

If You Are Careful, So Am I! How Robot Communicative Motions Can Influence Human Approach in a Joint Task

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Abstract. As humans, we have a remarkable capacity for reading the characteristics of objects only by observing how another person carries them. Indeed, how we perform our actions naturally embeds information on the item features. Collaborative robots can achieve the same ability by modulating the strategy used to transport objects with their end-effector. A contribution in this sense would promote spontaneous interactions by making an implicit yet effective communication channel available. This work investigates if humans correctly perceive the implicit information shared by a robotic manipulator through its movements during a dyadic collaboration task. Exploiting a generative approach, we designed robot actions to convey virtual properties of the transported objects, particularly to inform the partner if any caution is required to handle the carried item. We found that carefulness is correctly interpreted when observed through the robot movements. In the experiment, we used identical empty plastic cups; nevertheless, participants approached them differently depending on the attitude shown by the robot: humans change how they reach for the object, being more careful whenever the robot does the same. This emerging form of motor contagion is entirely spontaneous and happens even if the task does not require it.

Keywords: Communicative robots' movement · Implicit Communication · Generative Adversarial Networks · Robots' motion generation · Objects' manipulation · Human-Robot Interaction.

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1 Introduction

Humans routinely engage in joint actions and coordinate their movements with others, e.g. working together, playing a team sport, or merely moving objects. These tasks involve a collaborative process to coordinate attention, communication, and actions to achieve a common goal. During this process, humans observe the behavior of their partners to anticipate their actions and plan their own accordingly. Verbal communication is not the only means to express intentions. Since verbalizing every step of the interaction would be time-consuming and cognitively expensive, humans also exploit their bodies and movements to exchange information. While executing an intended action, we also implicitly communicate to others our goal, its urgency, and the required effort. This ability is referred to as non-verbal communication (i.e., non-verbal cues), and it can be expressed with our body: from turning the head or torso to a simple eye movement.

In ordinary life, humans are very proficient at monitoring different components of other people’s kinematics, which they leverage to disclose hidden qualities of a handled item. For instance, studies on human non-verbal cues found that joints kinematics and dynamics of hand manipulation are crucial features to estimate the weight of a manipulated object [1,19,23] or predicting action duration [9].

Given the importance of implicit cues in human-human communication, we believe it should be taken into account also in the robotic field. A robot meant to interact with humans, able to exploit the same communication channels as the partner, would guarantee a natural and less cumbersome experience. Indeed, numerous channels of communication may be employed to convey information between robots and people (such as synthetic speech, light-based, digital display, mixed or augmented reality [7,18,16]). However, a valuable alternative that does not require any training or explicit instruction is mediated by movement, and it should be sought whenever feasible. The impact of legibility and predictability of robot motion in human-robot interaction has been extensively studied by Dragan et. al [4], where especially the trajectory of the movements was modulated to convey information associated to the robot next task or goal. When designing a robot movement, other factors such as the velocity or the curvature can be taken into account, for instance to make the emotional attitude of the action more legible [24]. Human non-verbal cues from eyes, head, and arm movements encode the intention driving the action; when such cues are embedded onto a robot, they similarly allow to read the robot’s intention [6]. Regarding object manipulation, object affordances was popularized in robotics and linked to *(i)* the action associated with the object, *(ii)* a physical property, or *(iii)* the type of behavior required to manipulate the object [21,11]. Specifically, works on affordance reasoning examine the object’s properties [26,10,28], e.g., how to infer the water level in cups [17], although trying to directly detect such property from the object appearance, making it only possible with transparent cups and glasses.

