Heliyon 9 (2023) e18164

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

The robot eyes don't have it. The presence of eyes on collaborative robots yields marginally higher user trust but lower performance

Artur Pilacinski [a,b,c,*], Ana Pinto [c,d,e], Soraia Oliveira [c], Eduardo Araújo [d,f], Carla Carvalho [b,c], Paula Alexandra Silva [d,f,g], Ricardo Matias [d,h], Paulo Menezes [d,h], Sonia Sousa [i,j]

[a] Medical Faculty, Ruhr University Bochum, Bochum, Germany
[b] CINEICC - Center for Research in Neuropsychology and Cognitive Behavioral Intervention, University of Coimbra, Coimbra, Portugal
[c] Faculty of Psychology and Educational Sciences, University of Coimbra, Coimbra, Portugal
[d] Faculty of Sciences and Technology, University of Coimbra, Coimbra, Portugal
[e] CeBER – Centre for Business and Economics Research, University of Coimbra, Coimbra, Portugal
[f] Department of Informatics Engineering, University of Coimbra, Coimbra, Portugal
[g] CISUC - Centre for Informatics and Systems of the University of Coimbra, Coimbra, Portugal
[h] Electrical and Computer Engineering Department, University of Coimbra, Coimbra, Portugal
[i] University of Trás-os-Montes e Alto Douro, Vila Real, Portugal
[j] School of Digital Technologies, Tallinn University, Tallinn, Estonia

A B S T R A C T

Eye gaze is a prominent feature of human social lives, but little is known on whether fitting eyes on machines makes humans trust them more. In this study we compared subjective and objective markers of human trust when collaborating with eyed and non-eyed robots of the same type. We used virtual reality scenes in which we manipulated distance and the presence of eyes on a robot's display during simple collaboration scenes. We found that while collaboration with eyed cobots resulted in slightly higher subjective trust ratings, the objective markers such as pupil size and task completion time indicated it was in fact less comfortable to collaborate with eyed robots. These findings are in line with recent suggestions that anthropomorphism may be actually a detrimental feature of collaborative robots. These findings also show the complex relationship between human objective and subjective markers of trust when collaborating with artificial agents.

1. Introduction

Humans are a collaborative species. Hunting together, dancing together, and working together requires seamless communication and adaptation to the actions of the partner. Eyes are a critical element for human social life, as they communicate intentions [1], allowing the interaction partner to read and adapt to these intentions. Eye gaze predictively guides human actions [2] and is attracted to object affordances [3,4] which constitutes a critical element for reading other agents' intentions [1,5]. In recent years, robots have seen wider integration in human activities, a transformation accelerated by COVID-19 pandemic [6], leading human-robot collaboration (HRC) to become one of the most pressing issues to advance present society. Collaborative robots (cobots) can help humans in mundane or dangerous tasks across industrial or medical sectors. Some cobots are fitted with human-like eyes to give them a more anthropomorphic appearance for improving the naturality of their interface [7]. For example, the company Rethink Robotics included gaze as a feature in their Baxter and Sawyer cobots to putatively increase users' feeling of comfort [8]. In our study, we directly investigated whether the robot eyes indeed have positive impact on the objective and subjective markers of human trust during human-robot collaboration.

* Corresponding author. Chair for Neurotechnology, Universitätsstraße 142, 6. OG, Bochum, Germany.
E-mail addresses: ap@uc.pt, art.pilacinski@gmail.com (A. Pilacinski).

https://doi.org/10.1016/j.heliyon.2023.e18164
Received 2 March 2023; Received in revised form 21 June 2023; Accepted 10 July 2023
Available online 11 July 2023

