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Experimental testing of the CogLaboration prototype system for fluent Human-Robot object handover interactions*

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Abstract— **This article presents the design and execution of the experiments used to develop and evaluate a robot prototype system for fluent Human-Robot object handover interactions. A key aspect of our experimental methodology is the deep integration between Human-Robot and Human-Human object handover experiments. This provides a solid baseline and knowledge base for the prototype evaluation, both in terms of movement dynamics and in subjective user evaluation.**

I. INTRODUCTION

The CogLaboration project (http://coglaboration.eu/) was launched in 2011, as part of the EU FT7-ICT agenda for the development of service robotics, with the purpose of developing a prototype system for fluent Human-Robot collaboration. The project focuses on the object handover between a robot and a human, considered to be a key aspect to be addressed in order to provide successful and efficient robotic assistance to humans [1,2,3]. Within CogLaboration we address this challenge by integrating the study of Human-Human object handover interactions into the robot development process. By studying the quantitative and qualitative characteristics of successful Human-Human object handover in task settings that are closely inspired by realistic conditions, including typical variations and unplanned and unanticipated situations, we aim to characterize the arm and hand trajectories, the forces applied onto the object during the handover, the visual information used to correct the motion, and the way gestures are used to provide information or trigger the handover procedure. The same metrics that we derived from our studies of object exchange between humans are then used to evaluate the vision-driven robotic system, comprising a lightweight robotic arm and a hand with tactile sensors, following a scenario-driven methodology.

In this paper we present the design, execution and results of the scenario-driven evaluation of the first CogLaboration prototype for fluent Human-Robot object handover. Section II describes the design of the evaluation, including a description of the test scenario, the interaction manipulations, equipment and a brief description of the robot system. Section III presents the main results of experiments, comparing the participants' subjective ratings and handover behaviour during Human-Human and Human-Robot interactions. Section IV finally presents our conclusions.

II. EXPERIMENT DESIGN & EXECUTION

A. *Scenario driven methodology*

The experiment scenarios for the CogLaboration project were chosen based on real-life situations in which fluent object handover is critical for the a robot to be a successful assistant in the workplace. For the evaluation of the first prototype the scenario was based on a car mechanic working in a small garage with the robot in the role of an assistant who passes requested tools to the mechanic. Key elements of this scenario were the use of different workspace configurations, affecting the postures of the human and thus the interaction with the robot and a range of behaviour manipulations to human preferences among robot behaviour variations. The three test scenario configurations were:

1. The 'Engine Bay' configuration, in which the human mechanics bent over the task area, simulating work on the engine of a car by touching the 'simulated engine'. In this configuration the mechanics were able to see the object handover and experienced only minor restriction to their movement range. For the mechanics the handover involved a reaching movement that was mostly to the right and slightly backwards. The human was in full view of the robot/assistant at all times (Fig. 1a).
2. The 'Hydraulic Lift' configuration, in which the mechanics stood under the 'car' while reaching slightly over their heads to touch the underside of a 'car that was raised on a hydraulic lift'. In this configuration the movement range of the mechanics was only slightly impaired by the need to keep touching the 'car' and there was nothing to interfere with observing the object handover. The handover involved reaching to the right side and was in full

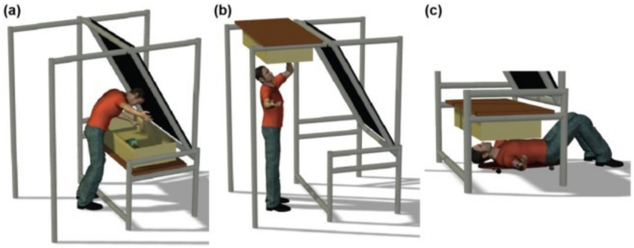

Figure 1. Human postures in the three car mechanic configurations

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view of the robot/assistant (Fig. 1b).

3. The ‘Lying under the car’ configuration, in which the mechanics simulated working while lying under a ‘car’. This posture severely limited the person’s ability to view the interaction and limited the range of their arm movements. In addition, the view of the person from the robot/assistant was also greatly reduced (Fig. 1c).

