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Adaptation to a humanoid robot in a collaborative joint task

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Abstract—**Mutual synchronization plays a decisive role in effective collaborations in human joint tasks. Interaction between humans and robots need to show similar emergent coordination. To this aim models of human synchronization have recently been ported on collaborative robots with success [1]. However, it is also important to consider under which conditions the human partner is willing to adapt to the robot while performing a joint task. The main research goal of this study is to understand whether the temporal adaptation usually observed during human-human interaction occurs also during human-robot cooperation. We present a collaborative joint task engaging both human subjects and the humanoid robot iCub in pursuing an identical common goal: putting blocks into a box. We examine human action timing, evinced from motion capture data, in order to investigate whether humans adapt their behavior to the robot. We compare a quantitative measure of such adaptation with the subjective evaluation extracted from questionnaires. We observe that on average participants tend to adapt to their robotic partner. Nevertheless, by looking at individual behaviors, only few showed a clear adaptation to its timing, despite the vast majority of the subjects reported to have been influenced by the robot. We conclude discussing the potential factors influencing human adaptability, with the suggestion that the speed of execution of the robot is determinant in the coordination.**

I. INTRODUCTION

Humans show a great efficiency in joint actions. This skill is the result of a combination of planned collaboration and emergent coordination [2], a collection of unconscious phenomena including mutual adaptation and synchronization, which facilitates the establishment of a smooth interaction. As a result, typical social behaviors take into account and minimize differences between the two partners in task execution, with each agent mutually adapting to the counterpart. For instance, when walking with someone else, we tend inadvertently to adapt to each other's walking speed and after observing someone else moving, we tend to automatically imitate the pace of their actions [3]. Recent robotics research proved that the synchronization of movements plays an essential role in the interactive behavior of humans. Such research investigates novel methods of goal-directed synchronization for robotic agents in repetitive joint action tasks, to promote optimal collaboration strategies [1]. Making the robot adapt to the human partner's timing has indeed been proven to make interaction more fluid and pleasant (e.g. [4] [5] [6]).

However, the adaptation between humans is often "mutual", therefore it might be relevant that also the human partner changes his behavior as a function of collaborator's behavior in a joint task. In current applications, when it is important to maintain a stable pace in action execution in the interaction with a machine (e.g., in chain production), the compliance of the human user is often enforced, with no possibility for the user to diverge. The use of humanoid robots might however trigger an automatic adaptation to the robot rhythm, leading to a more fluid and less fatiguing coordination. Indeed, there is evidence that humanoids moving according to biological motion rules can actually trigger automatic imitation, but so far the demonstration has been limited to actions performed in sequence and not embedded in a joint coordination [7]. Hence, it becomes important not only to propose robotic interactive behaviors that adapt to the human partner, but also to understand which of these behaviors are most effective in triggering a corresponding adaptation by the human partner.

To this aim, in this paper we investigate whether humans naturally adapt to the pace of a humanoid robot during a joint task, even though this is not required for task completion, and to which extent they aim for synchronization even when this requires a stronger modification of their execution timing. Furthermore, we want to understand how people perceive the influence of robot behavior on their own and which cues result for them relevant in the interaction.

To achieve this we designed an experiment in which a subject had to execute a joint task with the humanoid robot iCub. The two had to fill a box with Lego blocks provided in their hands. We altered the speed with which the robot iCub accomplished the action from relatively fast to very slow, in order to assess the willingness of the human counterpart to adapt in order to maintain synchronization. Last, we asked subjects their subjective evaluation about being influenced by the robot behavior. In the following sections we describe the experimental procedures and the measures examined (section II), we present the quantitative and subjective results (section III) and discuss their implications for future work (section IV & V).

II. METHODS

A. Experimental Design

We designed a joint task experiment to perform this study. The subject's assignment was to fill a box with Lego blocks, together with the iCub robot, sitting at a table face to face with the humanoid. Each trial started with an

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experimenter putting simultaneously two blocks, one in the open hand of the subject and one in the robot hand. This passage occurred only when both agents had their hands in a specific area (Start Zone, see Fig. 1). Therefore, robot and human actions always started at the same time, as each block was passed only when both the robot and the human moved their hand back to the starting position. The robot transported the object on its open palm, let it fall into the box and returned to the starting position with a preprogrammed action, which complied with biological motion kinematics (see subsection B for more details).
Subjects performed 2 sessions, each consisting of 10 repetitions (i.e., ten transport actions). We changed the speed of the robot hand between the two sessions to check how people adapted according to this parameter. After a few pilot tests we chose the speed that allowed the robot to accomplish the task in a reasonable time (the "Fast" speed). Then, we selected a slow speed value, forcing the subjects to put a consistent effort if they wanted to synchronize with the robot (the "Slow" speed). This way we could have a clear distinction between who was and who was not willing to adapt to iCub. The actual average speed of the robot was verified by computing it from the data recorded from the robot middle finger marker by the motion capture system (see Table I and Sec. IID for details).