To overcome the need to understand the properties of objects from their appearance alone, it is relevant to quantify the effect their features have on the kinematics of the action during manipulation. In our previous works, we focused on carefulness associated to human motion and we exploited human kinematics to infer the impact of cup water content on human motion, irrespective of the cup’s transparency [5,13]. Indeed, it has been shown that humans alter their behavior, adapting to the properties of the object they transport, such as weight, fragility, or content. Additionally, depending on the type of cup, these behaviors may be more predominant or less, which may indicate that the difficulty of the manipulation impacts the human motion [20]. Knowing from the mentioned studies that humans reveal some object properties through movements, in this work, we investigate if it is possible to modulate the movements adopted by a robot end-effector during the transport of an object to communicate some of its hidden properties. In a previous study [14], we assessed the communicative potential of movements on different humanoid robots, by asking participants to explicitly judge the robotic motion’s carefulness after observing it in videos; we also investigated which possible object features may induce a careful manipulation, since carefulness definition is not univocal. This study proposes a dyadic interaction with a new robotic manipulator in a realistic collaborative context. We used Generative Adversarial Networks (GANs) to synthesize and design the robot movements to convey a particular style feature associated with object manipulation: carefulness [8]. By using a generative approach, we can consistently produce novel but meaningful robot actions. Other strategies, such as dynamic motion primitives [22], transformer GANs [15] or variational autoencoders [3] may be applied to synthesize artificial kinematics data; however, our goal is not a comparison with other state of the arts methods: the main novelty is represented by how we apply synthetic data to generate communicative robots’ actions. In this study, we first explore (H1) whether the attitude conveyed by the robot’s movements is perceived as expected, i.e., if the carefulness (or its absence) is correctly expressed by our controller; in this sense, we hypothesize (H1.1) that participants would properly classify if the observed action was careful or not. We also verify (H2), if a robot transporting objects and expressing the appropriate human-like behavior can invoke motor adaptation in the human response. We assume (H2.1) that, if a contagion emerges, careful actions from the robot would elicit slower movements in the human, and vice versa.

2 Materials and Methods

The objective of our study is to assess whether the generated robot’s movements are informative of the properties of the transported object. Moreover, we evaluate if the robot behavior affects how humans perform their tasks.

We will now explain how we synthesized the required velocity profiles and controlled a Kinova Gen3 robot with 7 degrees of freedom to execute them; then, we will describe the experimental setup and design.

2.1 Generation of robot movements

To have the robot communicate through its movements the object properties, the robot’s end-effector follows the velocity profiles generated by the Generative Adversarial Networks (GANs) model. Our interest is in generating movements to convey whether the transported object requires caution and care to be transported (*careful* movement) or it is safe to move without any particular concern (*not careful* movement). Previous studies assessed this kind of object manipulation and showed a marked difference in the kinematics of the human hand associated with the two classes of motions [5,13]. The velocity profile in the case for *careful* movements are characterized by lower maximum velocity, a prolonged deceleration phase, and longer duration, compared to *not careful* movements. The modulation allows for the distinction of *careful* and *not careful* movements [5,12].

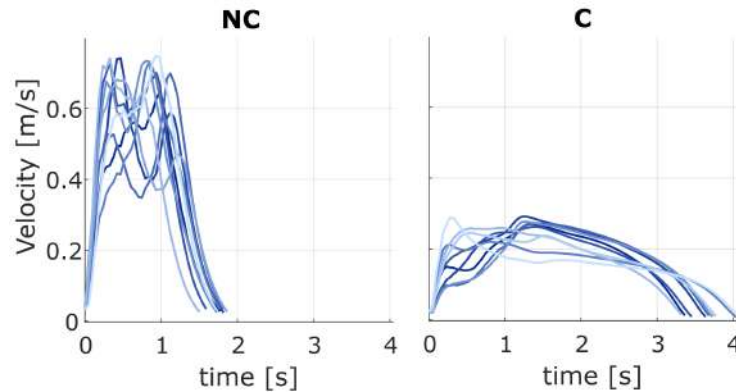


Fig. 1: Velocity profiles generated by the GANs associated to Not Careful (NC) and Careful (C) transportation of objects. These velocity profiles were used to control the robot during the human-robot experiment.

GAN To define meaningful movements associated with the properties of the carried object, we decided to modulate the velocity profile adopted by the robot end-effector. We used GANs to synthesize novel velocity profiles using an approach already tested [8]. The details on the Time-GAN model [27] and its training are described in [8]. The original data used to feed the GANs consisted of hand velocity profiles recorded with a Motion Capture System during the transport of glasses, either empty or containing water, at two possible weight levels. The trajectories followed by participants during the manipulations were designed to grant a good degree of variability. After training, each generative model can produce novel yet meaningful velocity profiles belonging to the distribution of the human data used during the training. This approach provides

new and unlimited synthetic data, always falling into the desired class of motion (careful or not), avoiding a trivial copy of the human velocity profiles. Moreover, learning the velocity norm is useful in generalization terms since the same pattern of motion can be applied to multiple spatial trajectories.