According to authors like Kuipers [9] or Hancock [10] trust is a key aspect in human-robot interaction (HRI); it enables successful cooperation between agents to produce better outcomes. Trust, which can be understood as "the willingness of a party to be vulnerable to the actions of another party based on the expectation that the other will perform a particular action important to the trustor", is a complex construct [11]. One of the core principles of human-machine interaction (HMI) is to go beyond technical-centric approaches towards a more human-centric approach [12,13]. This approach has been addressed in today's artificial intelligence (AI)-enabled systems in which the trustworthiness of technology has been explored [14–17]. The literature illustrates, for instance, that factors affecting trust in human-robot interaction span across user-, robot- and environmental factors, with robot characteristics being most important [18]. The same evidence was found in HRI, where robots' technical and design features can influence user acceptance and readiness to trust [9,19–22]. According to Morana et al. [23], benevolent features (e.g., anthropomorphism) could affect users' trust. Similar effects were found when interacting with conversational agents [23–26]. However, prior studies in HRC failed to demonstrate any strong effect of increased anthropomorphism on human trust and acceptability [27]. In a recent review, Roesler et al. [28] summarized those findings which suggested that robot anthropomorphism had no positive effect on perceived safety, empathy, and human task performance. The authors also showed that anthropomorphic effects on human behavior were highly heterogenous across studies, likely due to context-specific moderators. Another issue is low sample sizes in the prior studies. As pointed out by several authors [29], the use of small sample sizes and the low statistical power yielded may lead to conclusions that overlooked real effects or false positives. Given the small sample size used in a number of studies reporting the lack of positive anthropomorphism effects on human subjective trust/acceptability ratings and physiological signals [27,30], their negative findings in objective markers could have occurred indeed due to low statistical power. This overall lack of clear effect of anthropomorphism on HRI is surprising. Intuitively, one would expect that the more human-like the robots, the better the quality of human interactions with them [31]. This is not always true – if robots resemble humans too closely, they are perceived as strange and unpleasant to interact with [32–34]. First described by Masahiro Mori, this effect of repulsion to unrealistically anthropomorphic robots is called the "**uncanny valley**" [35]. The uncanny valley is not limited to humans: other social primates also show adverse behavior towards realistic avatars [33]. This suggests that the primate brain may have hardwired neural systems allowing for intuitive discriminating of "natural" behavior. The "**uncanny valley**" has been described for social HMI and shown to affect acceptability and trust [34]. There is evidence showing that human brain activities are modulated by whether they interacted with a human or a robotic agent [36], which suggests that human preference for interacting with humans might be indeed "hardwired" in the brain. How strong is this preference when it comes to cooperative behavior?

When humans cooperate, they establish trust by tracking the other person's behavior such as movement type, speed and precision and non-verbal cues such as their eye gaze target. Of those social cues, eyes seem to have a special value for human interaction [1], as eyes convey important social cues humans learn to interpret since infancy [37,38]. Likewise, human pupil size signifies interest in an object [39] or cognitive load [40] and synchronized pupil responses are a reliable proxy for establishing trust during human interactions [41]. One could then speculate that equipping artificial systems, such as robots, with eyes could lead to increased trust, but is this really the case? There seems to be no straightforward answer to this question. For example, in previous studies robots' gaze was usually confounded with their overall anthropomorphic appearance [27]. A notable exception was a recent study by Onnasch and Hildebrand [42] where a real, one armed (and thereby limitedly anthropomorphic) cobot could have its eyes (face) animation switched on and off depending on condition. No positive effect of cobot eyes was shown on human performance or on the perception of the cobot. As only a one-armed robot (Sawyer) was used in that study, it begs the question whether the presence of eyes on a non-anthropomorphic robot further increases the uncanny valley, and negatively impacts human reactions.

Here, we focused on the effects of eyes as a feature of a collaborative robot on human trust, using both subjective and objective measures. To investigate this, we used a realistic virtual reality scenario and a digital twin of a real collaborative robot. We used a two-armed robot (Baxter) for maximizing the anthropomorphic appearance of the robot. We placed the robot at two distances from the user to manipulate whether the user's body was within the reach of the robot or not. To obtain a clear effect of eyes, we used one robot model and manipulated the presence/absence of robot eyes while keeping the rest of interaction scenarios constant. Based on the previously suggested disparity between objective and subjective measures of trust and acceptability in HRI scenarios [27,28,30], we decided to combine both user self-reports and physiological measures, i.e., user's action performance (speed), heart rate, and pupil size. We additionally scrutinized whether users of different genders show different preferences to eyed cobots as gender seems to play an unclear role in HRI [43,44]. Similarly, we measured whether subjects with different technology acceptance levels differentially react to eyed cobots as technology acceptance and trust seem to be highly interconnected [45–47].

We expected that cobot eyes (independent variable: eyed/eyeless Baxter) will have a significant impact on user's trust ratings and their heart rate and pupil responses. Additionally, we expected a correlation between the trust ratings and physiological signals and the user's technology acceptance and gender. We further expected to find a negative correlation between users' trust ratings, pulse rate, and pupil response. We also expected that user trust correlates positively with efficiency resulting in faster task completion. Lastly, we expected the trust ratings and physiological signals to interact with distance between the user and the cobot, namely situations when the user is outside or within the cobot's reach, as the latter exposes the user to a potential threat of being hit by the robot and hence should lower the trust rating.

