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It's in the Eyes: The Engaging Role of Eye Contact in HRI

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Abstract
This paper reports a study where we examined how a humanoid robot was evaluated by users, dependent on established eye contact. In two experiments, the robot was programmed to either establish eye contact with the user, or to look elsewhere. Across the experiments, we altered the level of predictiveness of the robot's gaze direction with respect to a subsequent target stimulus (in Exp.1 the gaze direction was non-predictive, in Exp. 2 it was counter-predictive). Results of subjective reports showed that participants were sensitive to eye contact. Moreover, participants felt more engaged with the robot when it established eye contact, and the majority attributed higher degree of human-likeness in the eye contact condition, relative to no eye contact. This was independent of predictiveness of the gaze cue. Our results suggest that establishing eye contact by embodied humanoid robots has a positive impact on perceived socialness of the robot, and on the quality of human–robot interaction (HRI). Therefore, establishing eye contact should be considered in designing robot behaviors for social HRI.

Keywords Eye contact · Social human–robot interaction · Social attention · iCub

1 Introduction

Robots are rapidly advancing technically, and they may increase their presence in our society in the near future. Robotic agents will assist humans in daily activities, i.e. by operating repetitive tasks, facilitating teaching, and supporting clinicians [1–5]. Moreover, robots might become a new form of social companions, for example, for elderly people [6, 7]. For a smoother integration of robots in the complexity of human society, robots would require to attune to humans by responding to subtle social cues, coordinating with human actions, and adapting to human needs. In daily interactions, humans rely largely on non-verbal cues, such as partner's gaze. Indeed, during human–human interaction the eyes constitute an important channel for non-verbal communication. Through others' eyes, we gain information regarding their intent to interact with us, their action goals, and the focus of their attention [8–10]. In humans, eye contact is one of the powerful social signals as it is used to initiate communication and covey interpersonal signals [11, 12].

Eye contact modulates a wide range of cognitive processes in humans [13–16], including social attention and memory [17–23]. Early in development, humans are sensitive to eye contact [17]. For instance, it has been shown that newborns prefer direct rather than averted gaze or closed eyes [18]. Furthermore, it has been demonstrated that establishing eye contact is a prerequisite for following others' gaze and establishing joint attention in 4-and 6-old month infants [19, 20]. In adults, it has also been shown that eye contact can modulate joint attention. For example, using a non-predictive gaze-cuing procedure with iCub humanoid robot, Kompatsiari and colleagues found a gaze-cuing effect only for eye contact condition, while no gaze cuing effect was observed for the no eye contact condition [21]. Eye contact captures attention in two ways: either resulting in a delayed attentional disengagement from the gaze, or by enhancing other cognitive processes [14, 22, 23]. On the one hand, Senju and

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Hasegawa showed that faces with direct gaze compared to averted gaze or closed eyes, attracted attention and, as a consequence, delayed detection of a following peripheral target [22]. On the other hand, there is evidence that faces with eye contact, compared to faces with averted gaze, improved identity recognition [23] and gender discrimination [14]. Direct gaze does not only have an impact on cognitive processes but also on affectional aspects as arousal and likeability [24–26]. For example, Kuzmanovic et al. demonstrated that likeability was larger for virtual characters looking straight compared to showing an averted gaze and the likeability linearly increased with the increase of gaze duration (1, 2.5 or 4 s) [24]. Previous studies have also shown that the longer the eye contact duration was, the more favorably this person was judged with respect to likeability, potency, and self-esteem [13, 25, 27, 28]. Furthermore, it has been demonstrated that people engaging in eye contact are perceived as more likable and attractive than the ones who show averted gaze [29, 30].

Despite the importance of eye contact in human–human interaction, little is known about the role of eye contact in human–robot interaction (HRI). One limitation in implementing mutual gaze in HRI is the actual realization of human-like robot eyes, both in terms of appearance and capabilities. Despite the constraints, it has been shown that eye contact with a robot increases its subjective social evaluation, intentionality attribution, and engagement. For example, Yonezawa et al. showed that eye contact with a stuffed-toy robot induced a favorable feeling towards the robot and this feeling was enhanced when the robot further followed the user's gaze [31]. In another study, in which participants were teaching a robot object recognition, they interacted longer with the robot, were more attentive, and returned verbal responses more often to the robot with eye contact compared to a robot with random gaze [32]. The authors argue that all these cues imply an increase in the feeling of intentionality towards the "eye-contact" robot [p. 477, 32]. Furthermore, a robot holding its gaze while replying to a normal question seemed more sociable and intelligent relative to a robot with gaze avoidance, while the reverse effect held for an embarrassing question [33]. Finally, Zhang et al., by focusing on the implementation of a mutual gaze model, demonstrated that an intermittent eye contact behavior between a human and a robot resulted in a positive social effect, improved fluency in interactive applications, and drew more attention of the participants towards the robot compared to a continuous robot-user eye contact [34], see [35] for an extensive review on social eye gaze in HRI.

