. C: Graphical representation of the experimental setting for the perturbed trials. In these trials (20%), the participant's task is the same as in unperturbed trials, but the coexperimenter stretches out her right arm and unfolds her hand in a give-me-the-object posture.

ers were reconstructed with an accuracy of 0.2 mm over the field of view. The standard deviation of the reconstruction error was 0.2 mm for the vertical (y) axis and 0.3 mm for the two horizontal (x and z) axes.

Procedure. At all times, the participants' task was to begin the movement as soon as a tone (880 Hz, for 200 ms) was presented and then reach for, grasp, and lift the target object and transport it to a new location in which a round container (12-cm diameter) was placed. The container was located to the right of the target at a distance of 28 cm (see Figure 1A). Participants received written instructions and were explicitly told to complete this basic task irrespective of whatever event took place in the near environment. During these trials, a coexperimenter was seated on the left side of the work surface (see Figure 1B). Within a block of trials ($N = 50$), two types of trials were intermingled: (a) *unperturbed trials* (80% of the total number of trials), in which the task was completed and the coexperimenter simply observed the scene; and (b) *perturbed trials* (20% of the total number of trials), in which at the time the starting tone was presented and the participant started the action, the coexperimenter stretched out her right arm and unfolded her hand in a "give-me-the-object" posture (see Figure 1C). The coexperimenter was signaled in which trials she should stretch out her arm by means of an infrared light pointed at her feet, below the table surface. The signaling occurred before the starting tone was presented and was not visible to the naïve participant. The coexperimenter was introduced as another participant (confederate). To reduce expectancy and rhythmical effects, the duration between the end of the trial and the presentation of the tone for the new trial was varied.

Data processing. We used the ELIGRASP software package (BITISI) to analyze the data and provide a three-dimensional reconstruction of the marker positions as a function of time. The data were then filtered using a finite impulse response linear filter (transition band = 1 Hz, sharpening variable = 2, cut-off frequency = 10 Hz; D'Amico & Ferrigno, 1990, 1992). Following this operation, we computed the spatial trajectory and tangential speed of the marker on the wrist for the reaching component. For the grasp component, we computed the distance between the markers located on the index finger and the thumb. Tangential speed data were used to determine the onset and offset of the movement using a standard algorithm (threshold for movement onset and offset was ~ 5 cm/s).

Data analysis. Because the action was performed in two steps, we analyzed the reach-to-grasp phase (reach toward and grasp the stimulus) and the place phase (place the stimulus on the platform) separately. The parameters concerned with the grasp component were obviously considered only for the reach-to-grasp phase. Conversely, parameters concerned with the reaching component were analyzed for both movement phases. Data analysis was confined to the dependent variables thought to be specifically relevant to the hypothesis under test.

For both the reach-to-grasp and the place phases, we considered spatial trajectory measures that have been proved to be sensitive to variations in social context (Becchio et al., 2008a; Becchio, Sartori, Bulgheroni, & Castiello, 2008b; Georgiou, Becchio, Glover, & Castiello, 2007). These measures were the length of the trajectory path, the time and amplitude of the maximum height of the wrist trajectory from the working surface, and the time and amplitude of the maximum curvature of the trajectory path from an

ideal line linking the starting position and the object location. For this latter measure, we gave a positive sign to right deviations and a negative sign to left deviations. It has been demonstrated that the length of the trajectory path increased and the time and amplitude of the maximum height of the wrist trajectory from the work surface were respectively later and higher when an object was grasped with the intention to interact with a human agent than with an inanimate object (Becchio et al., 2008a, 2008b; Georgiou et al., 2007). Moreover, handing the object to a human agent rather than putting it in a container resulted in an anticipation of the time at which the peak of trajectory curvature occurred. Further, the curvature of the trajectory path from an ideal line linking the starting position and the object location was increased (Becchio et al., 2008a). Therefore, we expect that the social perturbation involving a sudden movement change resulting from a request by a human agent would bring changes to these measures. We determined for each participant the mean values for these kinematic parameters for the two experimental conditions.

For each dependent variable, we then entered the means for each participant into a within-subjects analysis of variance (ANOVA). The within-subjects factor was experimental condition (unperturbed or perturbed). Preliminary analyses were conducted to check for normality and univariate and multivariate outliers, with no serious violations noted.

