Science Robotics

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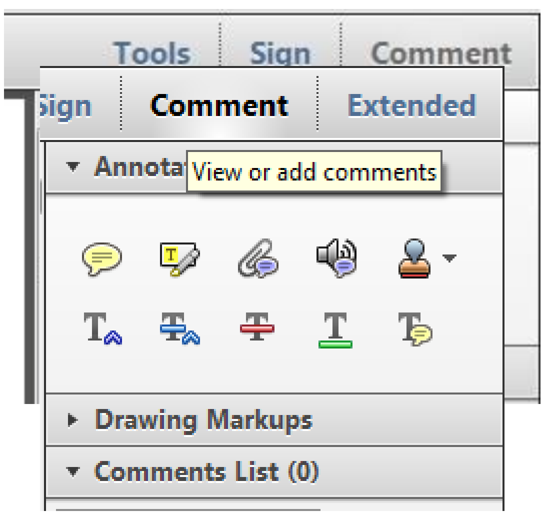

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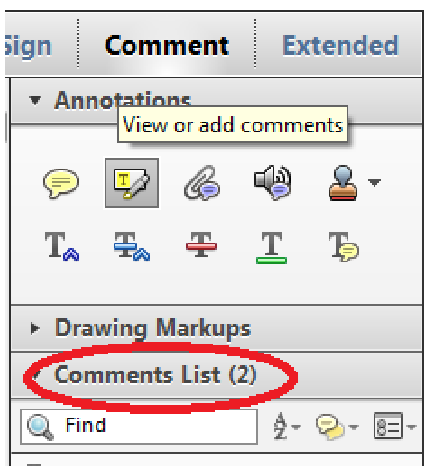

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HUMAN-ROBOT INTERACTION

The relevance of signal timing in human-robot collaborative manipulation

AQ1 F. Cini[1,2†], T. Banfi[1,2†], G. Ciuti[1,2], L. Craighero[3], M. Controzzi[1,2*]

To achieve a seamless human-robot collaboration, it is crucial that robots express their intentions without perturbating or interrupting the task that a human partner is performing at that moment. Although it has not received much attention so far, this issue is important when robots assist humans in physical and manipulation tasks. The main question addressed here is whether there is a more appropriate time to inform a human partner that a robot is requesting to pass them an object. This question is posed in a reference scenario where human individuals are involved in a continuous pick-and-place task that cannot be interrupted. Our findings showed that providing a cue at the beginning of a reach-to-grasp movement could severely interfere with the ongoing human action, increasing the number of errors made by humans, slowing down and degrading the smoothness of their arm movement, and deflecting their gaze. These disruptive interferences strongly decreased, until they disappeared, when the robot provided the cue to the human partners shortly after the participants picked up an object, identifying this as the best signaling timing. The results of this work showed how the signaling timing may have a decisive influence on the performances of the human-robot teamwork and contribute to understating the mechanisms underpinning the phenomenon of cognitive-motor interference in humans.

INTRODUCTION

Achieving intuitive and seamless interaction with robots is a long-standing goal. Within the realm of this research field, a growing effort is devoted to finding safe ways to enable the use of robots as companions and as work collaborators. Human-robot collaboration is being adopted worldwide, ranging from the household to industrial and health care fields (*1*, *2*). Beyond the improvement of safety during human-robot collaboration, finding optimal strategies that maximize the fluency and efficiency of human-robot interactions is still an open issue. A collaboration requires parties to coordinate their actions and communicate their knowledge and intentions to efficiently achieve shared goals while optimally exploiting their capabilities (*3*).

Among all the possible scenarios involving robots as partners in human tasks, the contribution in activities similar to pick-and-place tasks [i.e., an individual picking up a specified object and moving that object to another location; see (*4*)] is quite likely to happen. For instance, in a collaborative assembly task, where a human operator has to combine several components in a precise order, the help of a robot could lead to an improvement of the efficiency of the process and a reduction of human errors. However, a fundamental problem in this type of collaboration is to establish an efficient exchange of information between humans and robots.

In human-human teamwork, both verbal and nonverbal communication ensures a shared understanding of the task and a proficient motion coordination (*5*, *6*). Similarly, robots should be able to establish bidirectional communication with their human partners (*5*, *7*, *8*). To this end, research efforts are increasingly being devoted to enable robots to track and predict human motion and gestures (*9*–*12*) and to interpret humans' gaze behavior (*13*, *14*), facial expression (*15*), and operator muscle fatigue (*16*, *17*) to facilitate and speed up the collaboration and to improve safety and ergonomics of the working condition. However, allowing robots to properly perceive and interpret human actions and behaviors is not enough to establish an intuitive, effective, and efficient teamwork. A mutual understanding must be established to reach an optimal, human-human–like interaction. This mutual understanding implies that the robot should also be able to unambiguously communicate to the human operator its internal state and intentions (*18*, *19*). The understandability and intuitiveness of robotic behavior have been termed transparency or legibility (*19*–*21*). A transparent robot's behavior allows humans to easily understand what the system is doing, why the robot is behaving in a certain way, and what it will do next. Robots that act without properly communicating this information may create anxiety (*22*), degrading the quality of the user experience and the overall efficiency of the collaboration (*23*). Overall, to establish an efficient robot-to-human communication, two main features must be adequately designed: the signaling modality (i.e., the communication medium) and the signal timing (i.e., when to deliver a collaboration cue).

Recent studies investigated different types of communication modalities to increase robots' communicative efficiency. Implicit signaling strategies, such as legible robot motions (*24*, *25*) or human-inspired robotic gaze behavior (*26*–*28*), have been explored as methods able to convey a robot's intent and goals. However, these subtle cues are challenging to use with nonhumanoid robots and/or in real living and working environments. That is why several studies investigated the use of a more explicit medium of communication—such as natural language (*29*), auditory nonverbal sounds (*30*, *31*), visual displays (*31*), and colored light-emitting diode patterns AQ2 (*32*–*35*)—obtaining positive effects on the performances of human-robot teamwork. Recently, with the development of small wearable haptic interfaces (*36*, *37*), haptics has been chosen as one of the favorites and primary channels of communication between robots and humans. The reasons for this choice are manifold. The sense of touch is robust to a broad array of environmental noise because of

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the distribution of the haptic receptors in the whole human body
AQ3 (*38*). This is also favorable because the stimulus may be delivered to the human partner in different parts of the body without interfering with the task to be executed. Different from the sense of hearing and sight, the sense of touch also represents a proximal and somewhat private sense (*37*). These features enable haptic signals to be used also in cluttered and noisy environments (as those common among industrial settings) or in scenarios where other communicative channels (i.e., sight in pick-and-place activity) might be already involved in the task execution and thus not as effective to use. Haptic interfaces were successfully applied as informative feedback on the outcome of the task execution for the human-robot team navigation (*39*, *40*), augmented reality applications (*41*), and collaborative tasks (*42*–*45*).