Previous studies have examined the effect of eye contact using a screen-based agent [33], a non-humanoid agent [31], or a robot head [32, 34]. However, the importance and pivotal role of eye contact in human interactions calls for the need of examining meticulously and systematically the effect of eye contact in HRI using embodied humanoid robots. Towards this aim, we investigated the impact of eye contact using an embodied humanoid robot with human-like characteristics. Differently from previous studies, we used a well-controlled joint attention paradigm to test the role of eye contact across two different type of social interaction, i.e. when the robot behavior is neutral or has negative valence for the performance in the task.

1.1 Aim of the study

In the present study, we examined the sensitivity of humans to an eye contact initiated by a humanoid robot, the induced social engagement, and the attribution of human-likeness. In two experiments, we used an interactive non-verbal paradigm which encompasses eye contact (or not) and a subsequent referential gaze (gaze directed at an object or location in space), initiated by the humanoid robot iCub [36, 37]. In our paradigm, iCub detected the eyes of the participant and either established eye contact (eye contact condition) or avoided it by looking down (no eye contact condition), before shifting its gaze to the left or right to indicate a letter target appearing on two laterally positioned screens. The robot either directed its gaze to the same screen in which the letter appeared (congruent trial, see left panel of Fig. 1), or to the opposite screen (incongruent trial, see right panel of Fig. 1). The main task of the participants was to identify the target as fast as possible through a key press on a standard computer mouse. In this study we were interested in testing the effect of eye contact in social interaction qualified by neutral or negative valence. For this reason, across experiments, we manipulated the predictiveness of gaze concerning the target location, to be either non-predictive (Exp. 1: 50% congruency between gaze direction and target location) or counter-predictive (Exp. 2: 25% congruency). Since a non-predictive and a counter predictive referential gaze vary the cost of attending to the robot, these two types of social interaction could impact social engagement. We did not involve a predictive condition, as we were interested in the conflict situation (engaging eye contact and counter-predictive behavior). We included the non-predictive condition as the most neutral condition for comparison to the conflict condition.

In summary, we created two types of social interaction following the eye contact, i.e. a (1) non-predictive and (2) a

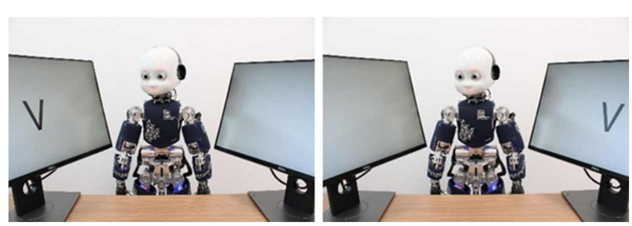

Fig. 1 Congruency between gaze direction and target location. Left panel: congruent trial. Right panel: incongruent trial

counter-predictive referential gaze and we tested the sensitivity to the eye contact, the engagement level, and attribution of human-likeness through analysis of subjective reports.

2 Experiment 1

2.1 Methods

2.1.1 Participants

The experiment was carried out at the Italian Institute of Technology (IIT). Twenty-four participants (mean age $= 26.71 \pm 6.39$; 11 female; 3 left-handed) took part in the study, and each participant received an honorarium for participation. Both experiments (Exp. 1: non-predictive referential gaze and Exp. 2: counter-predictive referential gaze) were approved by the local ethical committee (Comitato Etico Regione Liguria), and each participant signed a consent form before taking part in the experiment.

2.1.2 Apparatus and materials

Participants were seated face-to-face with iCub (125 cm away) at the opposite side of a desk. Two screens (21.5 inches) were used for stimulus presentation, and they were positioned on the left and on the right of the robot at the distance of 105 cm from the participants. Participants' eyes were aligned with iCub's eyes in terms of height. iCub was programmed to look to the following positions in every trial: 1. towards a location in space between the desk and participants' upper body (resting), 2.a. towards participants' eyes (eye contact), or 2.b.—towards the table (no eye contact), 3.a.—towards the left screen (left), or 3.b. towards the right screen (right).