Fig 2 shows the spatial layout of the experiment setup for the general interaction paradigm in which the robot (1) takes the object that was requested from the tool table (Fig 2. green rectangle), (2) gives it to the mechanic and (3) later receives it back from the mechanic. During this prototype evaluation, however, the object acquisition from the table was not considered; rather the objects were placed into the robot hand at the beginning of the trial by the experimenter. Fig. 3 shows images from the actual Human-Robot experiments in all three configurations. The work frame (and the bed that was used to emulate the ‘Lying under the car’ configuration with the mobility constraints of the stationary prototype system) was positioned such that the participants were 100-125cm away from the robot. This allowed their outstretched hand to be inside the robot’s workspace while their body remained safely beyond reach of the robot.

B. *Objects and behaviour manipulations*

The objects for the Human-Human trials were chosen for the range of grasp types they might elicit, specifically grasp types for the purpose of object handover that might be different from the grasp typically used to pick up the object. The chosen objects were: (i) Torch (light and easy to grasp with a clear front/back and the possibility to imbed a motion sensor inside the battery casing); (ii) Hammer (heavy on one end, easy handle, distinct head); (iii) Hacksaw (blade, asymmetrical, complex handle). For the Human-Robot handover interactions the initial design was to use the same objects. The hammer and hacksaw, however, were removed from the testing of the first prototype system due to recurring issues with the robotic arm when adjusting the hand orientation to grasp them.

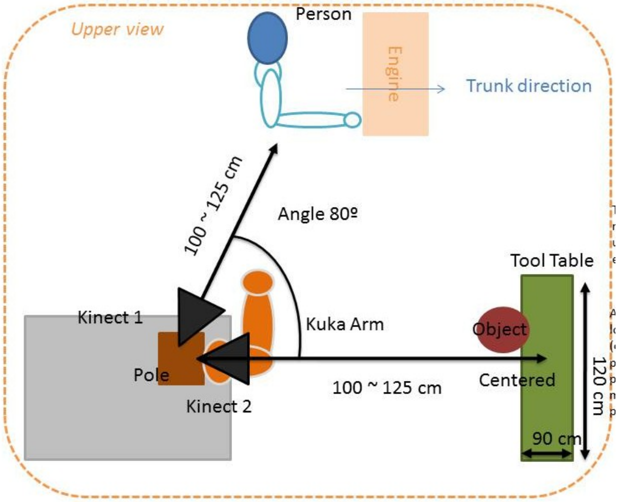

Figure 2. Spatial layout of the experiment setup. The position of the robot (Assistant) is indicated in orange and the Mechanic in blue.

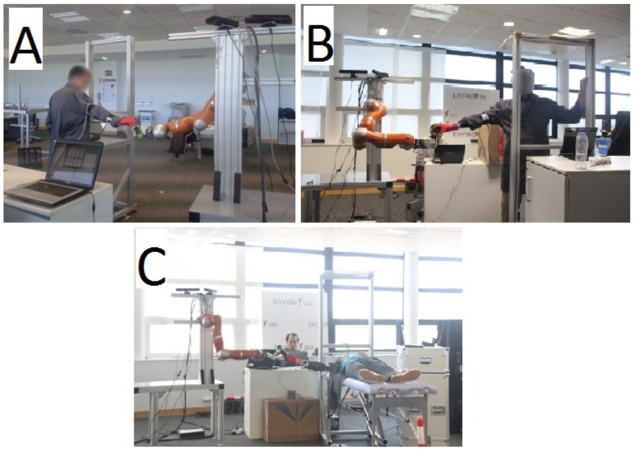

Figure 3: Illustrations of the three scenario configurations. (A) ‘Engine Bay’, i.e. standing with work area at waist height. (B) ‘Hydraulic Lift’, i.e. standing with work area above the head. (C) ‘Lying under car’, i.e. lying on a bed with work area above the head.