2. Materials and methods

2.1. Participants

Thirty-eight individuals (M age = 22.90 years old; SD = 5.65), between 18 (n = 6; 15.80%) and 42 years (n = 2; 5.30%), voluntarily participated in this experiment. The sample was mostly formed by women (n = 22; 57.90%), but also included men (n = 16; 42.10%). The imbalance resulted from recruitment procedures and could not be compensated for by recruiting more men. Participants were all right-handed except for one and had normal or corrected to normal vision.

2.2. Procedures

The study obtained ethical approval from the Ethics and Deontology Committee for Research (CEDI) of the Faculty of Psychology and Educational Sciences of the University of Coimbra: CEDI/FPCEUC:64/1, June 22, 2022. The experiment began with the participant's informed consent, where the goals of study were explained, and the anonymity and confidentiality of data collected assured. For this purpose, a six-digit alphanumeric code was used to anonymize subjects' data (i.e., first name letter and first surname letter, day of birthday, and cell phone number's last two digits). Participants completed a sociodemographic data questionnaire (e.g., gender, age), and pretest, i.e., Technology Acceptance Model Scale - TAMS [48] and Human-Robot Interaction Scale - HRITS [49]. Participants were informed on the experimental procedures and then helped to put on all the equipment (i.e., headset, remote, and pulse oximeter). The participants' well-being was ensured throughout the experiment.

2.3. Setup and physiological data preprocessing

The scenes ran in Unity (version 2019.2.8f1). Open BCI Cyton board (OpenBCI) was used to record pulse rate from a sensor fixed to the participant's index finger of their left hand. Vive Pro Eye was used to display the scene and recorded eye (pupil) data through Vive SRanipal SDK, and LabRecorder for logging and synchronizing physiological responses. Pulse data were lowpass-filtered with a Butterworth filter at 1 Hz cutoff-frequency. Pupil data was filtered with a lowpass Butterworth filter with a 2 Hz cutoff-frequency. As virtual reality (VR) ambient lighting was constant across experimental conditions, we used the average pupil width across all trials within a block to estimate pupil width per condition.

2.4. Baxter digital twin

We used a two-arms Baxter robot (Rethink Robotics) to maximize anthropomorphism. Baxter could use either hand (random) in interactions. The model was controlled through the Robot Operating System (ROS) framework (v. 1.15.9) and used the MoveIt [50] motion planner via RViz (v.14.14.4). We chose this motion planning platform for maximized realism and immersion. We used the maximum speed of Baxter arms allowed by the motion planner. The robot moved fully autonomously.

Baxter was placed at either 120/130 cm or 160–170 cm of distance to the operator, conditions named as "Near" and "Far" respectively. In the "Near" condition, the robot could potentially reach the subject's body, while it could not do so in the "Far" condition. The monitor displaying the robot eyes could be on and off depending on the experimental condition (see Study Design). During the movement, the robot monitor and eyes would follow the end-effector in a naturalistic manner.

2.5. Self-report scales

A self-report scale was used to scrutinize subjective perception of trust: Human-Robot Interaction Trust Scale - HRITS [49]. In addition, subjects were asked to fill out the Technology Acceptance Model Scale - TAMS [48] and a sociodemographic questionnaire (i.e., gender, age).

The TAMS [48] includes two forms: (a) Perceived usefulness of new technology (originally: electronic mail), and (b) Perceived ease of use of new technology. The first measures the extent to which individuals believe that using new technology improves their performance. The second measures how much individuals are convinced that using new technology frees them from mental and physical effort. Both forms are composed of 10 items, whose response options are according to a 7-point Likert scale: 1- strongly disagree, 2- disagree, 3- slightly disagree, 4- neither agree nor disagree, 5- slightly agree, 6- agree, and 7- strongly agree.

