

Human-robot adaptive control of object-oriented action

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Summary. This chapter is concerned with how implicit, nonverbal cues support coordinated action between two people. Recently, neuroscientists have started uncovering the brain mechanisms involved in how people make predictions about other people's behavioural goals and intentions through action observation. To date, however, only a small number of studies have addressed how the involvement of a task partner influences the planning and control of one's own purposeful action. Here, we review three studies of cooperative action between human and robot partners that address the nature of predictive and reactive motor control in cooperative action. We conclude with a model which achieves motor coordination by task partners each adjusting their actions on the basis of previous trial outcome.

1.1 Introduction

Social skills are what largely distinguish humans from other animals and they are considered to underpin the development of our civilization in the process of evolution [8][19]. It has been suggested that altruistic interaction among organisms in kin selection or prosocial reciprocity increases the chance of 'survival' [5]. In particular, cooperation, an act of working towards and achieving a shared goal with other agents, is a useful strategy to accomplish tasks that are otherwise inefficient or impossible to complete by a single person. From a psychological perspective, there is growing research interest in so-called *joint action*, an umbrella term which covers any form of social interaction between two or more people [41]. A series of studies on joint action has provided compelling evidence that the manner in which the central nervous system (CNS) represents the external world is constantly influenced by the presence of others. In particular, actions performed by others elicit similar neural changes to when the action is performed by oneself [42][49]. It has been proposed that this alteration of neural state is evidence for emulation of others' actions using one's own motor system, so assisting humans to appreciate action intentions of others and to engage in cooperative or competitive behaviours [26][38]. While

these studies have advanced our understanding of the cognitive architecture of the perceptual-motor systems that support joint action, only a small number of studies have directly addressed how the involvement of a task partner influences the planning and control of one's own purposeful action (e.g., [3][30][35]). In this chapter, we describe recent developments in our understanding of interpersonal interaction and present new studies that highlight predictive and reactive motor control during cooperative action.

1.2 Feedforward and Feedback Control in Single-Person Movement

Sensory-motor systems are subject to internal errors, including inaccurate target specification due to sensory noise and faulty movement execution due to motor noise, which manifests as fluctuations of movement over repetitions [13]. One approach to overcome such error is through on-line corrections wherein on-going movements are continuously monitored using sensory feedback and any difference between intended and actual movement is corrected whenever an error is detected. A weakness in this feedback control scheme is that the motor response is subject to a significant time delay caused by the relay of the sensory signals from the sensors to the cerebral cortex and the subsequent implementation of an appropriate response. In the case of object-lifting with precision grip (opposed thumb and index finger) by a single actor, somatosensory feedback about object slippage on the digits induces an adjustment of the grasping force to prevent further slippage, which lags at least 80-100 ms behind the onset of the slippage [23]. Given that the spinal reflex takes about 30 ms to trigger a reflexive response [9], the motor correction in response to slip is considered to require supraspinal structures. Another method for overcoming motor error is through learning and adaptation. In feedforward control, the CNS implements action using a model containing information regarding the expression of the motor commands in the environment and their action consequences, information learned from previous interactions in the same or similar environments [55]. An appropriate motor prediction can then be generated by inverting this internal model. Some theories of feedforward control suggest that the CNS generates predictions about the sensory consequences of a given action in order to help make that action become more accurate [24]. Hence, when the same movement is repeated, the CNS learns and adapts the movement to reduce the chance of making the same error by adjusting motor outputs [55]. It is thought that feedforward and feedback control are flexibly integrated depending on the nature of the task and its familiarity. In general, the CNS initially implements a control policy that is more reliant on feedback control and it gradually shifts towards feedforward control as the actor learns the task.