For the Human-Robot handover interactions a series of behaviour manipulations was included to test the human mechanic’s preferences concerning possible control strategies or system parameter settings (see Table 1). The manipulations were:

- the speed of the arm movement as fast (1 or ½ human), normal (2/5 human) or slow (1/3 or ¼ human) speed; where average human speed was 0.55m/s;
- a delay in the visually triggered hand-closing/opening (short, medium, long);
- hand open/close triggering through hand-contact force detection (through the force sensor embedded within the robotic arm);
- verbal hand open/close triggering;

TABLE I. HUMAN-ROBOT TASK MANIPULATIONS

# trials	**Behaviour manipulations**					
	normal	***Speed 5 speeds x 3 repetitions***	***Hand delay 3 delays x 3 repetitions***	***Hand force trigger***	***Hand verbal trigger***	***Arm motion verbal trigger***
Torch	5	15	9	5	5	5

TABLE II. HUMAN-HUMAN TASK MANIPULATIONS

# trials	**Behaviour manipulations**							
	normal	***fast***	***slow***	***Hand delay***	***Hand verbal trigger***	***Arm verbal trigger***	***Arm delay***	***Mechanic eyes on engine***
Torch	5	5	5	5	5	5	5	5
Hammer	5	-	-	-	-	-	-	-
Hacksaw	5	-	-	-	-	-	-	-

- verbal triggering to start the robotic arm movement.

During all modes other than the force triggered mode the operator manually triggered the motion start and the hand actions to focus the evaluation on the motion behaviour, and, like during Wizard of Oz tests, to analyze the potential benefit of specific behaviours not yet implemented (like verbal triggering). During the force contact mode, the hand actions were automatically triggered by the analysis of the interaction forces measured by the arm.

For the Human-Human handover interactions we attempted to replicate the robot's behaviour manipulations as much as possible, for the Torch object. Even though the role of the robot was performed by one of the experimenters, precise control of movement speeds or delays was impossible, thus the five robots speeds were replaced by the more fuzzy instructions of 'Fast', 'Normal' and 'Slow' and the three 'Hand delay' conditions became a single condition. The 'Hand force triggered' condition was also dropped since it was impossible to convincingly replicate. The removed conditions were replaced by an 'Arm delay' condition to simulate delayed movement onsets of the robot; and a 'Mechanic eye on engine' condition where the Mechanic had only peripheral visual feedback of the handover interaction (see Table 1).

C. *Experiment procedure*

In order to avoid frequent reconfiguring of the test setup between trials, and also to minimize participant fatigue due to prolonged experimentation, each scenario configuration was tested on a separate day.

Each configuration was run with naïve participants who were recruited from Tecnalia staff (4 male, 3 female), of whom five had little or no prior experience of interacting with robots.

The task manipulations per session are summarized in Table 1 (Human-Robot) and Table 2 (Human-Human).

The task for the participants in all experiments was to receive an object from the assistant/robot, take the object to the task area (e.g. 'Engine bay') and then hand it back to the assistant/robot. Thus each trial consisted of two phases:

1. Handover from Assistant/robot to Mechanic **(A→M)** consisting of: (1.1) Mechanic requests object by reaching towards the Assistant; (1.2) Assistant brings the object to the Mechanic; (1.3) Mechanic takes the object from the Assistant and brings it to the task area, i.e. the 'car'; (1.4) The Mechanic evaluates the handover.
2. Handover from Mechanic to Assistant/robot **(M→A)** consisting of: (2.1) Mechanic holds the object out towards the Assistant; (2.2) Assistant reaches for the object; (2.3) Assistant takes the object back to the tool table; (2.4) Mechanic evaluates the handover.

Once all the trials were completed, the participant was interviewed to provide additional feedback and qualitative evaluation of their experience during the interactions.

The participants provided evaluation ratings after each handover by giving a score between 1 (fully disagree) and 9 (fully agree) via a touch screen. The following evaluation statements were chosen to probe the subjective impressions the participant were forming about their interaction with the assistant/robot:

Q1: It was *easy* to receive the object

Q2: I was *satisfied* with the interaction

Q3: The interaction was *comfortable*

Q4: I felt *safe* during the interaction

In addition to the subjective evaluation, a set of objective behaviour measurements was recorded during the experiments, including:

- the location and pose of the human hand/arm as a function of time (providing movement kinematics);
- the articular pose of the robot as well as the measured efforts per joint;
- the timing of the events during the handover procedure (robot motion start, end, contact trigger, hand manipulations).