On the basis of the aforementioned considerations, we decided to use haptic stimulation as the robot-to-human signaling channel, and we investigated the signaling timing, which is the other key variable of successful information exchange during a collaborative task. Communicating information to a partner without considering their current state not only may be inefficient but also could negatively influence the overall team performance. Previous studies in human-computer interaction explored different methods to estimate when to interrupt humans through systems that provided visual or auditory notifications (*46*). For instance, it has been shown that during a human-computer interaction, the task boundaries represent suitable moments for interrupting the ongoing activity, enabling an easier resumption of the task at a later point (*47*–*49*). However, as underlined by these studies, the specific working context is a fundamental factor that influences how humans become
AQ4 aware of interruptions and respond to new requests for actions (*46*).
AQ5 Because the scenario of a human-computer interaction is different from that of a human-robot collaboration, it is important to investigate the most appropriate signaling timing in the specific scenario where robots assist a human operator in physical tasks such as object manipulation. In this type of collaboration, the main issue is that a request of interaction prompted by the robot, or the knowledge of its possibility, could be nonintuitive and could interfere with the task the human is performing. It is known that both perceptual and cognitive tasks can interfere with the execution of concomitant motor activity (*50*, *51*). What is still not clear, however, is at which stage of the execution the interference reaches the peak. Since the end of the 19th century, a distinction between the planning and control stages of action has been proposed (*52*), and the existence of these two stages has generally become accepted as an underlying principle of human motor behavior (*53*, *54*). In particular, before the execution of a movement, a motor program is selected, taking into consideration a broad range of cognitive and perceptual factors. Then, the execution of the action is carried on, leveraging on the increasing influence of a "control system" that combines visual and proprioceptive feedbacks, with an efference copy of the movement plan (*55*, *56*). The independence of these two stages (i.e., action planning and execution) is debated (*57*), as well as the possibility that the presence of a concomitant task can interfere only on the planning stage (*58*–*63*) or on both planning and control stages (*64*, *65*).

Therefore, assuming that a human and a robot have to collaborate to perform a primary task (that is, one included in common daily
AQ6 manipulation activities) such as pick and place, we do not have any help from the literature in identifying when it is more appropriate for the robot to warn the operator that it is about to pass them an object. The right timing is particularly relevant when we consider a continuous pick-and-place task during which the planning and control phases of two consecutive trials necessarily overlap. Identifying this timing is useful for minimizing interference phenomena on the human main task, thus enabling untrained users to properly interpret the robot's signal without effort. To address this open issue, 17 participants were asked to perform an experiment with one within-participant factor, i.e., the robot signal timing. During this experiment, participants were engaged in a continuous pick-and-place task designed to induce a high cognitive and attentional load. Participants were asked to move from one side of a table to the other four fragile objects (FOs), following a predefined order
(Fig. 1). They were instructed to move them as fast as possible F1
without breaking the objects. Occasionally, and at different moments of the reaching and placing action phases, a haptic cue (C) was presented on the participants' employed arm to signal the request for a secondary task. At C presentation, participants had to (i) complete only the specific pick-and-place action they were performing when they received the C, (ii) grasp and position an object offered by the robot, and (iii) resume the main pick-and-place task. Specifically, participants underwent four experimental sessions that differed in the timing of C delivery during the pick-and-place action. The C timings were chosen on the basis of the kinematic characteristics of goal-directed human arms' motion. A common characteristic of these type of motions (e.g., any aiming, reaching, and motion of handheld objects) is an initial phase carried at high velocities followed by a low-velocity final phase. The low-velocity phase consistently begins when about 75% of the movement duration has elapsed (*66*–*68*). Therefore, the C was delivered at around 25 and 75% of the duration of the reaching (C1 and C2 sessions) and placing phases (C3 and C4 sessions). This scheme was chosen to test the difference in interference effects when a C is administered during the accelerating or decelerating phase of each of the two phases of the task.

Each session was composed of 12 blocks. One block of the experiment included the transportation of all four FOs to the other side of the table and, therefore, consisted of four trials. A trial corresponds to a single pick-and-place action. During one randomly selected trial (C trial) of each block, C was delivered to participants. After the continuous execution of four blocks, participants could rest for up to 5 min. Before the beginning of each experimental session, a baseline was set by recording a session of four blocks without neither handover nor C delivery. The administering order of the experimental session was reasonably balanced across participants.

To evaluate the interference effect of each C on the execution of the main manipulation task, we counted the errors made by participants with respect to a personal baseline. Three types of errors were defined for each C timing: (i) failed C trials, if the participant moved the hard objects (HOs) before completing the ongoing trial, or ignored the C and the handling of the HO by the robot; (ii) wrong FO, if participants picked the wrong FO or placed the FO in a wrong release position; and (iii) broken FO, if participants broke the FOs they were manipulating. A higher number of errors essentially indicated a greater interference effect on the main task. The second group of indexes used to monitor C timing interference concerned the measurements of the participant's arm kinematics during the execution of the C trials. For each C timing, we evaluated the duration of the reaching (T_{reach}) and placing (T_{place}) phases of C trials with respect to a baseline and the difference in spectral arc length ($SPARC_{trial}$) of the participants' arm velocity with respect to a