Results and Discussion

Reach-to-grasp phase. For this phase, analysis of spatial trajectories revealed that the maximum curvature of the arm trajectory path was reached earlier for perturbed than for unperturbed trials, $F(1, 14) = 5.32, p < .05, \eta_p^2 = .21$ (see Figure 2 [black arrows] and Table 1). A further inspection of Figure 2 indicates that the maximum deviation for unperturbed trials was to the right of the ideal line linking the starting position with the target object, whereas for perturbed trials it was to the left (see Table 1). In addition, for perturbed trials the arm trajectory path started to veer significantly toward the coexperimenter (left deviation) during the initial phase of the movement (white arrow in Figure 2). At the same time, the arm trajectory path for unperturbed trials maintained an almost straight path with slight deviations to the right. We further explored such differential trajectory patterns by means of a break detection algorithm (Castiello et al., 1993; see the Appendix), which allowed us to determine at which point in time trajectories for perturbed trials started to significantly divert from those for unperturbed trials. The results indicated that the first significant change was evident on average after 165 ms after the coexperimenter started her movement, $t(45) = 22.38, p < .0001$.

Place phase. Strikingly, during this phase, even though the participants were instructed to place the target on the right side on the platform, in some trials they totally ignored the instruction and deviated the arm trajectory path toward the human coexperimenter, placing the object in the coexperimenter's hand (see Figure 3). Others started the action maintaining the arm trajectory path along the midline, then stopped the action and performed a slight movement toward the platform, but inevitably went for the coexperimenter's hand, suggesting that the social request had the potency to override the initial movement program. The analysis for the trials in which the task was correctly completed—therefore excluding from the analysis trials in which the participant handed the

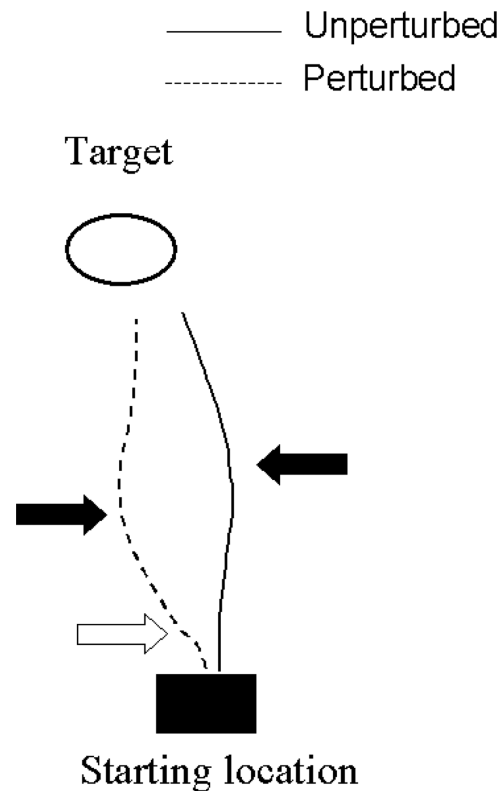


Figure 2. Experiment 1. Wrist average spatial paths in the plane of the table for unperturbed (solid line) and perturbed (dashed line) trials. Black arrows indicate the point at which trajectories reached the maximum deviation. The white arrow indicates when trajectories for unperturbed and perturbed trials start to significantly diverge.

object to the coexperimenter (20% of the total number of perturbed trials, i.e., 150)—also revealed effects of the perturbation. The maximum height of the wrist trajectory from the work surface was higher, $F(1, 14) = 10.43, p < .001, \eta_p^2 = .43$ (see Figure 4 and Table 1), and it was reached later in time, $F(1, 14) = 7.80, p < .01, \eta_p^2 = .36$ (see Figure 4 and Table 1) for perturbed than for unperturbed trials.

These results suggest that the exposure to an unexpected social request produced reliable changes on predicted kinematics variables. More important, the presence of the perturbation revealed changes that were evident very early on the trajectory path. Therefore, the kind of social perturbation reported here may point to a fast processing of the social meaning carried by the sudden environmental change.

Experiment 2: Robot Cue

The results from Experiment 1 suggest that exposure to a social request is critical for the perturbation effect to occur. In Experiment 2, we assessed whether this social effect depended on the action of a conspecific or whether the same functional action from a nonconspecific would be sufficient. To test this possibility, in Experiment 2 we replaced the human arm with a robotic arm model, which was programmed to execute a movement similar to that of the human agent. We reasoned that if the perturbation effect

bones. Movement was provided by a DC electric motor that tensed the tendons to open the hand. Springs were used to store energy and thus reduce the required power and size of the motor. The arm length was approximately 0.5 m.