The HRITS [49], based on the HCTM [51,52], aims to measure the user's *risk perception* (the impact of perceived risk on the degree of trust is relevant for understanding whether the user's subjective view of the risk corresponds to the safety level of HRI), *competency* (the notion of functionality closely linked to the concept of the gulf of execution in an attempt to understand how the object operates) *benevolence* (the entrusted acts in the best interest of those who trust, which proves to be relevant to trust, facilitating the correct assessment of risk.), and *reciprocity* (the notion of reciprocity is related to the emotional satisfaction factor), while interacting with a cobot. It comprises 11 items, answered on a 5-point Likert scale: 1- strongly disagree, 2- disagree, 3- neither agree nor disagree, 4- agree, and 5- strongly agree. HRITS is the Portuguese version of the HCTM Scale [49,51–53] for the human-robot interaction context.

3. Study design

3.1. Trial description

The scene consisted of the robot and user positioned at two sides of a table, on which a target item (tool was placed). The user's hands were animated and pressing the controller's trigger button initiated grasping movement of the virtual hand. Each trial started with a sound indicating that the robot had started reaching (passing the tool) to the user. The robot could use, randomly, either its right or left arm. The user could intercept (grab) the tool at any time. After the user grabbed the object, the robot hand returned to the initial position and the next trial began. See Fig. 1 for the detailed design and scene appearance. The user was instructed to use only their right hand as the pulse sensor was placed on the left one. It is important to note that as the robot was controlled through RViz motion planner and user responses, trial durations were not fixed.

The experiment consisted of four blocks (10 trials per blocks), followed by a posttest questionnaire between blocks (HRTIS). The

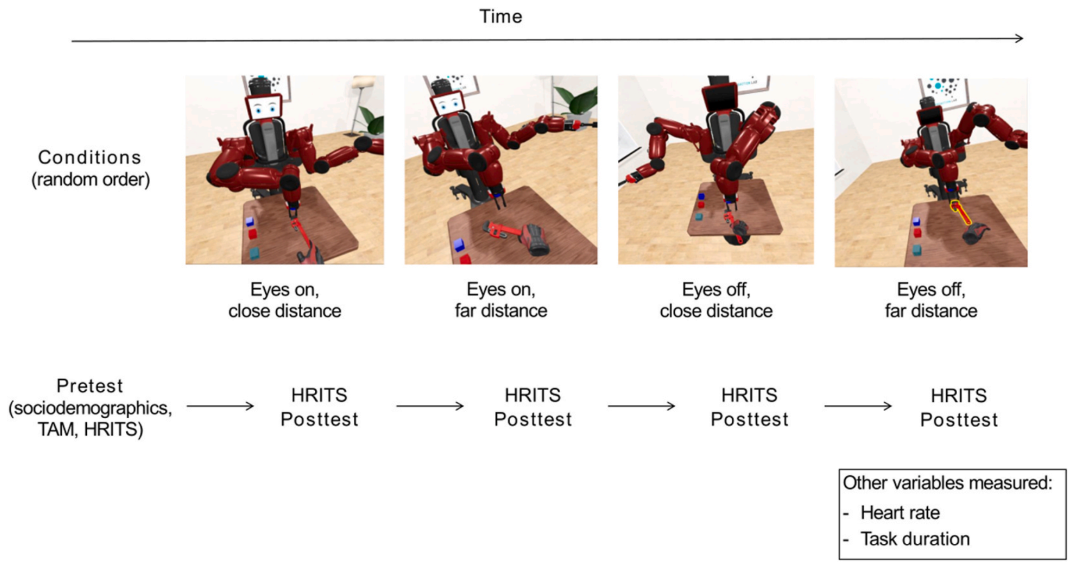

Fig. 1. An example timeline of the experiment together with visualizations of the collaboration scenes. The sequence of conditions was balanced across participants.

order of the four test conditions was randomized and balanced within the group. Heart rate, head and eye movement were measured continuously during the experiment.

4. Results

4.1. Human-robot trust scale

To test the direct impact of cobot eyes on perceived trust (Fig. 2), we performed a 2 × 2 × 2 ANOVA (Cobot eyes: On/Off; Distance: Near/Far; Participant gender: Male/Female). We found that eyed cobots yielded a significant, very weak effect of higher trust ($F_{(1,36)} = 10.7441$; $p = 0.002$; $eta^2_G = 0.003$; $M_{diff} = 0.07$). Cobot distance did not significantly affect trust ($p > 0.8$), neither did participant gender ($p > 0.4$). No interaction effects were significant ($p > 0.15$).

To test effects of cobot eyes and distance on objective variables, we used a 2×2 ANOVA with factors: Cobot eyes (On/Off) and Distance (Near/Far) for pupil size, task duration and pulse rate (Fig. 3A–C).