For this specific study, from the trained GANs, we synthesized ten velocity profiles for each of the two classes to be replicated by the Kinova robot. A representation of the generated data is available in Figure 1.

Robot Controller The Kinova Gen3 robot is controlled using ROS and the package `kortex_ros`¹. Such package provides a velocity controller in Cartesian space, which moves the end-effector at 40 Hz in linear (m/s) and angular (rad/s) velocities. Attached to the end-effector is the Robotiq 85 two-finger gripper² used to grasp the cups. This work applies two high-level controllers: (i) a velocity PI controller and (ii) a velocity GAN controller. The first controller is responsible for picking the cups from the table, and the second is for transporting and handing over the cups to the participant. The former generates a constant velocity profile throughout the trials, while the latter follows one of the 20 GAN velocity profiles selected (10 careful and 10 not careful) during the experiment. For each GAN motion trajectory, the velocity profile is decomposed into the 3D Cartesian velocity coordinates by setting the current location and final location (handover point) at each time step. The handover location was fixed in advance to avoid any variability that could influence participants during the experiment. The position of the participant’s wrist was tracked with the motion capture system, while the position of the gripper is computed by the robot’s forward kinematics given the known joint angles and the location of the robot base also tracked with the motion capture system. More details on the sensors are provided in Section 2.2. The handover release moment was obtained by applying a threshold: the robot opened the gripper to release the cup whenever the distance between the gripper and the participant’s wrist was below a fixed value. This simple design was enough to grant a smooth and reactive handover required for our experiment.

2.2 Setup, sensors and experiment design

Participants were asked to sort the items handled by the Kinova Gen3 robot by positioning them on the appropriate areas marked on the table where they were seated. We designed the experiment for the participants to focus on the robot behavior and not on the characteristics of the items. For this reason, we used identical plastic cups: in the instructions, we explained that we were simulating a cocktail bar scenario, where the robot and the human had to collaborate in sorting the glasses between those full to be served to the clients, and the used and empty ones, to be washed; in such context, the cups were meant to be either

¹ Official repository of the Kinova Gen3 ROS package: https://github.com/Kinovarobotics/ros_kortex

² Official website of the gripper: <https://robotiq.com/products/2f85-140-adaptive-robot-gripper>

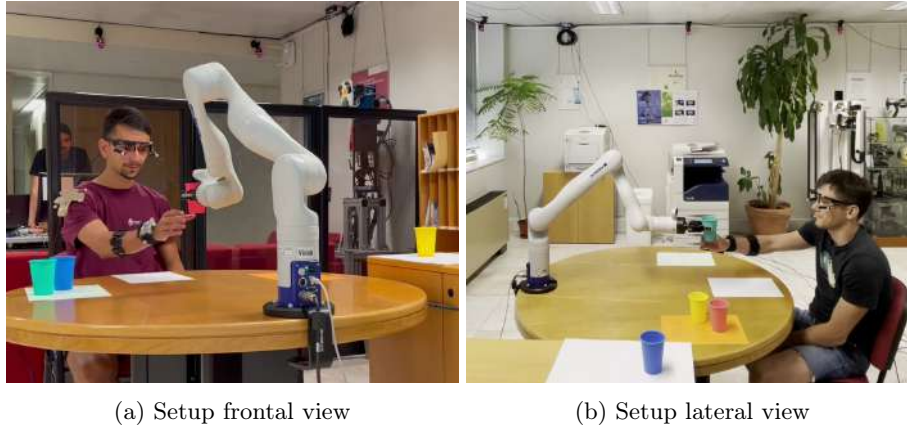


Fig. 2: *Setup*: when interacting with the Kinova Gen3 robot, participants seated at a table. Once grasped the cup from the robot gripper, they had to put it down on one of the three areas delimited on the table. The motion capture markers used to analyse the human kinematics are visible on the participants’ right wrist.

full of a liquid or empty: however, we explained to the participants that due to the danger of having a robot transporting water, all the cups were empty. This granted that participants could not rely on any visual cue or the actual object features to decide where to place the cup. In every trial, the Kinova robot grasped a cup from the table next to it (see Figure 2b) and transported it towards the participant, following either a careful (or not) velocity profile generated by the GANs (associated respectively, to the transport of a full or empty glass). The task for the participants was then to grasp the cup from the robot gripper and place it in the appropriate area on the table: on the “To be served” area, on the right, if they thought that the cup was actually meant to be full, or on the “To be washed” area, in case they assumed the cup was indeed empty. A third area, in the middle, was available to place the cups whose virtual content was not clear to the participant to avoid forcing them into making a decision. They were not informed about the modulation of the robot transport movements and, since the cups were all the same, they had to rely on the robot behavior to make their decision³.