1.3 Sensory-Motor Control in Cooperation Action

In contrast to individual action, cooperative action between two actors involves two independent sets of movements that are coordinated in time and space. Thus, the manner in which two partners intend to perform an action together may not at first be complementary to each other. A verbal exchange could be sufficient to share a general motor strategy for action such as the path to follow in picking up and moving an object together. Nevertheless, cooperative action with another person does not necessarily require conversation; other forms of sensory input can provide sources of information enabling prediction of a partner's action. As noted above, sensory-motor systems are subject to internal errors, including inaccurate target specification due to sensory noise and faulty movement execution due to motor noise [13]. When the motor outcome deviates appreciably from the intended movement, the CNS adapts and refines the output signal to minimise the risk of making the same error again [55]. Such adaptive behaviour can be accounted for by simple linear models [47][53]. In these models, motor output in a subsequent response is adjusted by some proportion of the observed error from the desired state in the previous movement. In principle, various adaptive models conform to this structure [1] [27][36]. This 'error-based learning' plays a key role in optimising anticipatory movements in individual action [47]. Similarly, evidence indicates that interpersonal motor adaptation may be based on previous performance error during cooperative action. In a study by Schuch and Tipper [40], participants either performed a speeded choice-reaction-time task or observed another person performing the same task. When a participant performed the task and made a mistake, the reaction time in the subsequent trial was slowed, a phenomenon termed as post-error slowing [34]. Interestingly, their results showed that the reaction time was also slowed after observing somebody else making the error. This study demonstrates that observing another person's error influences that observer's subsequent behaviour, strengthening the argument for the existence of common mechanisms for processing one's own errors and the errors of others [31]. In a recent study in our own lab we have more direct evidence of error-based learning in joint action involving cooperative lifting of a rigid bar. We examined cooperative object lifting using a humanoid robot as a task partner to precisely control behaviour of one of the partners so we could understand how a particular movement characteristic of the partner (i.e., robot) influences the action of the human participant. Participants sat at a table and grasped a 6DoF force transducer attached to one end of a bar; a robot held the other (see Fig. 4.1a). Their task was to lift the bar so it remained horizontal throughout the lift. The robot was programmed to produce a vertical movement trajectory based on a minimum-jerk trajectory [15] with a target movement height and duration of 40 cm over 3 seconds. In this, and the following studies, participants closed their eyes and wore a pair of headphones to prevent any visual or auditory feedback during performance.

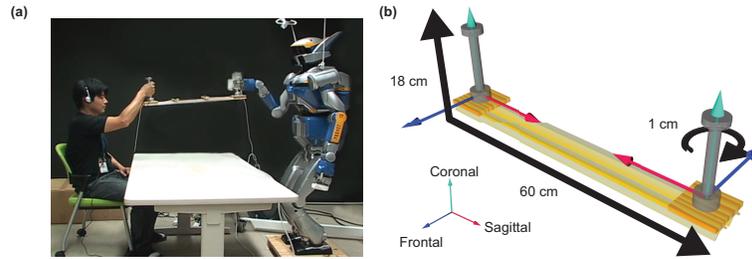


Fig. 1.1. (a) Experimental setup. HRP-2 (Kawada Industries, Japan) is a full-sized humanoid robot with 30 degrees of freedom (DoF). For this lifting task, only the 6 DoF of the right arm were used. A participant sat in front of the robot and jointly lifted a bar. (b) A schematic illustration of the bar. The bar consisted of two handles with force transducers attached onto their bases. The orientation of the transducers was expressed in ego-centric coordinates with respect to each partner.

We measured the maximum difference in the height of the two handles (i.e., position error), difference in the peak velocities of the partners (i.e., velocity error), and the maximum sagittal force and frontal torque (task-relevant) in order to study whether participants could improve cooperative performance with practice. Fig. 4.2 shows changes in these variables over 15 repetitions (averaged over 10 right-handed participants). Performance rapidly improved over successive trials, as shown by the reduction over a couple of trials in the position and velocity errors. The sagittal force reduced over trials, but more slowly over many trials. Thus, the smaller sagittal force is unlikely to be a simple by-product of reduced coordination error. Importantly, the sagittal force exchange between the partners is redundant (i.e., task irrelevant) to the primary goal of the task. Therefore, the reduction of the sagittal force may be linked to minimising redundant interaction in cooperative action [21].