We observed significantly smaller pupil size when interacting with eyed cobots (Main effect of eyes: $F_{(1,37)} = 6.99$; $p = 0.012$; $eta^2_G = 0.012$; $M_{diff} = -0.16$) and when the cobots were near to the user (Distance: $F_{(1,37)} = 7.6$; $p = 0.009$; $eta^2_G = 0.008$; $M_{diff} = 0.13$). There was no significant interaction effect ($p > 0.6$). Interestingly, task duration was longer for eyed cobots, especially those positioned farther away (Eyes: $F_{(1,37)} = 4.32$; $p = 0.045$; $eta^2_G = 0.034$; Distance: $F_{(1,37)} = 3.48$; $p = 0.07$; $eta^2_G = 0.01$; Interaction: $F_{(1,37)} = 5.44$; $p = 0.025$; $eta^2_G = 0.018$).

There was no significant effect of cobot gaze and distance on pulse rate (Eyes: $p > 0.8$; Distance: $p > 0.7$; Interaction: $p > 0.8$).

4.1.1. Correlations between variables

We investigated whether the variables that significantly differ for cobot eyes (such as HRITS score or pupil width) are further modulated by individual traits, such as technology acceptance. We found a moderate positive correlation between TAMa (perceived usefulness of technology) and HRITS ratings in all eyes and distance conditions, either significant or nearing significance (see Supplementary Table S1 for detailed values). A significant moderate to weak negative correlation was found between TAMb (perceived easiness of use of technology) and pupil size in most eyes and distance conditions apart from EyesOn Far. This difference in pupil size was not, however, accompanied by faster task completion, as there was no significant correlation ($p > 0.2$) between TAMb and task duration in any condition. There was also no correlation between pupil sizes and task durations in any condition.

5. Discussion

We observed a weak influence of cobot eyes on subjective trust, i.e.: cobots with eyes were rated higher by subjects on trust scale. We further observed that participants completed tasks faster when interacting with eyeless cobots which was accompanied by significantly larger pupil sizes. Interestingly, we observed a negative correlation between TAMb (perceived easiness of use of technology) and both task duration and pupil size.

Our study results show a very weak effect of cobot eyes on human trust, which is in line with other studies which suggested a rather limited impact of anthropomorphism on human perception of collaborative robots [28,42,54]. This further suggests that even if eyes as a pervasive feature of cobots indeed have any effect on subjectively rated trust, the effect is minimal.

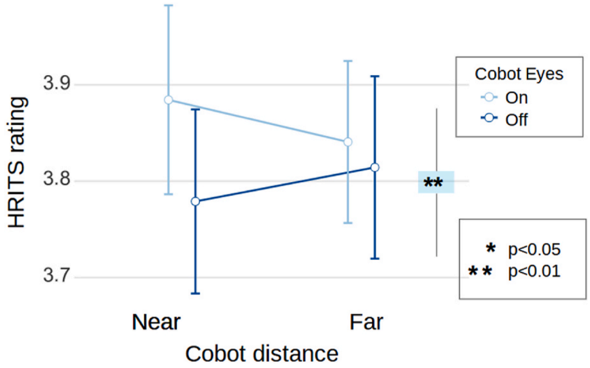

Fig. 2. Average HRITS ratings depending on cobot eyes (On/Off) and distance (Near/Far). Error bars denote SEM.

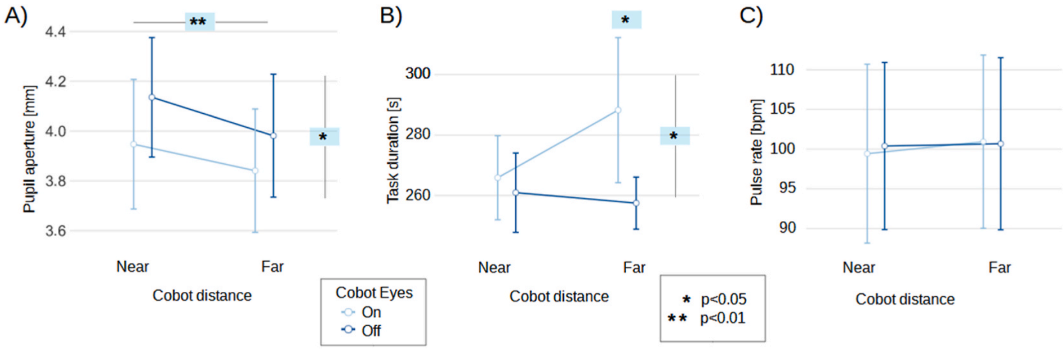

Fig. 3. Influence of robot eyes (On/Off) and distance (Near/Far) on pupil aperture (A), task duration (B) and pulse rate (C). Average pupil sizes when interacting with cobot were larger for eyeless vs. eyed cobots. They were also significantly larger for near than far cobots. Error bars denote SEM.