Stimulus, apparatus, data processing, procedure, and data analysis. These were exactly the same as those for Experiment 1, except that the robotic arm replaced the human coexperimenter. The robot was programmed to start moving when the starting tone was presented. Movement duration and the occurrence of key kinematic landmarks (i.e., time to peak velocity) were comparable to those of the coexperimenter in Experiment 1. The movement of the robot was quite smooth, and the action of stretching out the arm and unfolding the hand in a give-me-the-object posture was analogous to that of the human coexperimenter in Experiment 1.

Results and Discussion

An important aspect of the results is that all the participants ignored the robotic arm and fulfilled their task with no hesitation. Therefore, we found no differences whatsoever when comparing unperturbed and robotic perturbed trials in either the reach-to-grasp or the place phases. Specifically, for the reach-to-grasp phase the maximum curvature of the arm trajectory path was reached at a similar time for both perturbed and unperturbed trials, $F(1, 14) = 0.5, p > 0.05, \eta_p^2 = .03$ (see Table 1). The maximum deviation of the trajectory was similar for both perturbed and unperturbed trials, and no evidence of left deviations for perturbed trials was detected (see Table 1). That is, for both perturbed and unperturbed trials the trajectory path was slightly curved to the right. Application of the break detection algorithm revealed that at no point in time did trajectories for perturbed trials significantly divert from those for unperturbed trials. For the place phase, there were no cases in which the participants ignored the instruction and deviated the arm trajectory path toward the robotic arm, placing the object in its hand. Finally, the maximum height of the wrist trajectory from the work surface was similar for both perturbed and unperturbed trials in terms of amplitude, $F(1, 14) = 1.20, p > .05, \eta_p^2 = .1$ (see Table 1) and time, $F(1, 14) = 4.50, p > .05, \eta_p^2 = .1$ (see Table 1). Altogether, these results suggest that the lack of perturbation effect was due to the exposure to a nonbiological movement. To corroborate this conclusion, we compared the results obtained for Experiment 2 with those obtained for Experiment 1. We carried out an ANOVA with experiment (1 or 2) as a between-subjects factor and experimental condition (perturbed or unperturbed) as a within-subject factor for each of the dependent measures of interest. The interaction between experiment and experimental condition was not significant for the maximum curvature of the arm trajectory path, $F(1, 28) = 0.90, p > .05, \eta_p^2 = .04$, or the time and amplitude of the maximum height of the wrist trajectory, $F(1, 28) = 0.05, p > .05, \eta_p^2 = .002$, and $F(1, 28) = 0.04, p > .05, \eta_p^2 = .001$, respectively. These results suggest that although the robotic perturbation did not produce significant effects (see earlier analyses for Experiment 2) for certain dependent measures, there was a trend in the pattern of data in line with the significant results obtained for Experiment 1 (see Table 1). This may signify that the affordance of the give-it-to-me gesture performed by the robot had the capacity to determine differences between perturbed and unperturbed trials similar to that observed

in Experiment 1 with a human coexperimenter, although to a lesser, nonsignificant extent.

Experiment 3: Human Nonsocial Intention

Experiment 3 was complementary to Experiment 2. In demonstrating no perturbation effect during robotic arm movement, Experiment 2 indicated that the effect is related to biological movement. In Experiment 3, we sought to further refine the nature of the perturbed trials effect by asking whether a human arm movement conveying no social intention would exert a similar effect. To this end, we asked the human agent to perform a sudden movement to re-create almost the same trajectory pattern performed in Experiment 1. The relevant difference was in the type of hand movement: Whereas in Experiment 1 the experimenter's hand movement clearly conveyed a social request ("Give me the object"), in Experiment 3 the human agent laid her hand on the table, displaying the intention to neither communicate nor socially interact with the participant (see Figure 5). This procedure would allow us to dissociate the differential contribution of biological and social factors. If the perturbation effect depends on the observation of a biological human movement, it should be the same irrespective of whether one observes a sudden social gesture by a human agent (Experiment 1) or a human movement conveying no social intentionality (this experiment). In contrast, if the perturbation effect relates to the social nature of the observed gesture, then no similar perturbation effect should be revealed when comparing unperturbed trials and human nonsocial perturbed trials.