The results so far show evidence for motor adaptation to a task partner, when the robot repetitively executes an identical motion. However, performance of a human partner may vary from trial to trial. For example, various factors can influence one's action including a variety of internal factors such as sensory and motor noises in the CNS [13], exhaustion [28], or individual preference as well as external factors such as the presence of an obstacle in the movement path [18]. Thus, in another experiment, we investigated how people minimise an unpredictable motor error induced by a task partner. In this part of the study, the robot randomly introduced two perturbed trajectories (Retarded and Advanced, Fig. 4.3a) in addition to the previously used unperturbed trajectory (Standard). In Retarded trajectories, there was a sudden linear retardation in the velocity profile such that 70 ms after the perturbation onset, the vertical position of the gripper was 1.0 cm lower than at the equivalent time in the Standard trajectory. The Advanced trajectory was analogous to the Retarded trajectory except that this perturbation caused an advance of the time of peak velocity. The perturbation trials were randomly inserted

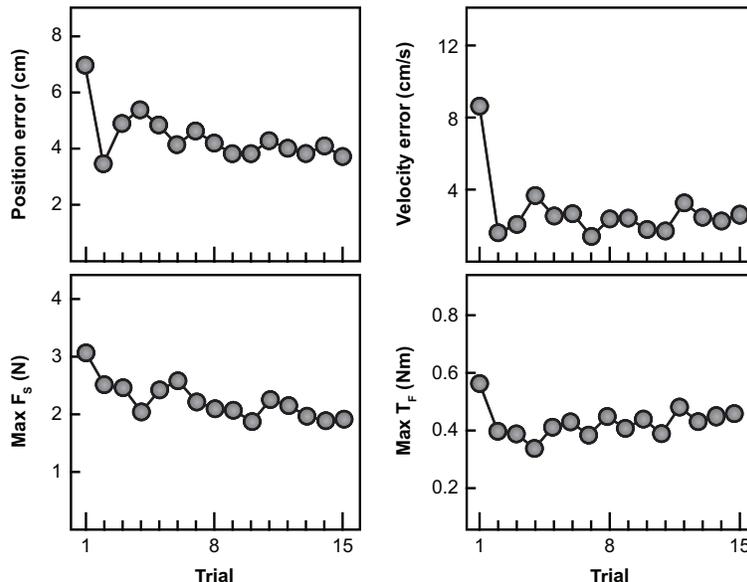


Fig. 1.2. Learning cooperative lifting. The position error, velocity error, maximum sagittal force (F_S), and maximum frontal torque (T_F) of participants when interacting with each trajectory type presented in the different conditions/blocks of trials.

between the Standard trials but they never occurred in adjacent trials. There were 15 Advanced and 15 Retarded trials and 90 Standard trials.

Fig. 4.3b shows the averaged kinematic differences between the participants and the robot. When an unpredictable robot movement was detected during lifting, the participants still managed to follow closely the robot's trajectory after an initial delay of approximately 150 ms (Fig. 4.3c). This is noticeably longer than the 80 ms or so taken, according to the literature, by the supraspinal reflex for movement correction via the somatosensory system [23]. Thus, in response to a sudden perturbation, the participants adjusted their on-going action to re-synchronise their own action to their partner's action, though the response was delayed possibly due to complex haptic feedback underlying cooperative object lifting. We recently obtained evidence of such use of haptic feedback in a two-person object lifting study in which we removed partners' torque feedback by adding ball bearings at the grasp points. This significantly disrupted motor coordination and between-trial learning compared to two-person object lifting task with fixed grasp points (ch4-Endo-sub1). In the human-robot cooperative lifting study, the on-line error correction was smoothly introduced and completed at around the deceleration phase of the lifting movement, with the Advanced trials associated with slightly faster recovery. Taken together, the two human-robot cooperative lifting studies