Furthermore, regardless of the higher self-reported trust, the presence of objectively measured signatures of trust like broader pupils and faster task completion for non-eyed cobots might indicate better (cognitive) performance when interacting with cobots without eyes. The results we present here and those from previous studies [28,42] show that trust, as a complex concept cannot be assessed on the basis of a single variable, be it self-reports or objective measures. In our opinion, however, that analyses considering multiple variables at once can lead to accurate and robust assessment of user trust in HRI.

Some authors concluded that anthropomorphism might be confusing to humans due to distraction when collaborating with an eyed robot [27,28,54]. Our results seem to corroborate this view. Moreover, the disparity between subjective and objective measures suggests that in assessing HRC, the latter may be more informative about the user's actual emotional and cognitive state, as suggested by several authors [30,42,55]. Subjective measures of acceptability and trust might be prone to confounds, as they might be driven, for example, by experimental demand characteristics, an often-overlooked effect [56,57]. The presence of demand characteristics could at least partially explain the different (or context-dependent) findings in studies looking at anthropomorphism in HRC but needs to be studied further.

Robot design seems to be one of critical features when integrating robots into human societies. As several authors pointed out, whether anthropomorphism helps humans to better (e.g., more efficiently) interact with robots is one of the primary problems to solve [28,54,58]. The question why anthropomorphism and especially having eyes would be a detrimental rather than a helpful feature of collaborative robots can be answered in more than one way.

Eyes play an important role in human social life. Eye gaze automatically captures and directs attention [1]. Pupils dilate to show interest in an object, increased cognitive load [59]. For this reason, pupillary responses are an important clue in social interactions. Synchronized pupil dilations seem to underlie trust in social interactions [41] and human brains synchronize faster during eye contact [60]. Such synchronization is suggested to underlie human empathy and the ability to coordinate actions. Likewise, brain oscillations have been shown to differ during interactions with robots vs. other humans [36] suggesting that the brain makes a substantial difference between those two agent classes. This may be one reason why eyes on a non-sentient agent are not perceived as natural, just as the uncanny valley model would suggest.

Another possibility is that eyes indeed give the robot a human-like appearance and the brain perceives it likewise. Humans are social animals with cooperation between them being crucial for their survival. Human evolution has favored communicative eyes [61]. For example, in the study of Singh et al. [62], having eye contact during norm-breaking behavior as compared to no eye contact led to a stronger increase in self-reported embarrassment, a higher heart rate, more hesitation and laughter. They concluded that eye contact gives people the power to punish norm breaking in others by inducing an aversive emotional experience. Therefore, one would expect that cobot eyes may actually result in worse performance by humans, dependent on the circumstances such as relative task difficulty level [63] or distraction [42]. Both larger pupil aperture and faster task completion when interacting with non-eyed cobots speak in favor of eyes as a rather detrimental feature of collaborative robots. Interestingly, some subjects spontaneously indicated that they perceived the eyed cobots as unpleasant and weird to interact with due to the sense of being observed (by robots). This aspect was not systematically investigated in post-test surveys other than HRITS but deserves further studies.

5.1. Limitations and potential confounds

While our current results seem rather clear, we identify a number of potential confounds to be addressed by future studies before we can generalize findings to formulate an exhaustive model of anthropomorphism impact on HRC. First, while our subjects completed multiple trials with the same cobot, we do not know how ratings and objective measures would differ after a prolonged duration of interactions and in a less repetitive setting. Would eyed cobots be more pleasant to interact with and facilitate human performance in a longer run? We believe that quantifying human experience with robots (for example testing experienced robot operators could yield different results than when participants are inexperienced). Likewise, we measured trust ratings only in posttest, therefore we cannot relate to dynamics of how the feeling of trust evolved in our subjects and how much resulted from post-hoc cognitive evaluations. Further studies should take this issue into account.