TABLE I. Measured speed of the robot hand

Condition	Robot Mean Speed
Slow	0.084 m/s
Fast	0.151 m/s

Seven subjects started with the slow movement and eight with the fast.
After the experiment, subjects were asked to fill a short questionnaire to gather information such as gender, age, handedness, experience with robots (1 none, 2 low, 3 medium, 4 high).
In addition we asked:

- Which parts of the robot did you pay more attention to during the interaction?
- Do you feel that the behavior of the robot influenced your actions? If yes, how?

We gave the possibility to add open comments about the interaction with the robot.

B. *Biological Movement Implementation*

We control robot movements by using the existing Cartesian controller interface [8] governed by a new high level controller built according to the Two-Thirds Power Law [9]. This is a common regularity of human motion, resulting in a maximization of action smoothness [10]. We decided to implement a motion complying with biological rules since it has been shown that biological kinematics is crucial to enable automatic imitation in HRI [7]. In particular, the law relates the curvature of the movement

Figure 1. Experimental setup

with the execution speed, generating faster motions when the curvature is low and slowing down at the increase of curvature. Given a specific trajectory, the controller provides a solution movement that is then executed with the Cartesian Interface. The motion pattern was pre-programmed and consisted of iCub repetitively transporting a Lego block on its open hand and releasing it into the box from above. To assess the impact of robot motion on the coordination, we decided to keep the oculo-motor behavior of the iCub very simple, making the robot follow its hand with its gaze during the whole trial.

C. *Subjects*

The experiment was performed by 15 participants (Mean age 30 years± 5 SD, 6 males, 9 females, 1 Left handed, 14 right handed).
The institutional ethics committee approved the protocol and all subjects gave informed consent before participating.

D. *Data*

Data collection included video recordings of each trial for each subject from two different points of view, kinematic data of the hand and arm performing the action acquired with Vicon motion capture system (both of the subject and the robot) and questionnaires. We acquired kinematic data with 4 markers: 3 on the hand and 1 on the elbow of both the subject and the robot (Fig. 2). We have position and speed in x,y,z coordinates of all the markers, for each time frame (100 Hz). We extracted the start of the action and the drop of the object. The starting instant is considered when the hand leaves the area in which the block is received from the experimenter (Fig. 1). For the subject we considered the wrist marker, for the Robot we considered the middle finger marker.
For what pertains object drop, by inspecting the videos, we found that 3 main different strategies were used by the subjects: some subjects accompanied the block into the box before placing it, some dropped the block from above the box and returned to the starting position, and some dropped the block and then waited with their hand in the box area. Therefore we decided to measure the approximated time of release through analysis of the kinematic data with different approaches, depending on the different strategies observed in the videos. For the former group (8 subjects), the last minimum of the speed computed on the wrist marker within

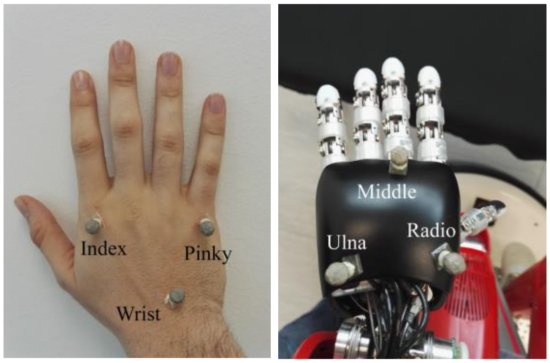

Figure 1. Markers position on the human (left) and robot (right) hands

the box area was considered the release moment. For the second group (2 subjects) the release moment corresponded to the instant in which the index and the pinky markers were on the same vertical plane, in the box area, indicating the hand rotation to drop. For the latter group (5 subjects), the release moment was considered in correspondence to the first speed minimum of the wrist marker within the box area. Visual inspection of the videos of a subset of trials confirmed that the estimate of the time of object release was accurate for the different strategies.
For the robot we considered as release moment the last minimum of the speed computed on the middle finger marker within the box area.