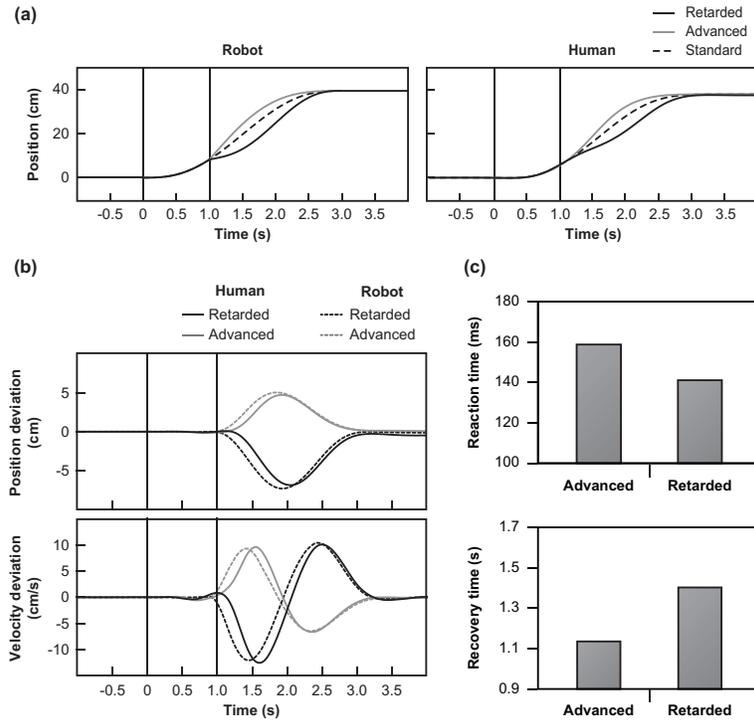


Fig. 1.3. (a) An example of movement trajectories by the robot and participant. The robot’s control signal instead of the recorded motion data was depicted. Averaged Standard, Advance, and Retardation trajectories from a single participant are presented. (b) Kinematic divergences of averaged Perturbation trajectories from the Standard trajectory of a single participant. The position and velocity profiles of the Standard trajectory were subtracted from the Perturbation trajectories. (c) The reaction time t_0 , and recovery time from, the Advance and Retardation perturbations.

demonstrate that the participants performed cooperative action using a form of control that could be flexibly switched between predictive and reactive modes depending on the reliability of the partner’s movement.

1.4 Mutual Error-based Learning in Cooperation

The above studies demonstrate between and within trial adaptation that people use to cooperate with a robot task partner that did not adapt to the human partner. Thus, in this sense at least, the partnership was asymmetric. In practice, purposeful interpersonal interaction does often involve asymmetric yet complementary actions. Simulation studies have suggested that asymmetric involvement in a task can effectively reduce conflict in cooperative interac-

tion [33][51]. Furthermore, differential role assignment has been associated with more flexible adaptation to environmental changes [45]. Behaviourally, functional asymmetry has been demonstrated in a situation where two people each apply force to achieve a shared goal. Reed and colleagues [35] used a device that allowed recording of forces created by two partners, which was a rotating table with two handles attached at each end. Using this device, paired participants grasped and moved one handle each to meet the visual target as quickly as possible. Even though the participants were instructed to refrain from verbal communication, they rapidly developed a strategy such that one was more involved in accelerating the device and the other in deceleration. The study by these authors, therefore, indicates that functional specialisation can be observed at an interpersonal level of action coordination. Hence orchestrating two effectors by functionally specialising the effectors in subtasks rather than producing identical movements may be an effective strategy. In motor interaction between humans, the movement coordination of two people is inter-dependent. Thus, the task partners may need to compromise their own individually preferred courses of action and adapt their own motor output to that of their task partner [10][46][48]. For example, either intentionally or unintentionally, the presence of others influences the timing of our behaviour. Thus, behavioural synchronicity of people, termed entrainment, has been reported in various forms and sizes of interaction such as dyadic walking rhythm [50][56], body gestures /citech4-Chartrand-1999 and conversational pattern /citech4-Wilson-2005. In a study by Richardson and colleagues /citech4-Richardson-2007, for example, paired participants sat on a rocking chair side-by-side and rocked the chair at a preferred frequency. Without instruction to do so, the participants started synchronising their movements to each other. On a much larger scale, spontaneous interpersonal movement synchronisation was reported in the hand clapping pattern of thousands of members of the audience at a concert hall /citech4-Neda-2000. Frequently, behavioural interactions of two people have been modelled in terms of a dynamical system. Namely, it has been proposed that two different sets of movements interact and mutually influence each other's state in order to find a stable solution /citech4-Oullier-2008/citech4-Schmidt-1998 or reduce their differences /citech4-Felmlee-1999/citech4-Kon-2005 in temporal motor coordination tasks. These studies provide specific predictions about how people may coordinate their movements with each other. However, the interaction process has not previously been studied in terms of cooperative goal-directed action such that the mutual interaction should relate to optimal performance of a cooperative outcome rather than merely reflect coordination of two sets of movements. In contrast, we recently studied how adaptation by a task partner affects own motor adaptation. In this joint adaptation task, the participant lifted an object with the robot, but now the robot's speed of the lifting was determined by a simple model, which reduced the peak velocity difference between the partners.