We used Optitrack⁴ motion capture system, with an acquisition frequency of 120 Hz, to track the position of the participant wrist and shoulder.

Twelve healthy participants, all members of Instituto Superior Técnico, voluntarily took part in the experiment. Each evaluated 20 robot movements, where the sequence of careful and not careful modulation was randomized once and then maintained for every participant. The interactions were organized as five

³ Sample video of the human-robot interaction: <https://www.youtube.com/watch?v=HVahS-0tn6g>

⁴ Optitrack website: <https://optitrack.com/cameras/flex-13/>

blocks of a sequence of four trials. At the end of each block, the experimenter put the cups on the table next to the robot. This resulted in a total of 240 movements evaluated, equally balanced between careful or not robot behavior.

3 Results

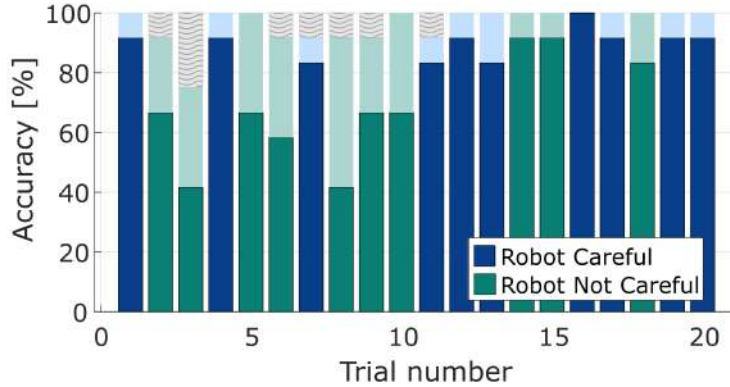


Fig. 3: *Perception of robot's movements*: Percentage of correct interpretation of the robot's transportation movements during the experiment. When the robot performed careful movements, in blue, they were correctly perceived 90% of the times. NC motions required more trials to be consistently classified. The dark bars represent the percentage of correct classification of the movement from the participant, the transparent bars the percentage of wrong attribution; finally, the light gray bars with a wavy pattern, the percentage of "Unknown" answers in each trial.

One of the aims of this study was to verify whether modulating the robot end-effector velocity to express carefulness can inform participants about the virtual content of the manipulated glasses. Figure 3 shows the participants' accuracy in evaluating, for each trial, if the observed transportation motion was meant to be associated with a delicate object, i.e., careful robot movement, or not. We represented with a dark bar the percentage of correct answers given by the participants, i.e., when they correctly interpreted the robot's attitude. Considering the total number of evaluated trials (240), 189 were correctly classified with no indecision, resulting in an accuracy of 78.75%. The transparent colored bars represent the misclassified movements. For instance, when we generated a robot action modulated to communicate a not careful attitude, while participants associated it with the transport of a full cup. As it can be noticed, misunderstanding a not careful action for a careful one was the most frequent occurrence, especially in the first trials. In detail, 90% of the careful robot movements were perceived

as such, whereas 75% of the not careful ones were correctly interpreted. Finally, the grey bars with a wavy pattern represent those trials where participants preferred not to make a choice and placed the cup on the neutral area on the table. Also, these occurrences, which happened in 9 trials out of 240, decrease as the experiment progresses.