Our study (and similar ones) used simplified robotic gaze in interactions. Human eyes are a very subtle and precise indicator of action intention [64]. Would cobot eyes have more impact on human performance if their gaze were more informative and helped tracking robot “intentions”? Whether the human brain relies on gaze in perceiving actions and intentions of non-human agents, remains to be determined. Due to motion planner constraints, the robot actions in our experiment were rather slow. We expect that the effects of gaze could be different if the collaboration was more dynamic and relied on more reflexive cues guiding human motor actions, eye gaze being one of them, as it has been shown to automatically guide attention [1].

Interestingly, pupil sizes were larger if the robot was placed closer to the participant, i.e. when the robot arm could potentially reach the participant. This is an important moderator to interpreting pupil data. Pupils dilate in case of emotional arousal like hazard perception [59]. As being within robot reach could be a potentially hazardous scenario, we believe that this particular finding shows the complexity and limitations of interpreting pupil size alone purely as the index of trust. As in our study the differences between experimental conditions were stable and controlled for, it is unlikely that the average pupil aperture resulted from any physiological confounds such as environmental lighting (as those were identical across conditions). However, pupil size is a dynamic variable and in future studies it is worth scrutinizing pupillary events and their differential causes. This can be done using multivariate analyses and more dynamic approaches to pupillometry, like index of cognitive activity which allows disentangling pupil events related to cognition, from responses to illumination changes [65].

Lastly, our study used a realistic virtual reality scenario and a digital twin of a real collaborative robot. As our findings were in line with those reported with real robots [42], we do not find the use of virtual reality simulation problematic, but a direct replication of our scenarios with real robots will be very beneficial for validating the reliability of VR in simulating HRC scenarios.

6. Conclusions

Cobot gaze may not be that important for manual collaboration. Humans seem to report marginally higher trust in eyed cobots when asked in self-reports. At the same time, objective metrics such as task completion time and pupil responses suggest more comfortable cooperation with non-eyed robots. This shows that humans might not need human-like machines to trust and work with them. Instead, they seem to collaborate better with machine-like, eyeless machines.

Author contribution statement

Artur Pilacinski: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper. Ana Pinto; Sonia Sousa; Carla Carvalho; Paula Alexandra Silva: Contributed reagents, materials, analysis tools or data; Wrote the paper. Soraia Oliveira: Performed the experiments; Analyzed and interpreted the data. Eduardo Araújo: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data. Ricardo Matias; Paulo Menezes: Contributed reagents, materials, analysis tools or data.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This study was funded by: Bial Foundation (Grant: 260/22); University of Coimbra: Sementes 2020; Fundação para a Ciência e Tecnologia: PTDC/MHC-PCN/6805/2014; UIDB/05037/2020; Trust and Influence programme grant agreement number 21IOE051. European Office of Aerospace Research and Development (EOARD). U.S. Air Force Office of Scientific Research (AFOSR).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2023.e18164.

Supplementary materials

Supplementary Table 1
Correlations between main variables related to cobot gaze and trust