$$Z_{Rn+1} = Z_{Rn} + \alpha_R(Z_{Hn} - Z_{Rn}) \text{eq.4.1} \quad (1.1)$$

where Z_{Rn} is the peak velocity of the robot at Trial n and α_R is the adaptation rate which reduces the mismatch with a human partner. Over trials the adaptation rate of the robot was either fixed ($\alpha_R = 0.8, 0.5, 0.2,$ or 0.0), or varied randomly between 0.0 and 1.0 in 0.1 increments. In order to keep the bar level the human participant would need to match the velocity of the robot. One way to do this would be to adjust the peak velocity;

$$Z_{Hn+1} = Z_{Hn} + (w - \alpha_R)(Z_{Rn} - Z_{Hn}) \text{eq.4.2} \quad (1.2)$$

where w is the net adaptation rate which would be set to unity for the most rapid reduction in error. It was therefore predicted that participants would increase their adaptation rate when that of the robot was small, and vice versa. In the case of the randomly varying rate it was expected the human partner's adaptation rate would equal the average rate of the robot. On the other hand, if the adaptation rate of the robot was not taken into account, it was expected that the adaptation rate of the human partner would be similar across the different correction gains of the robot. The adaptation rate of each participant (α_H) was approximated using the slope coefficient of the linear regression, with interpersonal difference of the peak velocity at a previous trial and the peak velocity adjustment made from this trial to the next trial as variables (Fig. 4.4a).

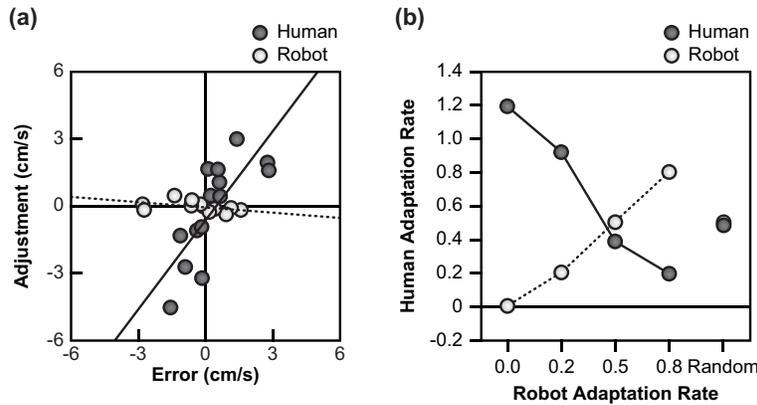


Fig. 1.4. (a) A scatter plot of an error and subsequent adjustment in the peak velocity from a single participant and the robot. The slope coefficient of the least-square-error represented the adaptation rate. (b) The adaptation rates of human participants across different rates set by the robot.

The results show that α_H generally varied inversely with α_R (Fig. 4.4b). Simple linear regression analysis confirmed that there was a negative relationship between α_H and α_R such that the increase of α_R led to a decrease

of α_H . The analyses provided clear evidence that human participants flexibly modulated their correction gain so that the summation of α_R and α_H (α_{NET}) remained constant at around -1. This study provides clear evidence that people can implicitly and flexibly adjust their adaptation rates with regard to the adaptation rate of their partner in order to optimise the performance at a cooperative level. This modulation of adaptation rate may crucially underlie social interaction, which enables people to respond flexibly to other people's actions in a wide variety of social interactions and thus facilitate goal-directed behaviour in joint actions. In this study, we used the regression between the motor error and subsequent adjustments to estimate adaptation rate. However, this method is susceptible to increasing bias as proportion of the error (adjustment) signal over the sensory-motor noise decreases /citech4-Vorberg-2002. However, this problem can be rectified by inserting random perturbations and measuring resulting responses and we recently completed a new study utilising this method /citech4-Endo-sub2. This study also showed complementary gain setting, albeit with lower adaptation gain than seen when cooperating with the robot.