2.1.3 iCub and algorithms

iCub is a full humanoid robot. The head has three degrees of freedom in the eyes (tilt, vergence, and version) and three additional degrees of freedom in the neck (roll, pitch, and yaw). In order to control the movement of the iCub we used YARP, which is a multi-platform open-source framework [37, 38]. To control the eyes and the neck, we used the iKinGazeCtrl (a YARP Gaze Interface), from the available open source repository,[1] which allows the control of iCub's gaze through independent movement of the neck and eyes in a biologically-inspired way [39]. iCub's gaze shift was always combined with a head movement, in order to make it more naturalistic. The vergence angle was set to 5 degrees, while the trajectory duration of eyes and neck movement was set to 200 ms and 400 ms respectively.

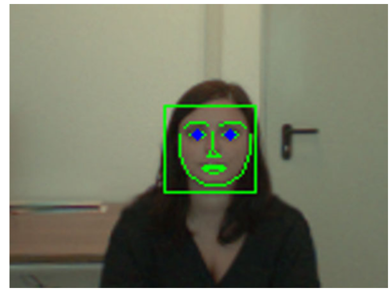

Fig. 2 Output of the left robot eye camera depicting the result of the face detector algorithm. Blue circles indicate the position of the detected eyes. (Color figure online)

The human eyes were detected using the face detector of the "human sensing" module,[2] which uses the Dlib library.[3] Dlib is a modern C++ toolkit containing image processing and machine learning algorithms and tools, used in robotics, embedded devices, and large high-performance computing environments[4] [40–42]. For this study, we integrated the Dlib face detection system with our infrastructure (YARP) to run on our robotic platform (iCub). The Dlib face detector algorithm is a face detection model [43–50], and is based on the Histograms of Oriented Gradients (HOG) features descriptors and linear Support Vector Machines. The model is built out of 5 HOG filters—front looking, left looking, right looking, front looking but rotated left, and a front looking but rotated right. Figure 2 depicts an example of the output of the face detector algorithm drawn from the left robot eye.

2.1.4 Procedure

Every trial started with the robot having its eyes closed for 2 s. Then, it opened its eyes and located the eyes of the participant based on the output of the face detection algorithm. Subsequently, it established eye contact (or not, depending on the experimental condition). If participants' eyes were not detected by the algorithm, the robot was programmed to look straight during the eye contact condition. After 2 s, the robot gazed laterally to one of the screens where the target letter (V, T) appeared for 200 ms. The robot looked at the screen until participant's response. The robot gaze was non-predictive of the target location (50% congruency). Participants were instructed to keep their eyes fixated at the face of the robot and discriminate the letter by pressing the mouse button as fast as possible. Half of the participants pressed the left button to discriminate the V stimulus and

[1] https://github.com/robotology/iCub-main/tree/master/src/modules/iKinGazeCtrl.

[2] [https://github.com/robotology/human-sensing.

[3] http://dlib.net.

[4] https://sourceforge.net/p/dclib/wiki/Known_users/.

Fig. 3 Gaze conditions. Left panel: eye contact. Right panel: no eye contact

Table 1 Questionnaire (Exp. 1)

Questions
1. How familiar are you with the robots (1 = not familiar–5 = very familiar)?
2. Did you perceive any difference across the trials (not related to the letter identity)?
3. In total, how engaged did you feel with the robot? (1 = strongly disengaged–10 = strongly engaged). Which factor influenced your engagement during the experiment?
4. According to you, was the robot thinking like a human (H) or was it processing like a machine (M)? Please indicate evidence for or against the statement
5. Did you feel that this was constant during the experiment? Please indicate evidence for or against the statement

the right button for the T, while the other half responded using the opposite mapping. One trial lasted for 6.2 s plus participant's reaction time (RT). Directly after a response occurred, a new trial started with the robot closing its eyes in the initial position. The experiment was divided in 8 blocks of eye contact condition and 8 blocks of no eye contact condition (eye contact/no eye contact was kept constant within block, see Fig. 3). Each block consisted of 10 trials. The block sequence was randomly selected a priori and it was the same for all participants. At the end of every block (the robot was still looking at the blank screen), participants were asked to rate aloud their engagement with the robot on 10 point Likert scale (1 = strongly disengaged; 10 = strongly engaged). The answer was noted down by the experimenter and the participant continued to the next block by pressing the central mouse button. The task lasted about 25 min. For a more detailed description of the experimental procedure see the video provided as Supplementary material.

After the completion of the task, participants filled out a customized questionnaire to assess the familiarity with the robot, the sensitivity to eye contact, the level of engagement, and attribution of human-likeness, see Table 1.