Method

Participants. Fifteen students (8 women and 7 men, ages 20–25 years) with the same characteristics as those who partici-

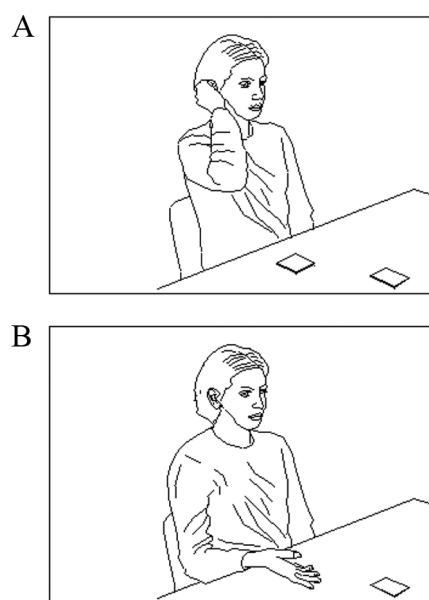


Figure 5. Schematic representation of the movement performed by the coexperimenter in Experiment 3. Panel A represents the coexperimenter running her fingers through her hair. Panel B represents the final posture and position reached by the hand.

pated in Experiment 1 volunteered to participate. None of them had participated in the previous experiments. One participant was excluded from the analysis for technical reasons.

Stimulus, apparatus, data processing, procedure, and data analysis. These were exactly the same as those for Experiment 1, except that the coexperimenter performed an action that did not display the intention to either communicate or socially interact with the participant (see Figure 5). The gesture performed by the coexperimenter was to run her fingers through her hair using the right hand (Figure 5A) and then lower the hand to the working surface in a posture similar to the give-it-to-me posture adopted for the perturbed trials in Experiment 1, but without the intention to convey any social request (Figure 5B).

Results and Discussion

We found no significant differences for the considered dependent measures when comparing unperturbed and human nonsocial perturbed trials in neither the reach-to-grasp nor the place phases. As in Experiment 2, the maximum curvature of the arm trajectory path during the reach-to-grasp phase was reached at a similar time for both perturbed and unperturbed trials, $F(1, 14) = 0.00, p > .05, \eta_p^2 = .03$ (see Table 1). Similarly, we found no differences between perturbed and unperturbed trials for the maximum deviation of the trajectory path and detected no evidence of left deviations for perturbed trials (see Table 1). Application of the break detection algorithm did not reveal points in time at which trajectories for perturbed trials started to significantly divert from those related to unperturbed trials. The lack of significant results also extended to the place phase. In no case did the participants deviate the arm trajectory path toward the human coexperimenter so as to place the object in the coexperimenter's hand. With respect to the height of the wrist trajectory from the work surface, we found no significant differences for perturbed and unperturbed trials in terms of both amplitude, $F(1, 14) = 1.0, p > .05, \eta_p^2 = .08$ (see Table 1) and time, $F(1, 14) = 0.20, p > .05, \eta_p^2 = .01$ (see Table 1). These results suggest that the lack of perturbation effect may be because the gesture performed by the human coexperimenter did not carry any social meaning. To support such a conclusion, we ran comparison analyses with experiment (1 or 3) as a between-subjects factor and experimental condition (perturbed or unperturbed) as a within-subject factor for each of the dependent measures of interest. The results for these comparison analyses indicate that the Experiment \times Condition interaction was significant for the maximum curvature of the arm trajectory path, $F(1, 28) = 5.20, p < .05, \eta_p^2 = .19$, and the time and amplitude of the maximum height of the wrist trajectory, $F(1, 28) = 8.10, p < .05, \eta_p^2 = .24$, and $F(1, 28) = 7.20, p < .05, \eta_p^2 = .23$, respectively. To sum up, this pattern of results indicates that the exposure to an unexpected noncommunicative human gesture is not enough to obtain a perturbation of the action kinematics as found in Experiment 1, in which the gesture was communicative in nature.

Experiment 4: Effects of Gaze

Results from Experiment 3 suggest that it is the intentional component embedded within the perturbation that is critical for the revelation of the effect reported in Experiment 1. Experiment 4 was designed to manipulate the coexperimenter's intentionality by

allowing or preventing the processing of her gaze. Gaze manipulation was chosen because, as previously demonstrated, gaze is one of the most important cues for the attribution of intentionality (Allison, Puce, & McCarthy, 2000; Castiello, 2003; Pelphrey & Morrison, 2006). If gaze processing is fundamental for the determination of the reported effect, then preventing access to gaze cues should diminish the potency of the coexperimenter's gesture. In contrast, if the intentionality of the gesture is chiefly conveyed by the give-me-the-object hand posture, then, independent of gaze, a perturbation effect should be evident.