1.5 Determinants of an adaptation rate

This joint adaptation study demonstrated that people can effectively accommodate contribution of an adaptive partner in a cooperative task so that the summed adaptation rates of the partners are sustained at a certain level. However, it remains unclear how a dyad delegates the adaptation rates between its respective partners. Recently, Braun and colleagues /citech4-Braun-2009 have described cooperative behaviour in terms of efficient decision making. In their study, two participants jointly moved a handle to a target, but the force required to move the handle in space varied. When they chose a "cooperative" path, the participants both received resisting spring force of 3 N/m towards the start position as they moved the handle to its target. When they both chose a "defective" path, they experienced a higher spring force of 7 N/m. When one person selected the "cooperative" path but the other one did not, the former received 10 N/m spring force and the latter experienced no spring resistance (0 N/m). Under such circumstances, the participants chose the "defective" path whereby their partner would never be at an advantage. When they performed the same task bimanually, in contrast, the participants actively achieved the cooperative solution. Thus it seems that people are estimating costs of relying on their partner when they make a decision about how they should perform the task. Although this study showed a tendency for people to optimise their individual action over cooperation, there is evidence suggesting that people do not simply discount the performance of others, but rather track the probability of their partner's reliability in making a decision. In a study by Behrens and colleagues /citech4-Behrens-2008, participants performed a decision-making task wherein a correct response could be predicted

by the pattern of previous correct responses as well as by a clue provided by a confederate. The reliabilities of the reward-based learning and confederate advice were independently varied to study how the participants' decision-making was influenced by the statistical properties of the reward prediction error and confederate prediction error. The results revealed that the participants could learn both reward and social value in a similar fashion but independently. This study provides strong evidence that the optimal response in decision-making is in consideration of both probability of the correct response and the probability of the correct advice by the confederate. Thus, the degree and type of joint adaptation may depend on the cost and gain of the cooperation outcomes as well as on other task-relevant information such as motor noise. These issues are particularly relevant to extending the joint adaptation model to a stochastic (i.e. probabilistic) model, and to understanding how the statistics about a task partner are established through the course of interaction.

1.6 Social Task Partner in Cooperative Action

In order to implement a specific reference trajectory for one of the pair, the studies from our lab that we described used a humanoid robot as a task partner. There is a continuing debate about the way people interact differently to movements of another person compared to non-biological agents. It is well known that people are tuned to detect biological motion and can extract a range of personal and psychological attributes from only a few points of markers representing movements of joints of a person such as the elbows and the shoulders [6][2][43]. Previously, it has been shown that believing one is coordinating an action with a human or a robotic partner can result in different behavioural responses by the perceiver regardless of whether the action is of human origin or a simulation of robot motion [44]. In addition, differences in neural responses have been demonstrated during observations of biological compared with non-biological movements, especially when the latter lacked the natural variability of human movements [16] or the former followed a non-Gaussian velocity profile [25]. In our study, although the robot executed minimum-jerk movements, which are known to closely approximate simple human arm movements, nonetheless the observer was fully aware from visual cues that he was interacting with a robot. Thus, caution should be exercised in generalising the conclusions regarding the results of this experiment to include natural social interaction between people. Nevertheless, it is interesting to explore how the adaptive behaviour described here is influenced by the social knowledge about the partner. For example, interpersonal interaction is known to be influenced by certain attributes such as emotional states [17][22], relative physical characteristics [20] as well as the history of interaction [32]. We therefore believe that the approach we have presented can potentially provide a useful platform for investigating social determinants of interpersonal behaviour.

1.7 Conclusions

While researchers have generally tackled the challenge of understanding the human brain by focusing on a single actor interacting with a controlled environment, there is a growing appetite in neuroscience for investigating how the CNS operates at a social level. In particular, much attention is being paid to those studies of 'joint action' which are laying foundations for an understanding of how people represent conspecifics in the CNS [41]. However, there have been very few studies specifically focusing on the sensory-motor interactions between people. In this chapter we have described an approach to the study of joint action that focuses on the movements of the partners. In this manner we have described how the CNS learns and controls movement with respect to concurrent movement executed by a partner thorough feedforward and feedback control.

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