E. Measures

We examined the duration, expressed as the time interval between the start of the action and the release of the block for each repetition.
To assess the similarity between subject's and robot transport duration we computed the absolute value of the difference between the mean duration of the robot and that of the subject, averaged across the slow and the fast conditions. A zero value would indicate that the subject has the exact same duration as the robot.
We then evaluated the variation of subjects' action duration when the robot was performing slow and fast movements and compared it with the percentage change in robot duration between the two conditions. To compute this value, we plotted subjects' transport durations as a function of robot transport durations in the same condition. Then we computed the slope of the line connecting the two points for each individual and computed the absolute difference from 1 (the ideal value corresponding to an exact copy of the variation in speed of the robot). This gives a measure of how much the subject adjusted his/her duration, according to the change of iCub's duration (Fig.3).

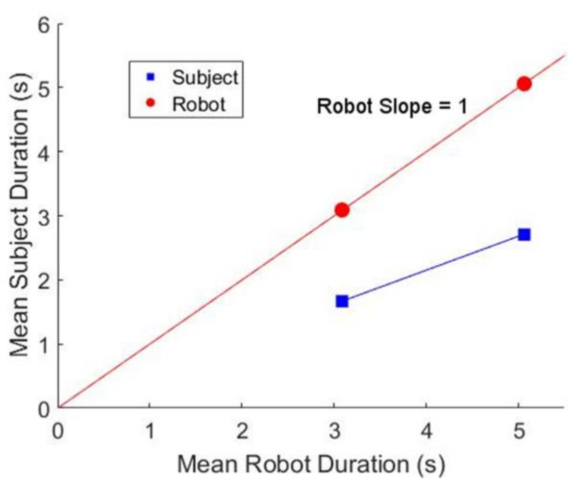

Figure 3. Example of the "Slope" computation, i.e., quantification of the variation of subject's action duration as a function of the corresponding variation of the robot action duration

III. RESULTS

The general aim of this study was to investigate whether people are prone to adapt to the action rhythm of a humanoid robot during a joint task and whether they are conscious of their adaptation. To achieve this we compared the duration of the transport action, from the beginning of the movement to the drop of the object, and how much this duration changed as a function of different robot action timing.

A. Mean Duration

First of all we looked at the average duration of the robot actions in the two velocity conditions and the corresponding average duration of the subjects. Two sample t-tests showed that human actions lasted significantly shorter that the robot ones at both speeds (Tab. II).

TABLE II. T-Test for the comparison of the durations of the transport actions between the subjects and the robot

Condition	T Test result
Slow	$t(13) = 7.0709$ $p = 1.6509e-07$
Fast	$t(13) = 7.3920$ $p = 7.5347e-08$