2.2 Questionnaire evaluation

Two independent evaluators rated the responses of the questionnaires and categorized them into four categories, see Table 2. More specifically, Category 1 included replies

Table 2 Categorization of the answers

Category	Explanation
1. Eye contact	Statements related to robot's gaze behavior that we manipulated
2. Other, robot-related	Statements about robot's behavior that we did not manipulate
3. Congruency	Statements referring to congruency between the robot's gaze direction and target position
4. Other, task-related	Statements about task features that we did not manipulate

related to the establishment of eye contact with the robot. Category 2 involved statements about robot behavior that we did not manipulate, e.g. participant's idea that the robot was moving more fluently after half of the experiment. In Category 3 were included statements related to the congruency of the robot gaze with respect to the target location (predictivity of its behavior). Finally, Category 4 included responses related to features of the task that we did not manipulate, e.g. participant's belief that one of the letters was more frequent in comparison to the other. Only responses that were assigned to the same category by both raters were included in the results. If a participant gave more than one responses to a specific question, each response was categorized accordingly. Questions 4 and 5 were combined and categorized as human-likeness attribution to the robot. In particular, if participants replied "human" or "machine" in Question 4 and their belief remained constant during the experiment (i.e. answering "yes" to Question 5), their response was assigned to the label "human" or "machine" respectively. If their belief changed during the experiment (i.e. replying "no" to Question 5) and they mentioned both human- and machine-like arguments, they were categorized as "both".

2.3 Results

The level of engagement with the robot across the blocks averaged to M = 6.32, SD = 1.64, on a 10-point Likert scale. Engagement ratings were firstly averaged across blocks for each condition (eye contact blocks, no eye contact blocks) and then submitted to Wilcoxon signed-rank test (2 paired-measurements). Users rated social engagement significantly higher in the eye contact (M = 7.0, SD = 1.34) compared to the no eye contact (M = 5.62, SD = 1.68): Z = − 3.93, $p < .001$. Figure 4 shows the mean participants' engagement ratings per gaze condition and per block.

The mean familiarity rating (answers to Question 1) was: M = 2.16, SD = .92. Related to the question of perceiving any difference during the experiment (Question 2), 22 participants (91%) responded "yes". 7 people were not included in further analysis, because they did not refer to the differ-

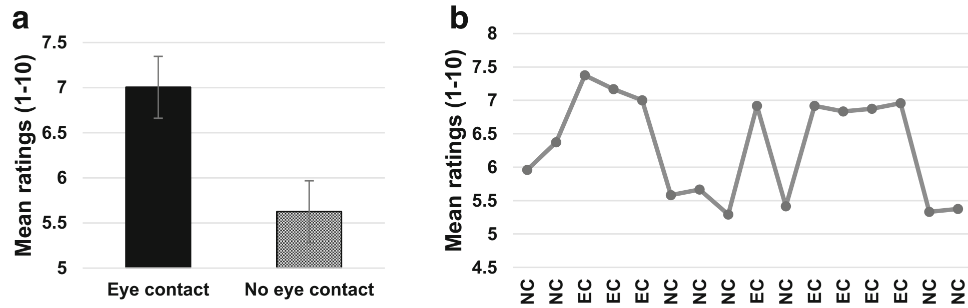

Fig. 4 Engagement ratings per gaze condition and across blocks. **a** Mean engagement ratings averaged per condition (eye contact condition, no eye contact condition). Error bars represent standard error of the means. **b** Mean engagement ratings averaged per block (EC = eye contact block; NC = no eye contact block)

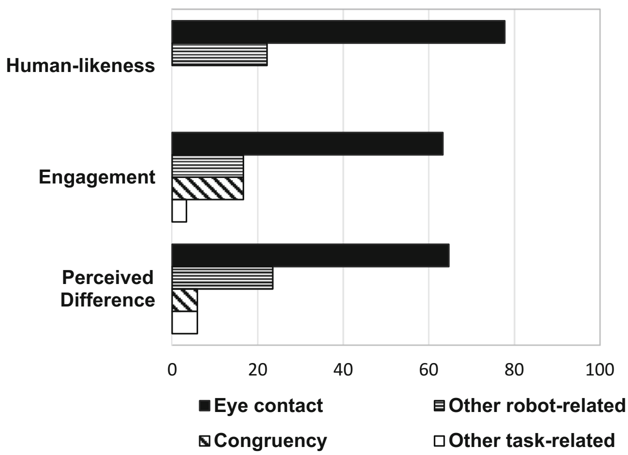

Fig. 5 Responses of the participants (in percentages) plotted as a function of four different categories: eye contact (filled bars), other robot-related (horizontally striped bars), congruency (diagonally striped bars), other task-related (empty bars). The lower bars refer to the responses to question 2 (perceived difference across the conditions), the middle bars display responses to question 3 (factor of engagement), and the upper bars account for answers to questions 4, 5 (features of human-likeness)

ence itself, their response was unclear or were classified into different categories by the two raters. The remaining 15 participants gave 17 answers in total, which were categorized in the four different labels as follows: 64.7% of the answers involved eye contact, 23.5% included other-robot related reasons, 5.88% indicated congruency, while 5.88% mentioned to task-related reasons (Fig. 5, lower bars). A one-sample Chi square test was run to investigate whether the frequencies of the assigned categories differed from expected equal frequencies (.25). The test showed that the frequency of the answers was significantly different from equal, χ^2 (3) = 15.7, p = .001.