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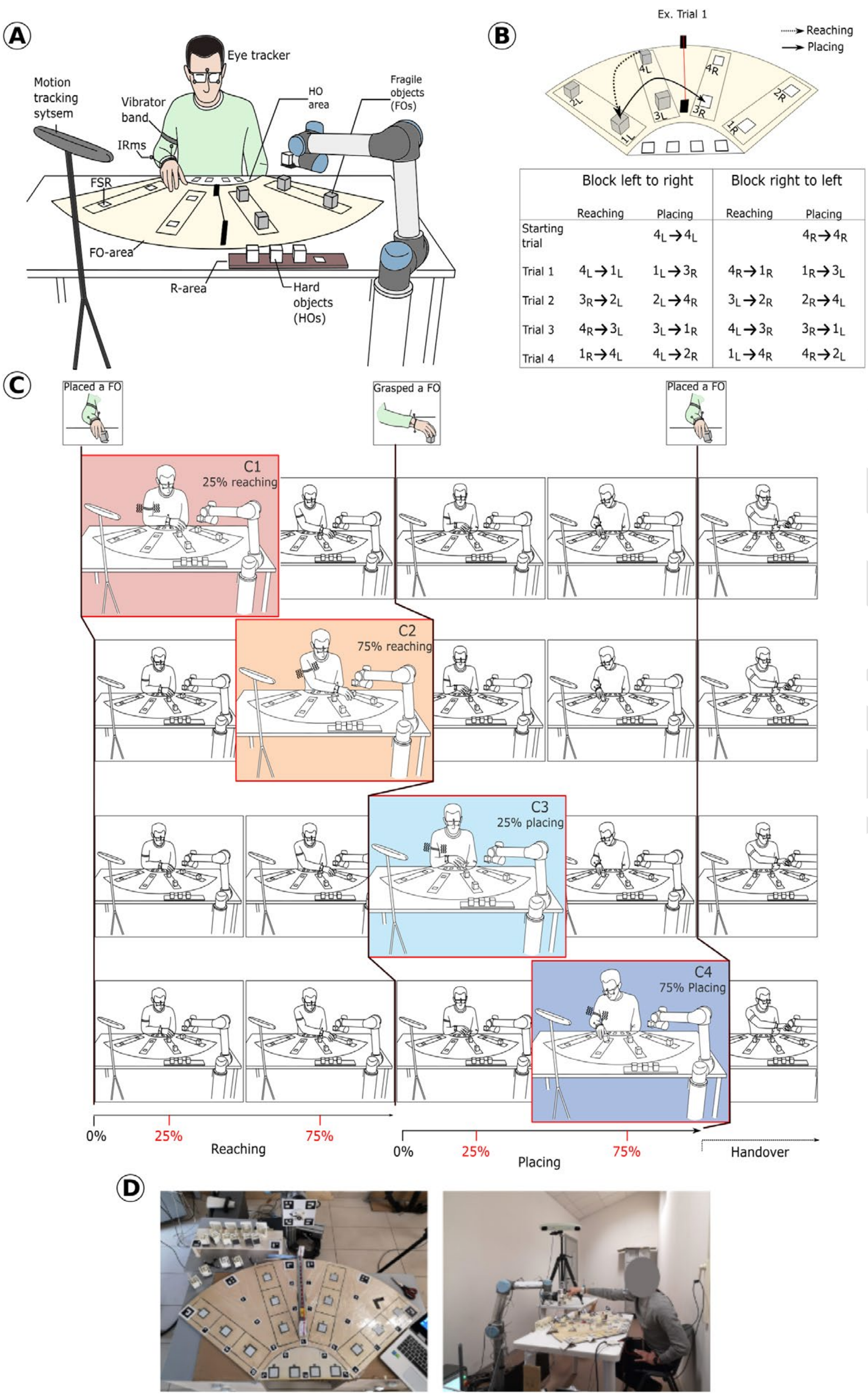

Fig. 1. Experimental setup and cue timings. The experimental setup is shown in (**A**), and the action sequence to move the FO across the table is reported in (**B**). An outline of a C trial for every experimental session of the experiment is shown in (**C**). (**D**) Photographs of the experimental setup.

baseline. SPARC is a measure that quantifies movement smoothness (*69*). Every notable difference in kinematics with respect to the baseline was considered an indication of a C timing interference on the main task. Last, we analyzed the occurrence of unnecessary observation of the robot during the C trials using eye tracking. During the handover of an HO, participants had to observe the robot to check its position and that of the object they needed to grasp. Differently, during the execution of the C trials, unnecessary observations of the robot may lead to inaccuracies in the execution of the main task, and moreover, such observation may hint to the presence of hesitations about when a participant should interact with the robot. Therefore, for each participant and each C timing, we calculated the overall duration of observations around the robot's end effector.

Our results confirmed that the signaling timing may have a decisive influence on the performances of the human-robot teamwork. In particular, providing a cue at the beginning of the reaching phase (C1) led to (i) an increase in the number of errors during the task, (ii) an extension of the duration of the reach-to-grasp movement, (iii) a degradation of the smoothness of movements, and (iv) unnecessary deflections of the human gaze toward the robot. These disruptive interference effects strongly decreased until they disappeared as the signal was provided during the placing phase and particularly during its early stage (C3), identifying this as the best timing. The number of errors committed by participants increased again when the cue was given too close to the end of the trial (C4).

RESULTS

Errors in performing the task

Figure 2 shows the relative frequencies F2 (normalized against baseline values) of the failed C trials, wrong FO, and broken FO errors made by participants in each experimental session. To assess the effect of the C timing, a Friedman test followed by Dunn's post hoc comparisons was performed on each type of error. The complete statistical results are reported in Table 1. T1

Our results showed a statistically significant effect of the C timing on both failed AQ7 C trials and wrong FO errors. In particular, Dunn's post hoc test assessed that C1 led to a statistically higher incidence of failed C trials [median, 8.3%; interquartile range (IQR), 17.8%] than C2 and C3 (both with median, 0%; IQR, 0%; Table 1 and Fig. 2). An increase in frequency of the failed C trials in C4 (median, 8.3%; IQR, 10.5%) when compared with C3 was also observed. However, even if this comparison produced a relatively low P value ($P = 0.020$), it became not statistically significant after a Bonferroni correction AQ8

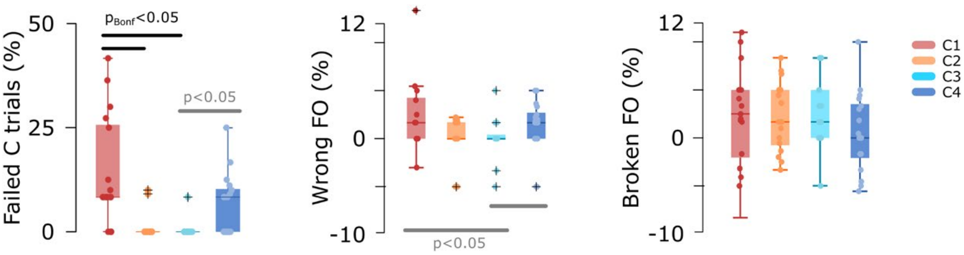

Fig. 2. Error frequencies. Boxplots showing the distribution of the relative frequencies of the errors (minus the frequency values recorded in the corresponding baseline sessions) made by each participant in each session of the experiment. Horizontal gray and black bars represent the post hoc comparisons that returned, respectively, a significant non-adjusted and significant Bonferroni-adjusted comparison with a P value or $P_{Bonf} < 0.05$.