Another aspect we were interested in investigating is if the two attitudes shown

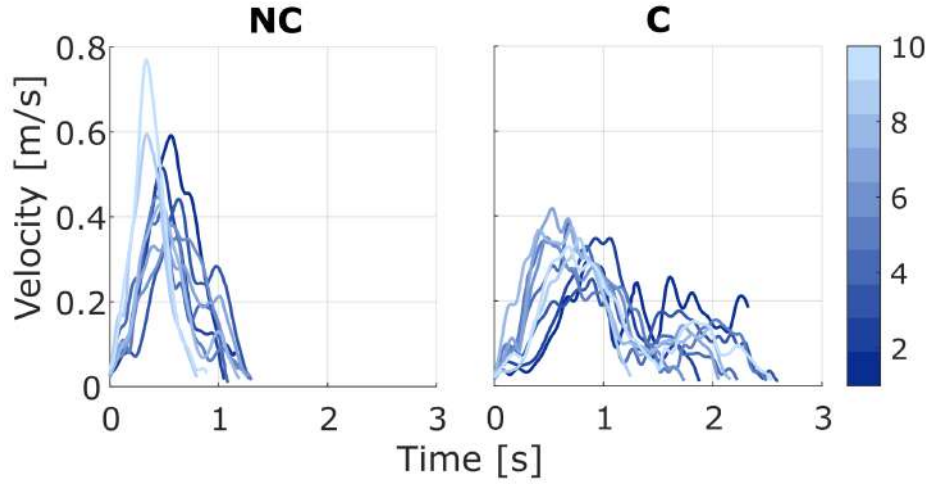


Fig. 4: *Velocity reaching movement*: profiles adopted by one participant when reaching for the cup in the robot gripper. It is noticeable a modulation of both the duration and the maximum velocity depending on the style of the movement adopted by the robot: not careful (NC) or careful (C). The colormap is associated to the trial numbers, in order.

by the robot had any effect on how participants performed their tasks. An exploratory inspection of the hand velocity data encouraged us to deepen this intuition: Figure 4 reports an example of the velocity adopted by one participant when reaching for the cup in the robot gripper. There is a noticeable modulation in the participant's movements that correlates with the attitude shown by the robot. When the robot handled the cup with a careful attitude, also the participant reached for it with slower and prolonged action compared to the not careful situation. To assess this modulation quantitatively in human actions, we considered the duration and median velocity of the movements as relevant features. To perform statistical analyses on the acquired data, we used Jamovi software⁵, in particular the GAMLj module⁶ for mixed models. Figure 5a shows the mean durations of the participants reaching movements toward

⁵ Jamovi software website: <https://www.jamovi.org>

⁶ General analyses for linear models Jamovi module: <https://gamlj.github.io/>

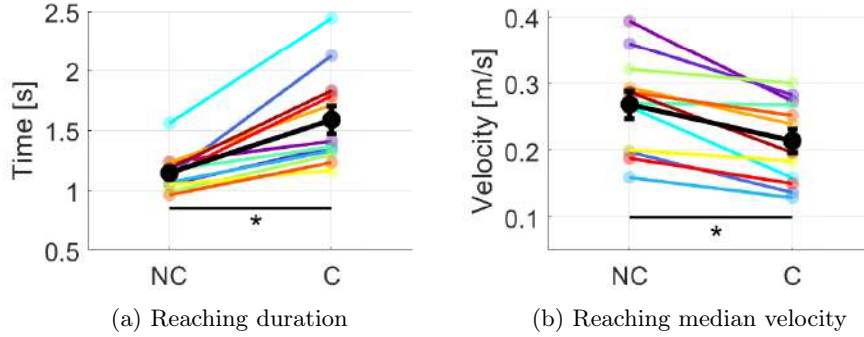


Fig. 5: *Reaching movement*: in (5a) mean duration of the participants reaching movements towards the robot’s gripper. When the robot performs a Careful (C) transportation movement, participants are significantly slower in reaching for the cup. Also the median velocity adopted in the reaching movements (5b) is modulated by how the robot moved when transporting the cup. The mean values for each participant are represented in a different color. The thick black lines represent the mean over the twelve participants, with the standard error. The star indicates a significant difference with $p < 0.001$.

the robot gripper. We ran a mixed model assuming the duration of the participants’ reaching movements as the dependent variable, the carefulness in the robot movement as a factor, and the subjects as cluster variables. The effect of condition resulted significant ($C - NC$, $estimate = 0.443$, $SE = 0.055$, $t = 8.00$, $p < 0.001$), indicating that when the robot end-effector was following a careful velocity profile, the subsequent human reaching action was longer, with an extended duration estimate of 0.443 seconds. A second mixed model was used to evaluate the median velocity adopted by the participants when reaching the robot gripper (see Figure 5b), using this time the median velocity as dependent variable: when the robot was careful, participants significantly diminished their median velocity, with an estimated reduction in speed of $0.055m/s$ ($C - NC$, $estimate = 0.055$, $SE = 0.012$, $t = -4.60$, $p < 0.001$). These findings prove that the modulation of the robot movements affected how participants moved to reach and take the cup from the robot. This happened even when there was no reason to adapt to the object properties since we consider a reaching movement and all the cups had exactly the same characteristics. We also verified, for both the duration and the median velocity of the reaching movements, if there was an interaction with the participants’ accuracy in evaluating the robot’s behavior in every trial. We used the accuracy in their classification as an additional factor in the mixed model, but we found no interaction with how they performed the reaching duration or velocity. The modulation in response to the robot attitude also occurred when participants did not recognize it explicitly.