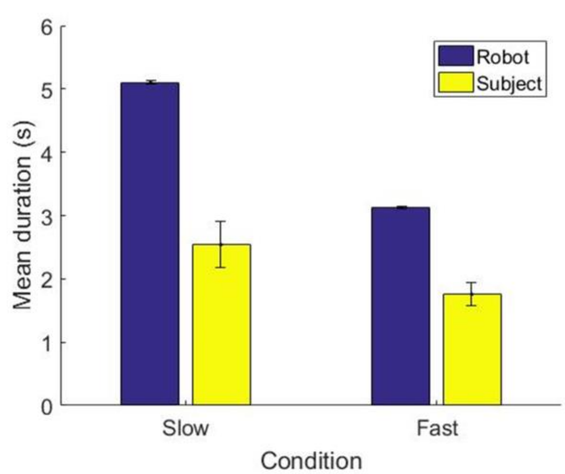

Figure 4. Mean duration comparison

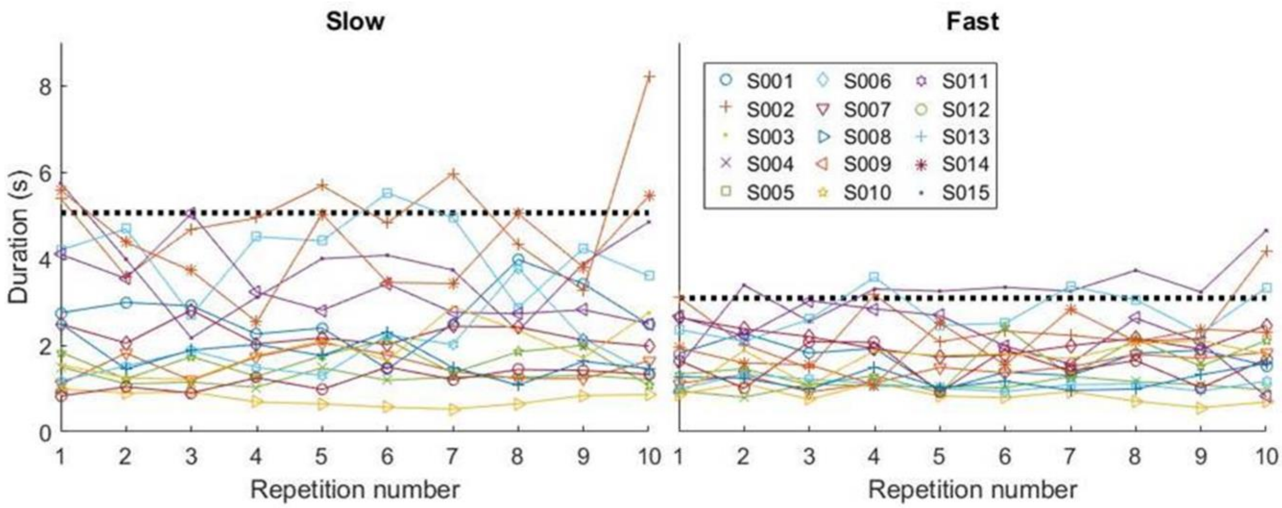

Figure 5. Repetition Effect. Different symbols represent different subjects, the dashed black line indicates the average duration of the robot transport actions in the two conditions.

However, comparing participants' actions in the two conditions, their transport duration when iCub was slower was significantly longer than when iCub moved at a faster pace (Fig. 4, paired t-test: $t(13) = 3.25$; $p = 0.006$). This result implies that on average subjects were influenced by robot action timing, significantly slowing down their transport when it moved at a slower pace. Then, we decided to deepen the analysis, inspecting whether this adaptation changed over the repetitions of the same session.

B. Repetition Effect

In the panels of Fig. 5 are represented the durations of all task repetitions for each subject in the fast and slow conditions. No clear adaptation can be seen from the figures with the progress of repetitions. Looking at individual timings, a division seems to emerge between subjects: some (e.g., red cross and orange star symbols) change their average duration to keep it similar to the robot in both conditions, while others (e.g., yellow triangle and purple circle) always move independently from it. This outcome persuaded us to expand the analysis introducing two parameters to quantify more in detail the degree of adaptation at the individual level.

C. Individual Adaptation

We consider two relevant parameters for the estimation of subjects' adaptation: a) the absolute value of the difference between the duration of the robot action and that of the subject, averaged between the slow and fast conditions, and b) the difference between variation of speed in the subject and variation of speed in the robot in the two conditions (see Methods and Fig. 3 for details).

The first parameter (Duration Difference) gives a measure of how similar to the duration of the robot is the mean duration of the subject. The second parameter (Slope Difference) returns a measure of how much the subject adjusted his/her speed, according to the variation of iCub's speed (Fig. 3). For both parameters lower values mean more adaptation.

From Figure 6, where these parameters are plotted on the X and Y axis for each individual, it emerges a gradual degree of adaptation among the subjects. To simplify the analysis we decided to split the sample into two main groups only: the markers down left represent subjects that are more eager to synchronize with the robot or imitate its movements, whereas the other markers show who moved with a timing independent from it.

D. Questionnaires

To assess the subjective evaluation of participants' adaptation, we integrated the quantitative analysis with data derived from the questionnaires. The first analysis was aimed at assessing whether the perception of robot influence corresponded with the actual degree of behavioral adaptation we measured. Interestingly, although 90% of the subjects claimed that their motion was influenced by the robot, 50-75% did not show a strong adaptation in their behavior (panel A of Fig. 7).

Answers to the question about how they adapted were very different: some declared that they changed their speed, some their trajectory, whereas others revealed that they tried different strategies to check whether the robot was adapting to them.

We then evaluated whether the degree of adaptation was related to subjects' prior experience with robots.

In panel B we can see that 100% of the subjects who declared to have low or no experience with robots are in the group with low adaptation. Instead, in the group of subjects more conditioned by iCub movements we can find only people with medium or high experience: a two sample t-test between the two groups demonstrates that these are significantly separated both in Duration difference ($t(13) = -2.64$; $p = 0.0296$) and Slope Difference ($t(13) = -5.73$; $p < 0.001$). To assess whether the tendency to adapt to the robot was associated to different attention allocation strategies during the task, we asked subjects *"To which parts of the robot did you pay more attention during the interaction?"*.