Method

Participants. Fifteen students (11 women and 4 men, ages 19–25 years) with the same characteristics as those who participated in the previous experiments volunteered to participate. None had participated in the previous experiments.

Stimulus, apparatus, data processing, procedure, and data analysis. These were exactly the same as those for Experiment 1, except that the same participants performed two blocks of 60 trials in a counterbalanced order. In one block, the gaze of the human coexperimenter was available to participants, as in Experiment 1. In the other block, the gaze of the human coexperimenter was covered by a mask. The percentage of perturbed and unperturbed trials within each block remained the same as in the previous experiments (i.e., 80%–20%). For each dependent measure of interest, we carried out an ANOVA with gaze (present or absent) and experimental condition (unperturbed or perturbed) as within-subject factors.

Results and Discussion

Erroneous trials in which the participants handed the object to the coexperimenter were 38 (17% of the total number of trials) for the gaze condition and 25 (11%) for the no-gaze condition. As in Experiment 1, we did not include these trials in the results of the analyses described next.

For the reach-to-grasp phase, the interaction between gaze and experimental condition was significant for the time at which the maximum trajectory deviation occurred, $F(1, 28) = 4.56, p < .05, \eta_p^2 = .35$. Post hoc contrasts revealed that when gaze was available, the maximum trajectory deviation occurred later for perturbed than for unperturbed trials ($p < .05$; see Table 1). When the coexperimenter's gaze was unavailable, the time at which the maximum trajectory deviation was reached was similar for both perturbed and unperturbed trials (see Table 1). It is important that we found the early left deviations as in Experiment 1 only for the gaze-available condition (see Table 1). When the gaze was not available, the arm trajectory path showed right deviations as found in Experiments 2 and 3. Application of the break detection algorithm indicated that only for the gaze-available condition did spatial trajectories for perturbed and unperturbed trials start to significantly diverge during the reach-to-grasp phase. Specifically, this occurred 171 ms after the coexperimenter started her movement, $t(1, 14) = 31.42, p < .0001$.

For the place phase, the main factor, experimental condition, was significant for time and amplitude of maximum height of the wrist trajectory, $F(1, 1) = 14.34, p < .001, \eta_p^2 = .37$, and $F(1, 1) = 10.50, p < .01, \eta_p^2 = 0.30$, respectively. Specifically, the time

and amplitude of the maximum height from the work surface reached by participants was earlier (369 ms vs. 385 ms) and lower (131 mm vs. 134 mm) for unperturbed than for perturbed trials.

Altogether, these results suggest that during the first reach-to-grasp phase, having access to the coexperimenter's gaze influenced the spatial trajectories. This may indicate that gaze is the first cue from which participants infer social intentions. However, during the place phase the presence or absence of gaze seemed to play no role (lack of the interaction between gaze and experimental condition). This may signify that during this phase, the coexperimenter's hand became a predominant cue that overrode the gaze cue and therefore guided the participants' response.

General Discussion

These results extend our knowledge about the influence of social context on action online control, suggesting that a motor response to a sudden change varies depending on the social salience of the observed change. Exposure to an unexpected movement conveying a social request exerted an effect of perturbation on preplanned actions: By disregarding the instructions, participants tended to comply with the coexperimenter's request (Experiment 1). This suggests that the initial motor program to transport the object into the container was modified on the basis of the social request. Critically, no perturbation effect was revealed for nonbiological stimuli (Experiment 2) or when the perturbation consisted of a human arm movement conveying no social or communicative intention (Experiment 3). This pattern of results was further confirmed in a series of analyses comparing the results of Experiment 1 with those obtained for Experiments 2 and 3. Finally, the manipulation of gaze cues affected the reach-to-grasp phase but not the place phase (Experiment 4).

Modulation by Social Relevance

The lack of perturbation effect during robotic arm movements and during human arm movements conveying no social intention is intriguing because it places new constraints on models put forward to explain how the brain represents movements and, more specifically, biological movements.