This result is in agreement with the output of the Friedman's test showing a significant effect of the C timing on $T_{Observation}$. Furthermore, post hoc comparisons showed that $T_{Observation}$ was significantly longer in C1 (median, 0.04 s; IQR, 0.51 s) than in C4 (median, 0; IQR 0), whereas the observed increase of $T_{Observation}$ in C2 compared with C4 resulted significant ($P = 0.016$) only without the Bonferroni correction (Table 1 and Fig. 4).

was applied (in our study, this correction is quite severe, implying to multiply the P value by 6; Table 1 and Fig. 2).

Similarly, the frequencies of wrong FO recorded in C1 (median, 1.7%; IQR, 4.5%) and those recorded in C4 (median, 1.7%; IQR, 2.9%) were statistically higher than those in C3 (median, 0%; IQR, 0.8%) AQ9 before the Bonferroni correction (Table 1 and Fig. 2). No significant effect of C timing on the broken FO error was found (Table 1 and Fig. 2).

Movement duration and smoothness

F3 Figure 3 shows the values of the average duration of the reaching and placing phases of C trials with respect to the baseline (T_{reach} and T_{place}) and the average $SPARC_{trial}$ of the C trials with respect to the baseline evaluated for each participant in each experimental session. To assess the effect of the C timing, a repeated-measures analysis of variance (ANOVA) followed by post hoc comparisons was performed on T_{reach} and $SPARC_{trial}$, whereas a Friedman test followed by Dunn's post hoc tests was performed on T_{place} (because the second set of data was not normally distributed, a Shapiro-Wilk test was used). The complete statistical results are reported in Table 1.

Results showed that C timing had a significant effect on the three metrics. Specifically, post hoc comparisons showed an increase of AQ10 T_{reach} in C1 (mean, 0.061 s; SD, 0.16 s) compared with C3 (mean, −0.09 s; SD, 0.15 s) and C4 (mean, −0.499 s; SD, 0.13 s); the last one became nonsignificant after the application of the severe AQ11 Bonferroni correction (Table 1 and Fig. 3). Furthermore, T_{place} was significantly longer in C2 (median, 0.031 s; IQR, 0.27 s) than in C3 (median, −0.093 s; IQR, 0.25) and, without applying Bonferroni correction, C4 (median, −0.08 s; IQR, 0.10 s) (Table 1 and Fig. 3).

Last, $SPARC_{trial}$ was significantly lower (i.e., rougher movements) in C1 (mean, −1.24; SD, 0.20) than in C3, C2 (mean, 0.01; SD, 0.12), and C4 (mean, 0.06; SD 0.11). Compared with C1, a notable increase in $SPARC_{trial}$ was observed in C3 (mean, 0.42; SD, 0.10). However, even if this comparison produced a relatively low P value ($P = 0.023$), it became not significant when the severe Bonferroni correction was applied (Table 1 and Fig. 3).

Gaze behavior

In each experimental session, for each participant, the total duration of robot observations (i.e., gazing time on or close to the robot end-effector) recorded during C trials ($T_{Observation}$) was computed F4 (Fig. 4). To assess the effect of C timing on $T_{Observation}$, a Friedman test followed by Dunn's post hoc comparisons was performed.

The number of participants who looked at the robot at least once during the C trials (i.e., those with $T_{Observation} > 0$) progressively decreased from C1 to C4 (C1 = 12; C2 = 9; C3 = 8; C4 = 2).

DISCUSSION

As the adoption of robots becomes more widespread in a variety of environments (*1*, *2*), their safe and efficient collaboration in physical proximity with humans becomes progressively more important. A fluent and intuitive collaboration between robots and humans requires the establishment of bidirectional communication that enables the effortless sharing of their state and future actions. To establish human-robot bidirectional communication, recent literature explored and compared several methods that allow robots to provide informative signals to their operator (*24*–*28*, *30*, *32*–*35*). However, these studies did not account for the fundamental aspect of signal timing. Investigating this aspect requires establishing when it is more appropriate for the robot to warn the operator of its intention to collaborate, to reduce the level of interference with the partner's actions. Several neuroscientific studies illustrate that motor activity can be severely perturbated by concurrent cognitive tasks or changes in social scenario (*70*–*73*). Still, even among this field of literature, very few published works considered the possibility that the amount of interference may vary as a function of the moment in which the concurrent event occurs. Therefore, the available literature is not able to identify the optimal signaling timing for realistic human-robot collaborative situations.

To fill this gap, we asked 17 participants to continuously perform a pick-and-place task as fast as possible with FOs, following a predefined order and receiving sporadically, and in different moments of the reaching and placing phases of movements, a C that informs when an interaction with the robot was requested. According to the kinematic characteristics of aiming arm movement (*67*), a C was delivered at the beginning (C1) and the end (C2) of the reaching phase, (i.e., when the hand approaches and reaches the manipulated object), and at the beginning (C3) and the end (C4) of the placing phase (i.e., when the hand completes the grasp and liftoff of the object, transports it, and places it on the final predefined position) of randomly selected trials. The design of the experiment (i.e., time pressure, predefined order, and presence of FOs) was tailored to induce a high cognitive and attentional load of the participants enhancing their susceptibility to errors (*74*, *75*). This methodological choice allowed us to identify the cue timing that requires the fewer human cognitive resources by comparing the interference effects on the pick-and-place task (i.e., the human main task) execution caused by each C. The results showed that the greatest interference phenomena occurred when the C was given during the acceleration phase of the reaching phase (C1). The interference effects decreased and almost disappeared as the signal was provided during the early stage of the placing phase (C3). At the same time, an increase of the

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Table 1. Statistical results. Results of the Friedman tests and its Dunn's post hoc comparisons and results of ANOVA tests and its post hoc comparisons. For the post hoc test, both the non-adjusted P values (P) and the corresponding adjusted P values applying the Bonferroni correction (P_{Bonf}) are reported. Significant results ($P < 0.05$) are highlighted in boldface.