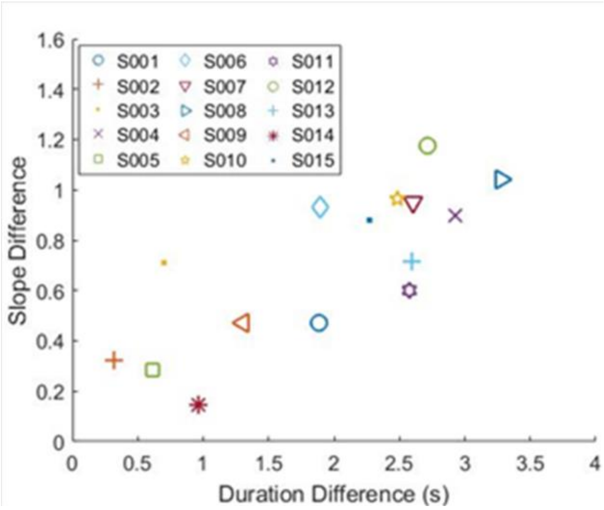

Figure 6. Degree of Adaptation. See text and Methods for variables definition.

The answer for 90% of the subjects was *"eyes"* and *"arm"* while the remaining 10% gave different answers (e.g., face, torso). By comparing the behavior of subjects who put "eyes" first with that of participants who first mentioned the "arm", it emerges that the former group exhibited a significantly stronger adaptation (Panel C, two sample t-test on Duration Difference: $t(13) = 2.82$; $p = 0.0168$ and on Slope Difference: $t(13) = 2.44$; $p = 0.033$). This result might suggests that people who consider eyes as the most important feature in the interaction tend to humanize more the robot, leading to a higher degree of adaptation.

We also explored whether the different transport and drop strategies adopted (described in the Methods) are associated to a different degree of adaptation. We can see from panel D in Figure 7 that the subjects who adopted Strategy 3 are all far from the behavior of the robot in both the X and Y dimensions. These are the subjects who grasped and placed the block into the box and then waited with their hand over the box: this means that they were faster than the robot in dropping the object in both sessions. On the contrary, the two subjects who exploited Strategy 2 are both very close to the timing of the robot: we expected this since they are the ones that imitate its transport modality (i.e., transported the block on the open palm as the robot). Results of subjects adopting Strategy 1 are more various and do not seem to show a clear common behavior.

Finally, we checked for potential differences between males and females, but we could not find any gender effect. This is confirmed by a two sample t-test between the groups (Duration Difference: $t(13) = 0.559$, $p = 0.585$; Slope Difference: $t(13) = 0.0689$, $p = 0.946$). Also the order of conditions (Slow/Fast) had no significant effect on the degree of adaptation (two sample t-test Duration Difference: $t(13) = 0.375$, $p = 0.713$; Slope Difference: $t(13) = 0.787$, $p = 0.445$).

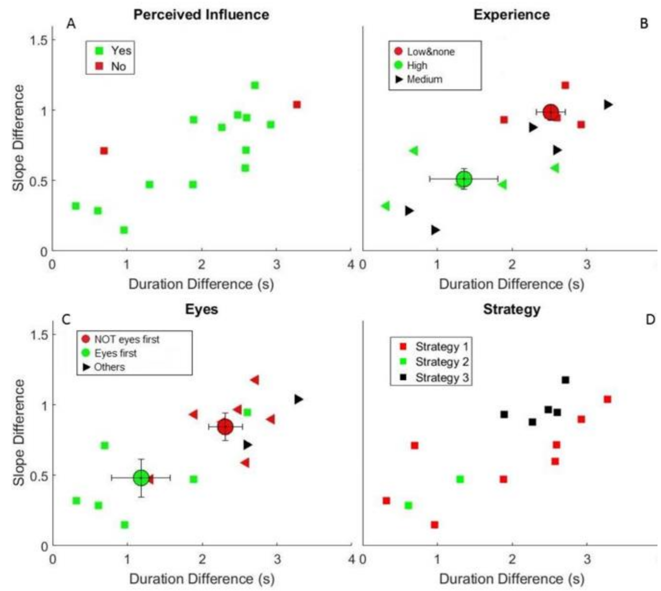

Figure 7. Adaptation Factors. Different colors represent participants belonging to different groups. In panel B and C bigger circles correspond to group averages for a subset of groups (see text). Error bars represent standard error of the mean.