D. *Equipment & Robot system*

The behaviour of the human participants in the experiments was captured through motion-tracking using the Polhemus Liberty magnetic motion tracking system (Polhemus Inc., Vermont, USA[1]). Four magnetic markers were used to record the position and orientation of the participant's right hand at 240Hz during the object handover. During the Human-Robot experiments all four markers were placed on the Mechanic participant, one on the shoulder, one on the back of the hand, one on the thumb and one on the index finger. During the Human-Human experiments two markers were placed on the Mechanic participant and two on the Assistant experimenter, one on the right shoulder and one on the back of the right hand.

The robotic system was composed of the KUKA's lightweight robot (LWR) [4] mounted on a frame, as illustrated in Fig. 4a, onto which the Prensilia's hand [5] was mounted at the end-effector (Fig. 4b).

The robot's visual perception was performed using a Kinect camera (at the top of the frame, Fig. 4a) and consisted of estimating the location of the human hand through colour segmentation. The control law driving the robot motion, guided by the visual perception, was based on the DMP formalism (Dynamic Movement Primitives) [6,7]. This control approach permits the system to reproduce a reference motion pattern while maintaining a reactive convergence towards the possibly changing target location (the human hand for performing the handover in our case). This framework was specialized in the context of the CogLaboration project to reproduce a human-like motion, using as reference pattern a human arm motion extracted from a previous set of Human-Human object handover

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[1] http://www.polhemus.com/motion-tracking/all-trackers/liberty/

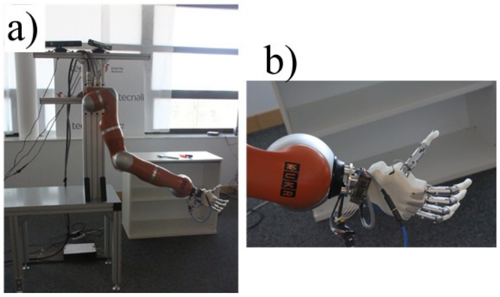

Figure 4. a) KUKA's LWR; b) Prensilia's hand

motion-tracking data. Since the robot control mechanism is not the focus of this paper, we would like to direct the interested readers to the two previously cited papers [6, 7] that respectively describe the DMP specialization for Human-Robot object handover, and an initial validation of the control law through a comparison with the human motion database created in the project [8].

In addition, an experimental motion and touch sensor developed by one of the CogLaboration partners (R. U. Robots Ltd., Manchester, UK) was mounted in the Torch test object to observe the motion of the object during the handover from the object's perspective [9]. The RUR Sensor contains a 3-axis accelerometer, 3-axis magnetometer, 3-axis rate gyroscope and four capacitive touch sensors and records the data from all of these at a rate of 50Hz. During all of the experiments, three types of data were gathered by the sensor: orientation, acceleration, and jerk. The touch pads were designed to facilitate identification of intervals when one or both participants are in contact with the object.

III. RESULTS

For reasons of space, the presentation of results will focus on the 'Engine Bay' configuration, unless stated otherwise.

A. *Human-Robot handover success*

Using only the torch object, the robot system achieved an overall success rate of 94% for the A→M handovers and 95% for the M→A handovers in all configurations and behaviour manipulations (This success rate is based on 3 (configurations) x 7 (participants) x 44 (manipulations) = 924 trials).

B. *Subjective handover quality ratings*

To compensate for individual differences in mean and standard deviations of responses across participants, all responses were transformed into z-scores, (i.e. subtracting the within-subject mean rating responses, over all manipulations, and dividing by the within-subject standard deviation). Fig. 5 summarizes the mean subjective ratings by the Mechanic during the Human-Human handover experiment (to save space, we show only the averaged results across the 'Easy', 'Comfortable' and 'Satisfied' ratings, as they were very similar). For the Ease (Q1), Satisfaction (Q2) and Comfort (Q3) qualities, the 'Slow', 'Hand delay' and 'Arm delay' conditions were given the lowest ratings (together with the Hacksaw object condition), indicating the perceived importance for rapid, responsive, interactions. As expected, the perceived Safety (Q4) was rated lowest for the 'Hacksaw' and 'Mechanic eyes on engine' conditions. Surprisingly, the 'Arm delay' condition also received low safety ratings.