	Friedman (χ^2) or ANOVA (F)	Post hoc test					
		C1-C2	C1-C3	C1-C4	C2-C3	C2-C4	C3-C4
Error analysis							
Failed C trials	**χ^2 (3) = 23.575 $P < 0.001$**	**$P = 0.002$ $P_{Bonf} = 0.011$**	**$P < 0.001$ $P_{Bonf} = 0.002$**	$P = 0.207$ $P_{Bonf} > 1$	$P = 0.642$ $P_{Bonf} > 1$	$P = 0.063$ $P_{Bonf} = 0.377$	**$P = 0.020$** $P_{Bonf} = 0.121$
Wrong FO	**χ^2 (3) = 9.321 $P = 0.025$**	$P = 0.073$ $P_{Bonf} = 0.437$	**$P = 0.024$** $P_{Bonf} = 0.144$	$P = 0.842$ $P_{Bonf} > 1$	$P = 0.642$ $P_{Bonf} > 1$	$P = 0.063$ $P_{Bonf} = 0.377$	$P = 0.039$ $P_{Bonf} = 0.237$
Broken FO	χ^2 (3) = 5.156 $P = 0.161$	–	–	–	–	–	–
Completion time analysis							
T_{reach}	**F(3,48) = 3.34 $P = 0.027$**	**$P = 0.050$** $P_{Bonf} = 0.297$	**$P = 0.026$** $P_{Bonf} = 0.154$	**$P = 0.041$** $P_{Bonf} = 0.244$	$P = 0.153$ $P_{Bonf} = 0.921$	$P = 0.544$ $P_{Bonf} > 1$	$P = 0.413$ $P_{Bonf} > 1$
T_{place}	**χ^2 (3) = 8.506 $P = 0.037$**	$P = 0.084$ $P_{Bonf} = 0.505$	$P = 0.288$ $P_{Bonf} > 1$	$P = 0.690$ $P_{Bonf} > 1$	**$P = 0.005$ $P_{Bonf} = 0.032$**	**$P = 0.034$** $P_{Bonf} = 0.201$	$P = 0.507$ $P_{Bonf} > 1$
Movement smoothness analysis							
$SPARC_{trial}$	**F(3,48) $P = 0.001$**	**$P = 0.004$ $P_{Bonf} = 0.022$**	**$P = 0.023$** $P_{Bonf} = 0.140$	**$P = 0.003$ $P_{Bonf} = 0.016$**	$P = 0.506$ $P_{Bonf} > 1$	$P = 0.176$ $P_{Bonf} > 1$	$P = 0.670$ $P_{Bonf} > 1$
Gaze behavior analysis							
$T_{Observation}$	**χ^2 (3) = 13.852 $P = 0.003$**	$P = 0.525$ $P_{Bonf} > 1$	$P = 0.090$ $P_{Bonf} = 0.538$	**$P = 0.002$ $P_{Bonf} = 0.014$**	$P = 0.289$ $P_{Bonf} > 1$	**$P = 0.016$** $P_{Bonf} = 0.097$	$P = 0.179$ $P_{Bonf} > 1$

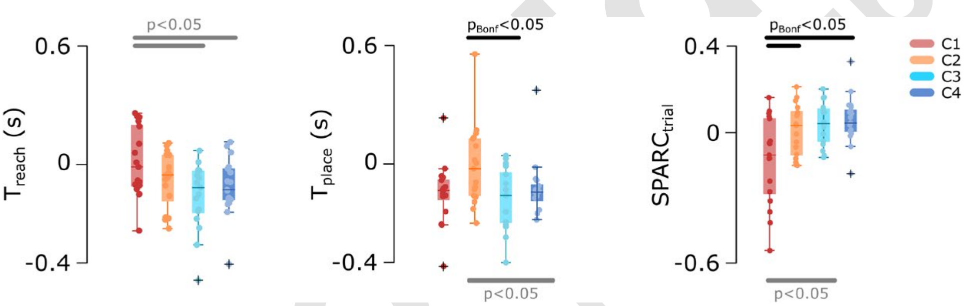

Fig. 3. Completion times and smoothness of participants' arm movement in C trials. Boxplots showing the distribution of the average time spent by participants to complete the reaching (T_{reach}) and placing (T_{place}) phases and the average $SPARC_{trial}$ (that quantifies movement smoothness) of each participants' arm velocity for those trials where a C was delivered. The metrics shown are normalized using the corresponding baseline sessions data. Horizontal gray and black bars represent the post hoc comparisons that returned, respectively, a significant but non-adjusted and Bonferroni-adjusted P value (P or $P_{Bonf} < 0.05$).

execution errors was observed again when providing the cue toward the end of a trial and close to the beginning of the subsequent one (C4).

Specific signal timing reduces cognitive-motor interference effects

Object manipulation is a complex task requiring resources to integrate sensory, motor, and cognitive systems (*59*, *76*) and the ability to adapt to a broad range of conditions (*77*). Furthermore, object manipulation in daily life is usually performed concurrently with other cognitive tasks. Previous studies based on dual-task paradigms have shown that cognition can severely interfere and negatively influence the realization of upper limb movements and manipulation actions (*70*, *71*, *78*). The possibility of motor-cognitive interferences is particularly relevant during a collaborative activity that intrinsically elicits a substantial cognitive load to coordinate the interaction and information exchange with partners. Cognitive-motor dual-task paradigms used to study the attentional demands of motor tasks usually require participants to continuously execute a cognitive task (e.g., a visual search combined with counting or a semantic activity) while executing actions (e.g., a series of precision grips). The comparison between the parameters of the movements performed with and without the concomitant cognitive task indicates which aspects of the action are the most disturbed and, indirectly, those that require more cognitive resources. In addition, a series of studies found that the social and working context influences object reaching and placing activities. An example of this phenomenon is shown by the behavioral modifications induced by an interaction request to hand over an object by another human individual. These AQ12 types of cue may interfere with and influence both action planning and execution (*46*, *73*, *79*–*83*). However, these studies open up the fundamental questions of the work presented here. Because they used a single timing scheme to present the concurrent perturbation, they did not assess whether the interference varies depending on the moment at which the request is presented. Also, in the protocol of those studies, participants' actions were segmented and externally paced. Thus, the moment when participants planned their motion never overlapped with the motion execution, which happens in a

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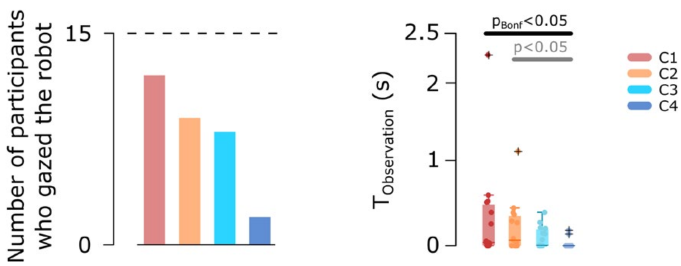

Fig. 4. Gaze analysis. The bar plot on the left shows, for each experimental condition, the total number of participants who gazed at the robot at least once during the C trials. The dotted line shows the total number of participants included in the gaze analysis. The boxplot on the right shows the overall time spent by each participant gazing inside the robot AOI ($T_{Observation}$) during all C trials of each condition. Horizontal gray and black bars represent the post hoc comparisons that returned, respectively, a significant non-adjusted and a Bonferroni-adjusted P value (P or $P_{Bonf} < 0.05$).

realistic self-paced continuous pick-and-place task such as the one used in this study. In the latter situation, it is not possible to assume when, during the execution of the movement, the next action is planned, and this problem is even more complicated when human operators know that they have to cooperate with a robot, but they are not aware exactly when.