IV. Discussion

Human beings have the tendency to adapt to each other during an interaction, trying to find a balance that is acceptable for both the actors involved in the action. The goal of this paper was to study to which extent a human tends to adapt to his partner during a joint task, when the latter is a humanoid robot and to assess whether he is aware of this adaptation. To measure the influence of robotic action timing on that of the human partners we measured the duration of their actions during a joint task with the robot iCub, where we fixed robot speed. The results show that although on average participants adapted to the robot by slowing their motion when the robot was slower, not all individuals were influenced to the same extent. The participants could actually be roughly divided into two groups: adaptive (about 40%) and non-adaptive (about 60%). The first group includes people who adopted task duration similar to the robot and also slowed their action when the robot slowed down, whereas the second group tended to keep a fixed pace, distinct from the robot velocity. Notwithstanding such separation, almost all participants answered that they were influenced by robot behavior in their movement. Hence, the perceived influence of the robot in general does not correlate with the actual performance during the collaboration.

To understand which factors might be important in determining the willingness to adapt to the humanoid robot, we investigated different individual characteristics. An important element seems to be represented by the previous experience with robots, as more experienced participants exhibited a higher adaptation. A possible explanation is that more experience might make participants aware of the limits of the robotic platform making them more eager to try and comply with them. Another peculiar distinction between the adaptive and non-adaptive group is the (self-reported) primary focus of attention: most people in the adaptive group reported to be focusing on robot eyes, whereas most non-adaptive participants focused at first on the robot hand. Since robotic gaze motion was not programmed to be human-like or informative for the completion of the task, we believe that the attention of the adaptive participants was driven by a-priori tendency to anthropomorphize the partner in the interaction, which might have in turn increased their adaptation. Beyond the timing, also the type of action performed (i.e., the transport and drop strategies) differed among subjects. Interestingly, the participants who selected an approach very similar to iCub, transporting the block on the palm and releasing it from above the box as the robot, also manifested a strong temporal adaptation. Hence, also the way an action is performed could be another indication of willingness to adapt to the robotic partner. Another key question is why only a small number of the participants strongly adapted to the robot. We believe that the relatively slow speed in performing the action played a relevant role in limiting the effect of automatic imitation. Beyond the increased effort required to participants to maintain an action pace much slower than their natural one, there is also the possibility that the low robot execution speed could have given a weaker implicit impression of biological movement. This hypothesis is coherent with evidence on human movements demonstrating that at very slow speeds the Two-Thirds Power Law does not apply [11].

Another reason for the lack of adaptation could be the non-natural gaze behavior of the robot, in particular the missing establishment of mutual gaze to regulate turn taking. This hypothesis is in line with previous results showing that mutual gaze enhances automatic imitation mechanisms in humans [12] and that a natural visuo-motor coordination has a significant impact on human interaction with a humanoid robot [13]. Also the responses to the questionnaires seem to confirm this view: some participants in the general comments about the interaction affirmed that with mutual gaze and an adaptive robotic behavior the feel of cooperation would have been stronger.

V. Conclusion

This study demonstrates that on average people are prone to adapt to a humanoid robot partner during a joint action. However looking at individual behaviors the degree of adaptation varies widely and seems to be dependent on the degree of experience in interacting with robots. Interestingly, however, our conclusions evidence that a vast majority of the subjects believe that the humanoid robot influenced their actions even when this was not the case. So in this context the subjective evaluation of adaption does not correctly represent interaction performance. Further, we highlight that the group of subjects that adapted most, reported to prefer to attend to the robot's eyes, showing an analogy with behavioral models of adaptation in human-human joint tasks [1]. These results imply that particular attention will be needed in the design of humanoid robot collaborative behavior if they intend to elicit an objective, rather than subjective, adaptation in the human partner to facilitate synchronization. In particular, to raise the feeling of cooperation during the task, the recommendations derived from the current work are to avoid robot low speed to reflect more accurately human movements and improve the gaze pattern of the robot: making it look for mutual gaze with the subject rather than only fixating the end effector. Of course, we expect that also the implementation of reciprocal adaptation, raising or lowering the speed of the robot according to the speed of the person will make a difference in the degree of adaptation by the human partner.

Future research will be dedicated to analysis of the role of robot kinematics during the collaboration, testing for the potential impact of non human-like behaviors on the fluency of collaboration. In addition we intend to investigate other measures of adaptation, to assess for example if people prefer to modify the speed of their action or rather wait for the robot either before or after task completion (which in the current scenario, corresponded to dropping the block).

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