Concerning the Question 3, i.e. the factor that enabled their engagement, 2 participants were not included in the analysis of the questionnaire because their responses were not clear. The responses of the remaining participants were 30 in total and they were evaluated as follows: 63.3% of the responses included eye contact, 16.67% other robot-related reasons, 16.67% mentioned congruency and a 3.33% reported other task-related reasons (Fig. 5, middle bars). According to the results of χ^2 the frequency of the answers was significantly different from equal, χ^2 (3) = 24.9, p < .001.

Regarding the responses related to human-likeness, 1 participant was excluded because raters assigned his/her response to different categories; 14 participants perceived the robot's behavior as pure mechanistic and their reasoning referred mostly to the random robot's behavior (50%) and its repetitive movements (33.33%). Finally, 9 participants were assigned to the category "both" as their belief about the nature of the robot behavior alternated between "machine-like" and "human-like". Among these participants, 77.78% of them reported eye contact as the factor that made them attribute a human-like behavior to the robot, while 22,2% mentioned other robot-related reasons (Fig. 5, upper bars).

2.4 Discussion

Overall, the majority of individuals were sensitive to eye contact initiated by iCub, even while performing another task, orthogonal to the eye contact manipulation. Additionally, participants felt more engaged with the robot during the eye contact condition compared to the no eye contact condition, mentioning mostly eye contact as the engaging factor. Finally, given the repetitive nature of the task, it is not surprising that the majority of the participants believed that the robot was processing like a machine. However, it is worth noting that although the eye contact itself was not sufficient for the attribution of human-likeness, the remaining 40% of the participants who thought that the robot was processing both as machine- and human-like reported eye contact as the main reason for attributing human-likeness. In conclusion, results from Exp. 1, show that establishing eye contact is a crucial factor impacting on the quality of human–robot interaction.

3 Experiment 2

Exp. 2 examined the sensitivity to eye contact, engagement, and the attribution of human-likeness when the eye contact is followed by a counter-predictive referential gaze, thus the interaction is qualified by a negative valence. In order to test the attribution of human-likeness, we investigated whether participants used more human-related vocabulary towards iCub when it looked at their eyes.

3.1 Method

3.1.1 Participants

Twenty-four new participants (mean age = 26.8 ± 4.4; 17 female; 1 left-handed) took part in the study and received an honorarium for their participation.

3.1.2 Apparatus, materials and procedure

The apparatus, stimuli and procedure were the same as in Exp. 1. Methods and algorithms for programming iCub's behavior were the same as in Exp. 1. However, iCub, after establishing (or not) eye contact with the participant, directed its gaze with a lower probability (25% congruency) to the screen in which the target letter would appear. In order to have a similar amount of congruent trials with Exp. 1 we increased the total amount of presented trials to 256 (divided into 16 blocks of 16 trials each). The block order differed across participants using the same (Sequence Type A) or opposite sequence (Sequence Type B) with respect to Exp. 1. In the opposite sequence, eye contact and no eye contact blocks were presented with an opposite order. At the end of every block, participants were asked to rate their engagement with the robot on 10 point Likert scale (1 = strongly disengaged; 10 = strongly engaged). The task lasted about 40 min.

After the completion of the task, participants filled out a questionnaire similar to the one used in Exp. 1. The questionnaire included 4 questions addressing familiarity with robots, sensitivity to eye contact, level of engagement, and attribution of human-likeness, see Table 3 (Questions 1–4). The last question (Question 4) was administered to investigate the interpretations that participants might have regarding the eye contact of the robot. The question was modified with respect to Exp. 1 in order to allow for more free and open responses, rather than biasing the responses into human-like or mechanistic categories. Furthermore, after filling out the abovementioned questionnaire, participants completed the Godspeed questionnaire [51] in order to acquire a standardized measure of Anthropomorphism and Likeability towards iCub. The Godspeed questionnaire was administered once for each gaze condition (eye contact, no eye contact), with the following instructions respectively: please indicate your impression when the robot was looking towards you; please indicate your impression when the robot was looking downwards.