It has been proposed that observed movements are classified as biological (human) or nonbiological (robot) and treated differently accordingly (Blakemore & Frith, 2005). In line with this proposal, kinematic studies have suggested that motor priming can occur from the observation of biological movements, but not from the observation of robotic movements (Castiello, Lusher, Mari, Edwards, & Humphreys, 2002). Similarly, it has been demonstrated that an ongoing action is interfered with by the observation of another human performing an incongruent movement, but not by the observation of a robot performing an incongruent movement (Kilner et al., 2003; see also Castiello, 2003). These findings have been interpreted as evidence of the brain's processing biological and nonbiological movements differently.

This finding adds to the evidence suggesting that movements may exert different effects on the observer's motor system depending on the perceived intentionality of the agent's gesture. This proposal is in line with findings demonstrating that interference effects are not simply the result of the biological origin of the observed movement, but crucially depend on perceived agency

(Stanley, Gowen, & Miall, 2007). Using a motor interference paradigm, Stanley et al. (2007) demonstrated that interference effects were present for both biological and nonbiological movement when participants believed that they were observing a human movement. This suggests that the intentional stance of the participant—that is, the fact that the participant views an entity as possessing intention, belief, and desires (Dennett, 1987)—might be a more important determinant than the biological origin of movement per se.

In neural terms, this might signify that intentionality modulates the way biological motion is perceived in the human brain. Brain areas identified in studies examining biological motion include the posterior superior temporal gyrus and sulcus, the motion-sensitive area V5/MT_p, and ventral temporal and parietal cortices (e.g., Beauchamp, Lee, Haxby, & Martin, 2002; Bonda, Petrides, Ostry, & Evans, 1996; Grèzes et al., 2001; Grossman et al., 2000; Peelen, Wiggett, & Downing, 2006; Peuskens, Vanrie, Verfaillie, & Orban, 2005; Saygin, Wilson, Hagler, Bates, & Sereno, 2004; Servos, Osu, Santi, & Kawato, 2002; Vaina, Solomon, Chowdhury, Sinha, & Belliveau, 2001). The involvement of the posterior superior temporal gyrus and sulcus is perhaps the most robust finding (see Puce & Perrett, 2003, for review), supported also by electrophysiological recordings in the macaque monkey (Oram & Perrett, 1996). More recently, in a functional MRI study, point-light biological motion has additionally been found to activate premotor and inferior frontal regions that are involved in action planning and execution (Saygin et al., 2004). A role for the motor system in biological movement perception is further indicated by other recent imaging and psychophysical studies (Calvo-Merino, Grèzes, Glaser, Passingham, & Haggard, 2006; Casile & Giese, 2006; Jacobs & Shiffrar, 2005; Gazzola, Rizzolatti, Wicker, & Keysers, 2007; Loula, Prasad, Harber, & Shiffrar, 2005; Tai, Scherfler, Brooks, Sawamoto, & Castiello, 2004), introducing a link to the body of literature on the primate action observation system (Gallese, Fadiga, Fogassi, & Rizzolatti, 1996; Rizzolatti & Craighero, 2004).

On the basis of these and previous findings (Stanley et al., 2007), one might advance that at least some of the areas associated with biological motion perception may be sensitive to the intentional component carried by the observed movement. Some support for this proposal comes from the demonstration that parietal activity during action observation is modulated by the relationship between an observer and an actor (Kilner, Marchant, & Frith, 2006). In the Kilner et al. (2006) study, magnetoencephalography was used to record cortical activity of human participants while they watched a series of videos of an actor making a movement. They found that the degree to which oscillatory activity is attenuated during action observation depends on whether the actor is facing toward or away from the participant. In the former case but not the latter, a modulation was observed in the pattern of oscillatory activity elicited by action observation. This finding has been interpreted as suggesting that signals about other people's actions are filtered, allowing only the most socially relevant actions to activate a motor representation. In this respect, our findings might provide some information regarding the timing of such filtering. The very fact that we found a response to the socially relevant stimulus after 165 ms indicates that socially relevant stimuli are acknowledged by the motor system very early.

Crucially, we observed no such early response for the no-gaze trials in Experiment 4. This finding confirms the crucial role played by gaze in reading other people's intentions (Allison et al., 2000). From the gaze of another person, we can infer what that person might be interested in or what he or she might desire and, consequently, what he or she might want to do next (Frischen, Bayliss, & Tipper, 2007). When gaze is occluded, processing a person's intention might become a less automatic process (Pierno, Becchio, Turella, Tubaldi, & Castiello, 2007). If intentionality modulates the way biological motion is processed, then the absence of gaze cues might well explain why the perturbation effect was delayed in no-gaze trials.