4 Discussion

In our study, we exploited a generative approach to produce robot movements that could implicitly communicate if a handled object required or not carefulness to be transported. To avoid influencing the choice, all the items transported by the Kinova robot were identical (empty plastic cups). The participants had to decide if they were supposed to be virtually full or empty, without any particular hint or instruction on how to proceed. Firstly, we assessed (H1) whether our controller can express caution in the gestures or its absence. According to the results shown in Figure 3, our hypothesis (H1.1) was verified: we notice that the *careful* robot actions have been perceived as such since the first trials of the experiment. Regarding the *not careful* actions, there is a learning trend in how they were perceived during the experiment. In the first trials, they were sometimes mistaken for actions associated with transporting a full cup. As the experiment progressed, the difference between the two modulations became more evident, with an accuracy in the participants’ choices above 80%. Reflecting on the original dataset of human movements used to train the GANs associated with the transport of full and empty cups [13], we can observe that a *not careful* attitude is the standard in our actions. Indeed, when no particular circumstances are forcing us, for instance when picking and placing an ordinary object, we tend to move in a “neutral” way, and we can shortly describe our approach as not careful. On the contrary, a strong kinematics modulation appears when we are paying attention to not spill the contents of a glass [5,12]. This careful kinematics shaping is what we truly modeled in the communicative robot’s movements, and it is rewarding that careful movements were perceived correctly from the beginning.

This study also allows us to evaluate (H2), the effect that the implicit modulation of the robot actions has on the interaction. Even though participants knew from the beginning that the plastic cups were all the same and all empty, there was a modulation in how they approached the robot gripper, confirming our second hypothesis (H2.1). We gave an overview of this phenomenon in Figure 4 and a quantitative assessment in Figure 5. If the robot manifested a careful attitude, adopting a lower magnitude in the velocity profile and a longer duration of the movement (see Figure 1 for reference), also the reaching movement of the humans was significantly slower. Interestingly, this also happened when participants had trouble explicitly recognizing the motion style and classifying the cup: the contagion in how they performed the reaching task was still present. This result emphasizes how important it is to modulate the actions of robots appropriately, with a view towards collaborative interaction. Indeed, we proved a motor contagion from the robot to the human, even if there was no need for the participants to directly associate with the task and adapt their motor strategy. We observed natural coordination emerging from such a simple task, where the pace of the human spontaneously adapted to the robot one, mimicking, even unconsciously, the attitude observed. Human-robot motor contagion on velocity was already observed whenever the robot velocity profile is biologically plausible [2,25]. In our approach, the reasonableness of the velocity profiles was granted us-

ing a generative network trained on human examples. The findings in our study extend the existing evidence of motor contagion in Human-Robot Interaction, proving that robotics arms can also leverage it to convey appropriate ways of handling fragile objects.

5 Conclusion

In this study, we showed how a generative approach could be used to generate meaningful and communicative robot actions that a human partner can successfully interpret to infer some properties of the involved objects. This modulation on the robot side also led to a motor contagion in how the human performed its actions and synchronized with the pace of the robot; through motion alone, it was possible to open a channel of communication between the two agents, with measurable effects on the interaction.

Finally, it should be noted that we obtained these results by modulating the movements of a 7 degrees of freedom robotic manipulator, not a humanoid robot. Nevertheless, even though its kinematics was far from the one of a human arm, it was possible to achieve the desired communication intent by simply modulating the end-effector control. This proves the power of the proposed approach and its potential scalability in other contexts and with other robots, also industrial ones, where implicit communication through motion could improve the efficiency and safety of a joint collaborative task.

In future works, we plan to exploit the same controller and have the robot actually manipulate full and empty cups to assess how the movement’s modulation affects trust, perceived competency, and efficiency in a dyadic interaction, while facing a challenging task.

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