Fig. 6 summarizes the mean subjective rating responses by the Mechanic during the Human-Robot handover experiment (presented in the same way as in Fig. 5). Comparison of the ratings for the initial and later 'Normal' trials suggests that participants rapidly got used to the robot behaviour. For the Ease, Satisfaction and Comfort qualities, the 'Fast' and 'Slow' movements were both rated equally badly, though probably for different reasons as suggested by the corresponding Safe ratings, which were very low for the 'Fast' condition but high for the 'Slow' condition. Among the hand control manipulations, the 'Long hand delay' was rated worst whereas the 'Verbal triggering' was rated best.

The Human-Robot interaction results for the 'Slow' and 'Long hand delay' conditions match the corresponding Human-Human interaction results and were further confirmed by the statements participants made during the post-session interviews in which they expressed frustration when the robot was slow to respond (slow movement or long hand delay). The interview responses also supported the preference for the verbal commands, with participants indicating that this condition gave them an increased sense of control. The bad ratings for the 'Fast' movement trials were indicated to be related to the increased jerkiness of the movements, which was caused by joint limit overshooting in the robot control loop.

Analysis of the handover quality ratings for the Human-Robot interaction experiment showed a skewed response distribution with more than 60% of ratings at 8 or 9 and less

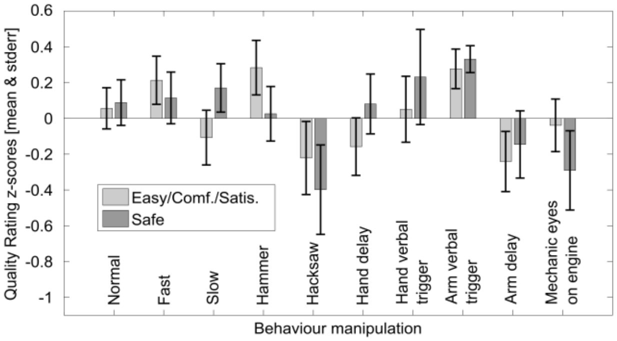

Figure 5. **S**ubjective ratings for the Human-Human object handover experiment [error bars indicate standard error].

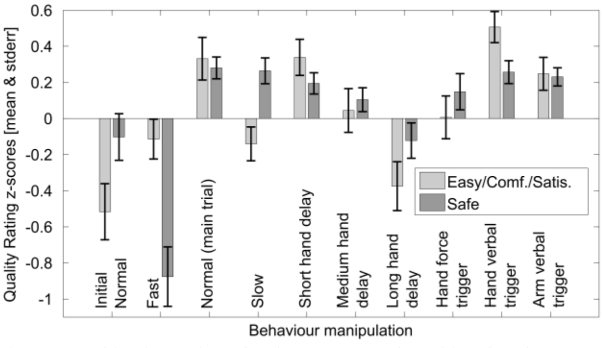

Figure 6. **S**ubjective ratings for the Human-Robot object handover experiment [error bars indicate standard error].

than 10% of ratings at 5 or less. These high ratings show that participants had a generally positive impression of their interaction with the robot and/or were less critical when evaluating Robot behaviour because they may have had very low expectations of its performance.

C. *Handover movement behaviour*

Based on the motion–tracking data that was collected during the experiments, we computed a range of core movement descriptors:

- ‘Start/End time difference’ (Assistant movement time – Mechanic movement time).
- ‘Movement distance’ (Euclidean distance with separate analysis for the horizontal plane (XY) and the vertical direction (Z)).
- ‘End correction’ (difference between reaching movement end-point and retracting movement start-point).
- ‘Peak velocity’ (maximum velocity during the reaching movement).
- ‘Peak velocity time’ (measured relative to the movement start time).

For this analysis we focused on the ‘Speed’ and ‘Verbal arm triggering’ conditions since these were most closely replicated in both the Human-Human and Human-Robot experiments and, unlike the hand behaviour conditions, these conditions directly manipulated arm movement properties. The main results from this analysis are summarized in Fig. 7. The following patterns could be observed:

1. During Human-Human trials the Mechanic moved a larger distance during the M→A handover than the A→M handover, irrespective of the Assistant’s handover speed. Interestingly, however, this pattern was predominantly due to distance travelled in the horizontal (XY) plane. Along the vertical (Z) axis the pattern was reversed.
2. During Human-Robot interactions, however, this pattern was not maintained, probably because the robot did not reach the Mechanic in time to facilitate this natural rhythm of behaviour.
3. Comparison of start and end time differences between the Mechanic and Assistant shows that in Human-Human interactions the party who is giving the object starts to move first, but that the receiving partner partially catches up before the movement ends (‘End time difference’ < ‘Start time difference’).
4. In the Human-Robot interactions the robot always started after the Mechanic, even when the robot was giving the object, the timing difference increased during the movement (‘End time difference’ > ‘Start time difference’). Interestingly, despite the increasing time difference at the end of the movement, the robot did match the human assistant’s peak velocities fairly closely.
5. The Mechanic exhibited much higher peak velocities (with a very large standard-error) when interacting with the robot than during the Human-Human handover interactions.
6. The Mechanic’s peak velocity time during the Human-Robot interactions was generally earlier (relative to the Mechanic’s movement onset) than during the Human-Human interactions, especially when requesting the object from the robot. This may reflect a difference in the qualitative nature of the action since the reaching movement in the Human-Robot experiments generally served as a trigger signal for the robot (experimenter who controlled the robot triggering), whereas in the Human-Human case the Mechanic waited for the Assistant to move first when requesting the object from the Assistant. This is supported by the data indicating that the peak velocity time of the Mechanic during the Human-Robot experiments was latest on the ‘Verbal arm triggering’ trials.

D. *Other data/analysis that were collected but could not be included in this paper*

The data collected by the RUR Sensors permitted the analysis of the mean object movements and the correlation between the object movement behaviour and the handover quality ratings. Such information is available in the publically accessible internal CogLaboration project report [9].

Other results from the experiment include an analysis of the relative importance of spatial and temporal precision for the subjective experiences of participants during Human-Robot object handover interaction, which was recently published in [10]; and a detailed evaluation of the effect of variations in the speed parameter of the robot on the movement properties of the Human-Robot interaction and

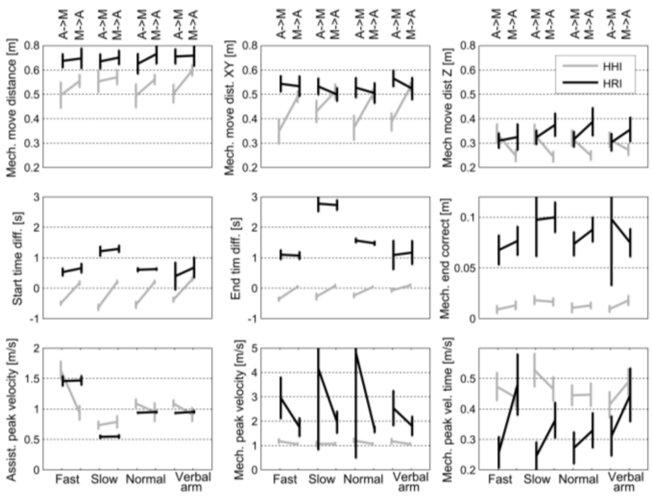

Figure 7. Behavioural movement properties during the Human-Human (grey) and Human-Robot (black) object handover interactions [error bars indicate standard-errors]

the correlation to perceived handover quality [11].

IV. CONCLUSIONS

By performing both Human-Robot and Human-Human object handover experiments with the same task scenario we were able to analyze and compare the behaviour of the human participants in the Human-Robot trials against the equivalent behaviour between humans. Another key part of our robot prototype evaluation was the use of subjective rating feedback on a trial-by-trial basis. The use of such intensive subjective feedback monitoring is especially important in the context of developing service robots that must perform direct Human-Robot interactions since ultimately it is the subjective experience of the human users which will determine whether social robots will be accepted into everyday work and life setting.

Based on the behaviour measurements we identified that there were marked differences in the human participants when interacting with the Robot as compared to a Human, in (i) the movement distance patterns, (ii) the timing of the movements and (iii) the velocity profiles. Importantly however, the trial-by-trial ratings showed that the perceived quality of the handover was primarily affected by the temporal aspects of the interactions.

The take-home message for future developments in service robots, and for the future improvements of the CogLaboration robotic system for object handover, is that people interacting with robots are reasonably forgiving of spatial inaccuracies in robot behaviour but require a fast responsiveness to gain a positive impression of the interaction. We therefore recommend that, as far as permitted by safety requirements, the speed-accuracy trade-off in the control of social robots be weighted more towards rapid responsiveness.

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