Table 3 Questionnaire (Exp. 2)

Questions
1. How familiar are you with the robots (1 = not familiar–5 = very familiar)?
2. Did you perceive any difference across the trials (not related to the letter identity)?
3. Concerning the question during the experiment: "How much did you feel engaged with the robot", which factors did enable your decision
4. Why do you think the robot orients its gaze towards your eyes?

3.2 Questionnaire Evaluation

The same evaluating procedure was applied and the same categories were used for the first three questions. As mentioned above, the Question 4 was used as a test of human-likeness attribution towards the robot's eye contact. The following labels were used to categorize responses to Question 4:

1. Human-like explanation of the behavior (e.g. to distract me, to grab my attention);
2. Mechanistic explanation (e.g. to test my engagement in the task, to replicate eye contact);
3. Task-related (e.g. signal the position of the letter).

The responses of the Godspeed questionnaire were averaged for the Anthropomorphism and Likeability subscales separately for every participant while the statistical difference between the averaged ratings of the two gaze conditions (eye contact vs no eye contact) was assessed using a Wilcoxon signed-rank test.

3.3 Results

The level of engagement with the robot across the blocks averaged to M = 5.82, SD = 1.8. Similarly to Exp. 1, ratings were first averaged across blocks for condition (eye contact blocks, no eye contact blocks) and then submitted to Wilcoxon signed-rank test (2 paired-measurements). Participants rated social engagement significantly higher for the eye contact (M = 6.15, SD = 1.65) compared to no eye contact condition (M = 5.49, SD = 1.9): Z = − 2.85, p = .004, see Fig. 6 for the mean engagement ratings per gaze condition and per block.

The mean familiarity rating (Question 1) was: M = 1.6, SEM = .78. Regarding the question about differences during the experiment (Question 2), 22 participants responded "yes". 4 people were not included in further analysis, because they did not refer to the difference itself, their responses were unclear or were classified into different categories by the two raters. The remaining 18 participants gave 19 answers

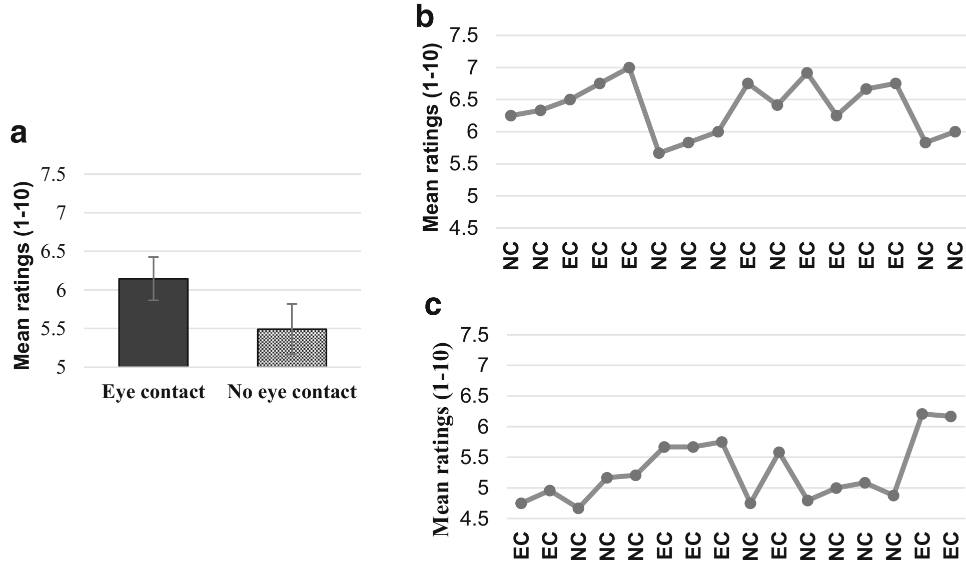

Fig. 6 Engagement ratings per gaze condition and across blocks. **a** Mean engagement ratings averaged per condition (eye contact condition, no eye contact condition). Error bars represent standard error of the means. **b** Mean engagement ratings averaged per block (EC = eye contact block; NC = no eye contact block) for sequence A. **c** Mean engagement ratings averaged per block (EC = eye contact block; NC = no eye contact block) for sequence B