Our results confirmed that the amount of disruptive effects induced on the main task by a concomitant interaction request is influenced by the time when the signal request is presented during the action. We observed that the greatest interference phenomena occurred when the signal was given at C1. Specifically, in a significant number of C1 trials, participants wrongly interrupted the ongoing main action to immediately grasp the object presented by the robot (i.e., failed trials), disregarding the experiment instructions (Fig. 2). Furthermore, in those trials of C1 where no failures occurred, we observed, especially compared with C3, a moderate increase of the occurrences in which participants wrongly grasped or moved an FO (i.e., errors defined as wrong FO) and a moderate elongation of the average duration of the reaching phase (T_{reach}) of the C trials. During C trials, C1 also induced a significant deterioration of the participants' arm movement smoothness ($SPARC_{trial}$) (Fig. 3).

These results showed that the cue perturbed the participants' motor activity and almost automatically elicited a complementary motor response (*73*, *79*, *84*). A similar behavior was observed also by Sartori *et al.* (*73*). In their experiment, participants were requested to reach for and grasp a target object and then move it into a container. In 20% of the trials, the experimenter stretched out their right arm and unfolded their hand to ask for the object when the participant started the action. The participants were expressly told to ignore the experimenter's movement. Similar to what was observed in the present work during C1 failed trials, Sartori and colleagues reported that in some cases participants, disregarding the instructions, interrupted their main action and responded to the request by placing the handled object in the experimenter's hand. According to the authors, these types of phenomena occur because unexpected requests induce participants to comply with them, activating the appropriate motor response and perturbating, or in some cases overriding, the ongoing movement programs.

Similar to what was observed in this work during the C1 trials, Chinellato *et al.* (*72*) showed that, during reach-to-grasp movements, the perception of concurrent stimuli (e.g., the observation of an agent acting with interactive purpose) induced a delay of the movement completion time and an increase of variability in the movement trajectory. The latter was evaluated by analyzing over time the distance of the arm trajectory path from an ideal straight line linking the starting and the target position of the movement. Therefore, an increase of the variability of the movement trajectory may implicitly indicate a decrease in the movement smoothness, and thus, it is compatible with the reduction of the $SPARC_{trial}$ index (*69*, *85*) observed in C1 trials. This implies that the motor perturbations induced by C1 when participants did not completely fail also agree with the interpretation that the robot cue activated a motor program incompatible with the predetermined one, triggering a demanding competition between them (*72*, *86*, *87*). This interference probably resulted in an escalation of the uncertainty in prioritizing the task goals and led the participants to perform the task less efficiently.

Nevertheless, all the interference effects observed with C1 strongly decreased with C2 and almost disappeared in C3 and C4. In particular, the only relevant motor perturbation induced by C2 was an elongation of the average duration of the placing phase (T_{place}) of the C trials. However, in this experimental session, participants failed only rarely if at all, interrupting the ongoing action to immediately respond to the robot's request. This suggests that compared with C1, the robot's request provided in C2 interfered less with the ongoing action and that its elicited motor response was more easily suppressed by participants. However, the response suppression is an active process that closely interacts with the motor system and may impair manipulation actions because they compete for the same, finite, attentional, and cognitive resources (*77*, *88*, *89*). Therefore, the observed elongation of T_{place} can be explained by the fact that C2 was probably delivered when several of the cognitive resources of the participants were already recruited to efficiently grasp the FO, and the additional concurrent cognitive activity needed to suppress the elicited motor response overloaded the attentional-control system, inducing participants to slow down the immediately following manipulation actions.

All the effects mentioned above almost disappeared in C3 (Figs. 2 and 3), showing that this signaling timing allowed participants to process and handle the robot's request while minimizing its negative interference effects. C3 was probably delivered in a time window when the object transport was executed almost automatically, recruiting limited or no cognitive resource, as it happens AQ13
during the automatic coupling of the grip force and load forces to avoid object slippage or breakage (*71*). Moreover, general findings about motor cognition (i.e., stimulus-response compatibility) (*90*–*92*), as well as previous works about human interruptibility in the field of human-computer interaction (*46*), show that the disruptive interference between perceived stimulus and actions increases with the degree of similarity between the ongoing movements and the concurrent stimulus-induced response. Our outcomes are in accordance with these findings. The similarity between the response elicited by the collaborative affordance (i.e., to pick the object passed by the robot) and the preplanned movement during the reaching phase (i.e., to pick the predetermined object) was greater than the similarity with the preplanned movement of the placing phase (i.e., to place the handled object on the predetermined position). As a consequence, during the placing phase, we observed a lower interference of the C, and participants were less attracted by the object offered by the robot, even considering that their hand was already occupied by an FO.

A different negative effect is the one induced by C4. Only during this experimental session, we observed that in some cases, and especially in the first C trials, participants were failing the task, ignoring the robot's signal and the associated handover request while grasping the following FO instead of receiving the object from the robot (Fig. 2). We believe that this erroneous behavior can be explained by the request to perform the pick-and-place task as fast as possible and thus under time pressure. C4 was delivered near the end of the trial, when participants were probably planning or had already scheduled the next actions to start the following trial. This implies that, with respect to the other sessions, C4 gave participants a limited amount of time to complete the ongoing manipulation and concurrently integrate the robot's request, deciding how to correctly reschedule the following activities. Thus, it is likely that participants were more prone to making the wrong decision and ignoring the robot's request during a stressful period of time, owing to the instruction to perform the trials as fast as possible. This situation is also likely to be further exacerbated by the novelty of the experimental condition. Furthermore, time pressure could also have contributed to confuse participants about when they received the timing, favoring the failure of the trials not only in C4 but also in C1. These hypotheses are coherent with previous studies showing that time pressure deteriorates the quality of judgment, decision-making, and problem-solving (*74*); affects attentional orienting; and increases error occurrences (*75*).

Early robot signals take the partner's eyes off from the action

Human gaze behavior has been studied in various daily living activities. Among these activities, a common experimental finding is that people tend to gaze toward specific landmarks that are relevant for the task to gather useful information to guide manipulatory actions (*26*, *93*, *94*). In this work, the analysis of gaze behavior of participants during C trials showed an increase of the unrequested observations toward the robot ($T_{Observation}$) in C1 and C2 (Fig. 4), revealing an interference of the robot cue with the main manipulation task. This interference created an escalation of uncertainty that led participants to check the status of the interaction, reducing attention from their main action and inducing them to gaze toward the robot.