Beyond Reenactment: Evidence in Favor of a Complementary Mechanism

Raising an empty hand toward another person represents a specific request, equivalent, in many aspects, to a verbal utterance: "Give me the object." A possible explanation for the perturbation effect is that socially motivated actions (like the request gesture) act as an affordance that activates an appropriate motor response. Once this request has been processed, the activation of the appropriate response is almost automatic: Ignoring the instruction to put the object in a container, participants deviated the trajectory path toward the human agent.

One interesting aspect of this behavior is that it represents a complementary response to the human agent gesture. This behavior is suggestive of a more complex mechanism than the simple reenactment of perceived actions postulated by ideomotor theories (Sebanz, Bekkering, & Knoblich, 2006). Ideomotor theories (Greenwald, 1970; James, 1890; Jeannerod, 1999; Prinz, 1997) predict that the specific actions of others can selectively affect one's own actions, as observed in mimicry (Chartrand & Bargh, 1999), priming (Wegner & Bargh, 1998), and imitation (Brass, Bekkering, & Prinz, 2001; Prinz & Meltzoff, 2002). According to these theories, when an observer perceives somebody else performing a body gesture, the perception of that gesture will tend to activate its execution by the observer. As a result, the observer will tend to reenact the observed action.

In this study, the human agent stretched her hand toward the right: If participants had simply reenacted the human agent's action, we should have observed a deviation toward the right. The fact that we observed a deviation toward the left—that is, toward the human agent—suggests that participants did not simply activate the representation of the gesture made by the human agent, but the representation of the complementary action. In other words, they responded to the perturbation by programming an appropriate complementary action.

As noted by Sebanz et al. (2006), although social interaction may sometimes require imitative kinds of movements, in many situations imitating the actions of others would be dysfunctional. Successful interaction requires instead that the complementary movement be selected. A possible mechanism by which this form of complementary coordination might be achieved was proposed by Wilson and Knoblich (2005). Assuming that perceiving other people's behavior activates imitative motor plans in the perceiver, they suggested that these motor plans are used simultaneously for predicting the future course of others' actions and for planning an appropriate complementary action. This account implies that a

rapid integration of self- and other-produced actions in real time can be achieved. Given the online nature of our tasks, it is tempting to speculate that the incongruent manipulation effect observed in our study is achieved through a similar real-time integration mechanism. Because request gestures usually occur in a cooperative context involving complementary actions, this may well explain why seeing such gestures automatically activates the corresponding "giving" motor program.

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(Appendix follows)

Appendix

Simple Baseline Break Detection Algorithm

Following is a description of the semiautomatic procedure used to determine the moment at which the hand began to deviate in the perturbed trials.

The algorithm uses the trapezoidal rule to compute the integral of an array relative to a baseline value:

n = number of samples; h = sampling interval;

b = baseline value, $n = \{a_0, a_1, \dots, a_n, -1\}$

$$I(a, b, n, h) = \sum_{i=0}^{n-2} \left(\frac{(a_i - b) + (a_{i+1} - b)}{2} \right) h.$$

This can be computed more efficiently as

$$I(a, b, n, h) = \left(\frac{h}{2} \right) \left(a_0 + 2 \left(-b(n-1) + \sum_{i=1}^{n-2} a_i \right) + a_{n-1} \right).$$

Beginning at trial onset, the algorithm computes the integral of a section (window) of the array, the duration of which can be modified by the user. Baseline for the integral is taken as the amplitude of the first sample (data

point) of this window. The window then shifts 1 data point to the right and the second integral is computed.

$$F(a, i, n, h, w, m) = \begin{cases} 0 \leq i \leq n - w: & \left(\frac{h}{2} \right) \left(a_{i+w-1} - 2na_i + 2 \sum_{j=i+1}^{i+w-2} a_j \right) \\ n - w < i < n: & a_i \\ i \geq n: & a_{n-1} \end{cases}.$$

where w = window size, adjustable by user, and m = multiple of a_i , adjustable by user. The integral is evaluated for each subsequent window until the result exceeds the product of a user-determined multiple (of integral) and the integral of the first data point of the current window. With presentation of this result, the user chooses to accept, adjust, or reject. New values for window duration and baseline multiple can be entered to improve the ensuing selection procedure. With rejection, this sliding calculation of the integral continues until the end of the array.

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