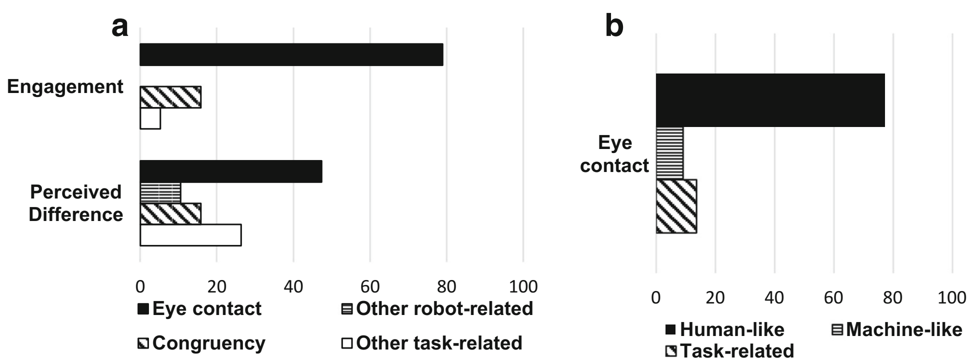

Fig. 7 **a** Responses of the participants to question 2 (lower panel) and 3 (upper panel) in percentage plotted as: eye contact (filled bars), other robot-related (horizontally striped bars), congruency (diagonally striped bars), other task-related (empty bars). **b** Responses of the participants to question 4 in percentage plotted as: human-like explanations (filled bars), machine-like (horizontally striped bars), other task-related (diagonally striped bars)

in total, and were categorized in the four different labels as follows: 47.4% of the answers involved eye contact, 10.53% included other-robot related reasons, 15.79% indicated congruency, while 26.32% mentioned task-related reasons, see Fig. 7 (panel a, lower bars). The results do not provide evidence that the four categories were not equally preferred, χ^2 (3) = 6.05, p = .1.

Concerning the Question 3, in which participants explained the criteria according to which they rated their engagement during the task, 7 participants were excluded from the analysis, since their response was not clear, or were not categorized identically by the two evaluators. The responses of 17 remaining participants (19 responses in total) were further labelled into the four categories. More specifically, 78.95% of the responses mentioned eye contact, 15.79% mentioned congruency, 5.26% referred to other task-related reasons. No one reported other robot-related statements, see Fig. 7 (panel a, upper bars). Due to null amount of responses for the robot-related category, no statistical analysis was performed for this question.

Concerning the Question 4, 3 participants were excluded from analysis because their responses were labelled differently by the two raters. The remaining 21 participants gave in total 22 answers which were categorized into the following way: 77.27% included human-like explanations, 17.14% mechanistic, 17.14% task-related reasons, see Fig. 7 (panel b). The Chi square test indicated that the frequency of the answers was significantly different from equal, χ^2 (2) = 19.82, p < .001.

Concerning the Godspeed questionnaire, the responses were averaged for the Anthropomorphism and Likeability subscale for every participant. Participants rated the eye contact as more human-like compared to the no eye contact, $Z = -2.11$, $p = .04$ ($M_{\text{eye contact}} = 3.32$, SD = .78; $M_{\text{no eye contact}} = 3.07$, SD = .91). Similarly, participants rated the eye contact as more likeable in comparison with the no eye contact condition, $Z = -3.5$, $p < .001$ ($M_{\text{eye contact}} = 4.15$, SD = .71; $M_{\text{no eye contact}} = 3.58$, SD = .78).

3.4 Comparison between experiments

In order to examine whether the predictiveness of the referential gaze (non-predictive, counter-predictive) influenced the level of engagement elicited by eye contact, we compared the engagement ratings across the two experiments using a Mann–Whitney U test of two-independent samples. There was no significant difference in ratings either in eye contact ($Z = -1.7$, $p = .09$) or no eye contact condition ($Z = -.19$, $p = .85$).

Furthermore, a Chi square association test was conducted to investigate whether the frequencies of answers for the perceived difference and the engagement factor differed across the two experiments. Regarding the questions of the perceived difference along the experiment there was no statistically significant association between Experiment and perceived difference, χ^2 (3) = 4.4, $p = .22$. Concerning the engagement factor, we included only the answers categorized as eye contact, congruency and task-related since no reply of Exp. 2 was categorized as robot-related. Again, no significant association emerged between Experiment and engagement factor, χ^2 (2) = .16, $p = .93$.

4 General Discussion

In the present study, we examined sensitivity of humans to detect eye contact in a humanoid robot, and the impact of eye contact on perceived human-likeness and engagement. We manipulated the gaze of the iCub robot in two similar non-verbal experimental paradigms. In Exp. 1, iCub either looked toward participant's eyes or downwards and then gazed randomly at one of the peripheral screens where a target appeared (Exp. 1: non-predictive referential gaze, 50% congruency). In Exp. 2, iCub established eye contact or not with the participants, similar to Exp. 1. However, it then gazed most frequently at the screen that would not contain the target (Exp. 2: counter-predictive referential gaze, 25% congruency). This was done in order to examine whether the effect of eye contact would impact differently the results according to the valence of the interaction with the robot; neutral (50% congruency), or negative when the referential gaze was counter-predictive (25% congruency). During and after the completion of the task, participants filled out a questionnaire to assess their engagement, sensitivity to eye contact, and attribution of human-likeness to the robot.