CONCLUSION AND FUTURE WORK

Our results showed that the timing used by the robot to send an interaction request to a human partner by means of a C plays a crucial role in establishing an efficient robot-human communication and coordination for collaborative manipulation tasks. In particular, a collaboration request should not be sent when the preplanned movement is similar to the response required for the interaction because it can interfere with the current action execution, inducing higher error rates, longer completion time, and reduced motion smoothness. For the specific type of task in this experiment, i.e., a pick-and-place task, robots should send a collaboration request at the beginning of the placing phase (as in C3) to interfere the least with their human partner's motor activity.

In accordance with the considerations drawn by Breazeal *et al.* (*28*), our results underline the importance and benefits of designing the robot-to-human interaction following the neuroscientific principles underpinning human perception and motion control. In future work, additional studies administering a similar experimental protocol but changing the informative content of the cue and the signal modality (e.g., visual and auditory) could be performed. These additional analyses may provide useful insights in understanding the correlation between signal timing and the type of communication channel used and information conveyed by the cue. Moreover, we envisage to include in future experimental protocols the administration of a specifically designed questionnaire to assess the participants' subjective perceptions and experience. Because we aimed to identify an intuitive signal timing, our experimental protocol was designed to limit possible effects induced by the human adaptation phenomenon, typical of a long-term collaboration. Future work may clarify how much effort and time humans need to learn how to properly interpret the C1 and C4 signals that were the most disruptive timing strategies for our manipulation task.

MATERIALS AND METHODS

Participants

Seventeen participants (right-handed, 7 females; 27 ± 3 years old) took part in the experiment. The number of participants enrolled has been limited as a contingency measure to reduce the risks associated to the spread of coronavirus disease 2019 (COVID-19). None of the participants reported any history of sensory or motor impairments, and all of them claimed to have normal or corrected to normal vision. Informed consent in accordance with the Declaration of Helsinki was obtained from each participant before conducting the experiments. This study was approved by the local ethical committee of the Scuola Superiore Sant'Anna, Pisa, Italy (approval number 2/2017).

Experimental setup, stimuli, and procedure

The experimental setup comprised four FOs, four HOs, a robotic arm, an instrumented table, and a customized vibrator band (Fig. 1A). AQ14
The four FOs were three-dimensionally (3D) printed blocks with a metal sheet latched at the bottom (40 mm by 40 mm by 70 mm; weight 100 g) and were equipped with a magnetic fuse that exploits the attraction force between two magnets to maintain a fixed distance amid the two opposite walls of the block. When a block was grasped with a grip force larger than the attraction force between the two magnets, the FO collapses (i.e., its opposite walls move closer), and it is considered as broken (*95*). The four HOs were 3D printed unbreakable blocks (40 mm by 40 mm by 70 mm; weight 100 g) with a similar appearance to FOs. Each HO had a conveyor tray with a metallic insert. The robotic arm (UR5, Universal Robots, www.universal-robots.com) was equipped with an electromagnet placed on its end-effector, which allowed the robot to attach and move the conveyor tray of each HO.

The instrumented table (120 cm by 75 cm) was divided into three areas: (i) the R area, in which the robot was present; (ii) the HO area, in which four predefined places to insert the HOs passed by the robot were present; and (iii) the FO area, in which eight predefined FO positions were indicated. The FO area was subdivided into two halves by means of a 15-cm-tall wall (red line in Fig. 1A) so that four FO predefined positions were present in the left half of the table (1_L, 2_L, 3_L, and 4_L) and four FO predefined positions were present in the right half of the table (1_R, 2_R, 3_R, and 4_R).

All the predefined positions on the table were equipped with a contact FSR sensor (FSR 406, Interlink Electronics; AQ15
www.interlinkelectronics.com) to detect when and where FOs were

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placed on the table. A custom data acquisition system acquired and digitized with 12-bit resolution the analogic signals of the FSR sensors at a frequency of 100 Hz. The acquisition system ran in real time on a development board integrating a microcontroller (Photon, Particle
AQ16 Inc.; www.particle.io). A customized vibrator band was placed around the upper right arm of each participant, delivering a short-lasting (500 ms) vibration upon command.

The gaze of participants was recorded using the Pupil Core eye tracking headset (participant field of view camera speed, 30 Hz; eye camera speed, 120 Hz) and its companion software (Pupil Labs GmbH; www.pupil-labs.com) in conjunction with AprilTag markers. The markers were placed around the robot's end effector, creating
AQ17 an AOI (see the Supplementary Materials), allowing the Pupil Labs software to record over time when the gaze fell inside or outside the predefined area.

AQ18 The motions of participants' right wrists were tracked and recorded using a Polaris Spectra stereoscopic tracking system (Northern Digital Inc.; www.ndigital.com) together with custom MATLAB (The MathWorks Inc.; www.mathworks.com) code. Two frames equipped with a unique pattern of infrared reflective markers (IRm) were exploited. One frame was fixed on the table, and its coordinate system was used as the global reference for the wrist tracking system; the other one was attached to the right wrist of the participant. The Polaris Spectra system was set to track and report at a frequency of around 30 Hz the position of the frame on the wrist with respect to the global reference. The marker placed on the wrist used an optimized geometry to further enhance tracking robustness as described
AQ19 in detail in (*96*). A custom application (WPF, Visual Studio, Microsoft, USA) running on a PC was used to record data acquired from all the sensors as well as to control the robot and the sensory feedback system.

Each participant was seated facing the robot and in front of the instrumented table, wearing the eye tracker on her/his head, the vibrator band on the upper right arm, and the frame equipped with
AQ20 IRm on the right wrist. At the beginning of the experiment, the four HOs were presented on their conveyor in the R area, and the four FOs were placed on the left half of the table (1_L, 2_L, 3_L, and 4_L) (Fig. 1A).

Participants were asked to use their right hand to reach, grasp, and lift each FO and move and reposition it on the correct position on the right half of the table. Once all the four FOs were transported to the right side of the table, participants again had to grasp each FO and reposition it on the correct position on the left half of the table.

Once the experiment was started, the task should have been done as fast as possible without breaking the FOs. A trial corresponded to a single pick-and-place action, subdivided into a reaching phase (i.e., the hand approaches, reaches, and grasps) and a placing phase (i.e., the hand lifts the objects, moves toward the predefined position, and places the object on it). A block consisted of moving all of the four FOs to the other half of the table (experimental trials 1, 2, 3, and 4). Participants were required to start each block by picking, lifting, and placing down the first to-be-moved FO again in
AQ21 the same position (starting trial) to ensure that they started each block by moving the hand from about the same position.

Before the beginning of each block, the robot picked up an HO, moved the end effector holding the object toward its home position, and started to perform some continuous little movements. The robot's home position was right in front of the participants, on the opposite side of the table (Fig. 1A). During one randomized experimental trial of each block (C trial), at different timings, the vibrator band delivered a burst, and soon after, the robot moved slightly forward, reaching the handover position (Fig. 1A). Participants were instructed to receive the HO only after having completed the trial they were performing. Once participants grasped the HO from the robot, they had to place it on a predefined position of the HO area and then immediately resume the original pick-and-place task. The vibration burst (acting as a C), conveying the robot's AQ22
intention to cooperate, was delivered at four different timings: around 25% (C1) and 75% (C2) of the duration of the reaching phase and around 25% (C3) and 75% (C4) of the duration of the placing phase.

Participants were assigned to four experimental sessions of 12 blocks each, differing for the C timing (one within-participant factor). In each experimental session, after continuous execution of four blocks (i.e., after filling all HO positions), participants could rest for a time period of up to 5 min. At the beginning of each experimental session, a baseline session of four blocks without handover or C signal was performed. The order of the experimental sessions was reasonably balanced across participants, and the trials in which the C was delivered were randomized within the 12 blocks of each session from a total of 24 possible orders (see the Supplementary Materials). For each participant and each experimental session, C was administered comparing the real-time measure of the distance of the participant's right wrist above the table, with a threshold evaluated using the wrist movements collected during the corresponding calibration session. The correctness of C timing delivery was checked offline, and in cases when C was delivered at a wrong time within the trial, the corresponding block was not included in the analysis (Excluded block) (see the Supplementary Materials).

Before the beginning of the experiment, participants were informed by the experimenters about the correct FO movement order and their final position (Fig. 1B). Each participant was trained to perform a correct block by executing some training attempts. Participants did not express relevant difficulties in learning the task. Furthermore, they were informed about the correct interaction with the robot, the meaning of the C, and the necessity to complete the trial in progress before handling the HO offered by the robot. Last, participants performed the calibration procedure of the eye tracker as suggested in its user manual (see pupil-labs/calibration for further details). Each experiment lasted about 45 min.

Data analysis

Analysis of errors

For each participant and each C timing, we evaluated and analyzed three types of errors:

1) Failed trials, i.e., those trials in which the participants did not correctly perform the task after C delivery, e.g., receiving the HO before completing the trial in progress or ignoring the C and the handling of the robot. This type of error was recorded manually by the experimenter. The frequency of failed trials on the total number of C trials in the experimental session (n = 12 minus the number of eventually excluded blocks) was calculated.

2) Wrong FO, i.e., when participants picked the wrong FO or placed the FO in a wrong release position. These errors were recorded automatically by the PC custom application using the online FSR data. This also allowed the PC to emit a beeping sound when a wrong FO error occurred. The frequency of wrong FO on the total number of trials in the experimental session (n = 60,

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48 experimental trials and 12 starting trials, minus the number of trials of eventually excluded blocks) was calculated.

3) Broken FO, i.e., when participants broke the FOs they were manipulating. These errors were recorded manually by the experimenter. The frequency of broken FO on the total number of trials in the experimental session (n = 60, minus the number of trials of eventually excluded blocks) was calculated.

The frequency of the errors was also calculated for each baseline session. For each C timing and each participant, we computed the net relative frequency of each type of error by subtracting the frequency of errors recorded during the baseline session from that recorded during the experimental session. The obtained net relative frequencies of each error were then submitted to a Friedman test, followed by a Dunn's test with post hoc Bonferroni's correction, to compare the number of errors of each C timing.

Analysis of movement duration and smoothness

Using data acquired from FSR sensors that recorded when a specific FO was lifted off or placed on the predefined positions of the table, it was possible to evaluate for each trial of the experiment the duration of the reach and place participants' movements. Furthermore, AQ23 for each participant and each C timing, the average of the duration of all the reaching and placing phases of all C trials was calculated. For each C timing and participant, the baseline values of the average duration of the two phases were also calculated, computing the mean of the duration of all the reaching and placing action performed during the baseline session. To obtain a net value (T_{reach} and T_{place}), we subtracted the corresponding baseline duration values from the average durations of each C timing. To compare reaching and placing duration of each C timing, and according to the presence of data normality, T_{reach} was submitted to a repeated ANOVA followed by t test post hoc comparisons, and T_{place} was submitted to a Friedman test. Post hoc Bonferroni's correction for post hoc comparisons was applied.

The SPARC of the participants' arm velocity is a recent approach to quantify movement smoothness. Compared with the other commonly used metrics such as jerk-based measures and number of peaks measures, SPARC was shown to be more robust to signal-to-noise artifacts, and it is independent of temporal movement scaling (*69*). A detailed explanation of the SPARC measure and its calculation methodology is described in the appendix of (*69*).

Thus, for each trial of the experiment, the velocity of the participants' arm movement was calculated using the data recording their wrist movement over time. Then, for each participant and each C timing, the average SPARC value of all C trials was calculated. For each C timing and participant, the average SPARC baseline value was also calculated, computing the mean of the SPARC values of all the trials performed during the baseline session. To obtain a net value ($SPARC_{trial}$), we subtracted the corresponding baseline value from the value of each C timing. To compare $SPARC_{trial}$ for each C timing, data were submitted to a repeated ANOVA, followed by Bonferroni corrected post hoc t tests.

Analysis of gaze behavior

The Pupil Labs software recorded over time whether the gaze of participants was inside or outside the AOI defined around the AQ24 robot's end effector (see the Supplementary Materials). For each participant, and each C timing, we evaluated the sum of the amount of the time spent by participants' gaze inside the AOI during all C trials ($T_{Observation}$). Then, we counted the number of participants who looked at the robot at least once during the C trials (i.e., whose $T_{Observation} > 0$). To compare $T_{Observation}$ of each C timing, data, given the absence of normality, were submitted to Friedman test, followed by a Dunn's test with post hoc Bonferroni's correction. This analysis AQ25 was carried out on a total of 15 participants because 2 participants were excluded due to a failure of the eye tracker system.

SUPPLEMENTARY MATERIALS

www.science.org/doi/10.1126/scirobotics.abg1308
Haptic cue delivery and offline check
Figs. S1 and S2
Movie S1

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Abstract

One-sentence summary: A robot should communicate its intention to collaborate shortly after a human has picked an object to avoid interferences.

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