The results of both Exp. 1 and 2 showed that in the majority of the given responses 64.7% (Exp. 1) and 47.4% (Exp.2) the eye contact was referred as a noticeable difference along the experiment, suggesting that users were sensitive to the eye contact while executing an orthogonal task. There was no significant difference between experiments regarding sensitivity to eye contact.

Concerning the level of engagement, participants rated eye contact condition as significantly more engaging, compared to the no eye contact condition in both experiments. Although the engagement level for eye contact was lower in Exp.2, it did not differ from the level of engagement for eye contact reported in Exp. 1. It should be noted that participants rated higher the eye contact condition compared to the no eye contact condition repeatedly across Exp. 1. In Exp. 2, the same effect is clear for Sequence A (same sequence with Exp.1), while for Sequence B the level of engagement seems to stabilize after block 6, i.e. after participants experienced both conditions. Regarding the criteria that participants used to rate their engagement with the robot, the majority of the participants mentioned eye contact in both experiments, 61.3% in Exp. 1 and 79.8% in Exp. 2. No significant difference between experiments emerged regarding social engagement with iCub.

The responses regarding attribution of human-likeness in Exp. 1 show that almost 40% of participants attributed mental states to the robot. Within this group, the main reason mentioned by participants was eye contact (77.8%). A similar result was found for Exp. 2, where the majority of the responses 77.2% included human-like explanation for the establishment of eye contact by the robot (Question 3).

Results from the Godspeed questionnaire showed that on anthropomorphism subscales, ratings were significantly higher for the eye contact than the no eye contact condition. Finally, in Exp. 2 participants liked significantly more the robot when it was looking at them, compared to when it was looking toward a neutral position.

It is worth noting here that we aimed at creating a negative conflicting condition (counter-predictive gaze) between the observer and the robot, and compared it to a neutral condition (non-predictive gaze). Our results suggest that the valence of the interaction did not affect the engagement, sensitivity or human-like attribution to the robot. In future research, it would be interesting to compare the current findings with a positive type of social interaction, i.e. a predictive referential gaze.

Overall, our findings show that eye contact with a humanoid robot is quite noticeable, even if the task is orthogonal to detection of eye contact. Eye contact is perceived favorably, increases perceived human-likeness of the robot, and engages users more in the task they are performing with the robot. Such results could have important implications in designing behaviors in robots. For example, a robot designed to perform as a teaching assistant should actively establish eye contact with its audience in order to increase their engagement. In a clinical context, it is known that children with autism spectrum condition (ASC) face difficulties in initiating and responding to social cues, such as eye contact and joint attention. Such social capabilities could be enhanced by the appropriate design of robot assistants in therapies that would crucially engage children with an online eye contact and subsequently train other social signals [52]. However, it remains to be tested if eye contact has the same impact on clinical populations as it does on typically developed (adult) brain. Furthermore, in terms of other applications, since eye contact is easily detected even when humans are engaged in another task, robots placed in public spaces could use eye contact to grab users' attention.

More generally, understanding factors that positively impact social interactions with robots benefits not only HRI, but informs also research related to social cognition in humans. It has been recently argued that with the use of natural interactive paradigms, we gain knowledge about social cognition that is over and above knowledge acquired through more classical experimental protocols with stimuli presented on the screen and participants passively observing them [53, 54]. Our approach of using robots in interactive experimental paradigms increases ecological validity of paradigms used in social cognitive neuroscience, and also allows high degree of controllability, relative to human–human interactions. Therefore, embodied robots provide an efficient tool for studying human cognition [e.g., [55] (see also [56, 57] for a review). This study is an excellent example where—through the use of an embodied robot and naturalistic eye contact—we gained new insights regarding human mechanisms of social cognition. Our results showed that, for example, attribution of human-likeness to a robot is dependent on subtle human-like features in robot's behavior (eye contact) to which humans are apparently very sensitive [58–60].

5 Conclusions

The results of our study indicate that eye contact increases the level of engagement, likeability and attribution of human-likeness to a humanoid robot independently, and orthogonally, to the task participants are actually performing. We suggest that embodied humanoid robots which can establish a human-like eye contact can be easily socially-attuned to humans allowing for a smoother HRI and higher degree of engagement of the user. Eye contact can be used as a signal to attract (and keep) attention of users towards the robot.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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