					HRITS				Pupil size				Task Duration			
			TAM_a	TAM_b	EyesOnNear	EyesOn Far	EyesOff Near	EyesOff Far	EyesOn Near	EyesOn Far	EyesOff Near	EyesOff Far	EyesOn Near	EyesOn Far	EyesOff Near	
	TAM_a	Pearson's r	–													
		p-value	–													
	TAM_b	Pearson's r	0.115	–												
		p-value	0.498	–												
HRITS	Eyes Near	Pearson's r	0.293	−0.186	–											
		p-value	0.074	0.271	–											
	EyesOn Far	Pearson's r	0.332 *	−0.238	0.927 ***	–										
		p-value	0.042	0.156	<.001	–										
	EyesOff Near	Pearson's r	0.306	−0.211	0.943 ***	0.927 ***	–									
		p-value	0.061	0.210	<.001	<.001	–									
	EyesOff Far	Pearson's r	0.276	−0.277	0.945 ***	0.916 ***	0.896 ***	–								
		p-value	0.094	0.096	<.001	<.001	<.001	–								
Pupil	EyesOn Near	Pearson's r	0.084	−0.463 **	0.289	0.307	0.336 *	0.366 *	–							
		p-value	0.617	0.004	0.078	0.061	0.039	0.024	–							
	EyesOn Far	Pearson's r	0.025	−0.226	0.213	0.200	0.280	0.251	0.810 ***	–						
		p-value	0.883	0.178	0.200	0.229	0.089	0.128	<.001	–						
	EyesOff ear	Pearson's r	0.019	−0.411 *	0.277	0.259	0.319	0.323 *	0.837 ***	0.825 ***	–					
		p-value	0.909	0.011	0.092	0.116	0.051	0.048	<.001	<.001	–					
	EyesOff Far	Pearson's r	0.005	−0.329 *	0.258	0.223	0.274	0.269	0.773 ***	0.721 ***	0.858 ***	–				
		p-value	0.976	0.047	0.118	0.179	0.097	0.103	<.001	<.001	<.001	–				
TD	EyesOn Near	Pearson's r	−0.075	0.046	−0.109	−0.030	−0.104	−0.137	−0.076	−0.045	−0.172	−0.119	–			
		p-value	0.653	0.786	0.516	0.859	0.535	0.413	0.649	0.790	0.303	0.476	–			
	EyesOn Far	Pearson's r	−0.013	−0.090	−0.047	−0.024	−0.031	−0.080	−0.017	−0.135	−0.156	−0.155	0.791 ***	–		
		p-value	0.938	0.597	0.780	0.886	0.854	0.634	0.922	0.420	0.349	0.354	<.001	–		
	EyesOff Near	Pearson's r	−0.135	−0.016	0.019	−0.004	0.051	0.012	0.132	0.213	0.204	0.184	0.037	0.157	–	
		p-value	0.420	0.926	0.909	0.982	0.761	0.943	0.431	0.200	0.220	0.268	0.824	0.347	–	
	EyesOff Far	Pearson's r	0.007	0.211	−0.100	0.000	−0.045	−0.053	0.150	0.165	−0.125	−0.301	0.414 **	0.349 *	0.112	–
		p-value	0.966	0.210	0.550	1000	0.788	0.750	0.367	0.322	0.454	0.066	0.010	0.032	0.503	–

References

[1] N.J. Emery, The eyes have it: the neuroethology, function and evolution of social gaze, Neurosci. Biobehav. Rev. 21 (6) (2000) 581–604.
[2] R.S. Johansson, G. Ran Westling, A. Bä, J.R. Flanagan, Eye-hand coordination in object manipulation, J. Neurosci. 21 (17) (2001) 6917–6932.
[3] F. Osiurak, Y. Rossetti, A. Badets, What is an affordance? 40 years later, Neurosci. Biobehav. Rev. 77 (Jun. 2017) 403–417.
[4] A. Pilacinski, S. De Haan, R. Donato, J. Almeida, Tool heads prime saccades, Sci. Rep. 11 (1) (Dec. 2021).
[5] K. Zuberbühler, Gaze following, Curr. Biol. 18 (11) (Jun. 2008) R453–R455.
[6] E. Guizzo, R. Klett, How robots became essential workers in the COVID-19 response, IEEE Spectrum (Sep. 30, 2020). https://spectrum.ieee.org/how-robots-became-essential-workers-in-the-covid19-response.
[7] T. Fong, I. Nourbakhsh, K. Dautenhahn, A survey of socially interactive robots, in: Robotics and Autonomous Systems, Mar. 2003, pp. 143–166.
[8] S. Kessler, This industrial robot has eyes because they make human workers feel more comfortable, Quartz (Apr. 17, 2017). https://qz.com/958335/why-do-rethink-robotics-robots-have-eyes/.
[9] B. Kuipers, How can we trust a robot? Commun. ACM 61 (3) (Mar. 2018) 86–95.
[10] P.A. Hancock, D.R. Billings, K.E. Schaefer, Can you trust your robot? Ergon. Des. Q. Hum. Factors Appl. 19 (3) (Jul. 2011) 24–29.
[11] R.C. Mayer, J.H. Davis, F.D. Schoorman, An integrative model of organizational trust, Acad. Manag. Rev. 20 (3) (1995) 709–734.
[12] W. Xu, Toward human-centered AI: a perspective from human-computer interaction, Interactions 26 (4) (2019) 42–46.
[13] N.K. Lankton, D.H. Mcknight, J. Tripp, Technology, humanness, and trust: rethinking trust in technology, J. Assoc. Inf. Syst. Online 16 (10) (Oct. 2015) 880–918.
[14] B.C. Smith, The Promise of Artificial Intelligence: Reckoning and Judgment, Massachusetts Institute of Technology, 2019.
[15] S. Leijnen, H. Aldewereld, R. Van Belkom, R. Bijvank, R. Ossewaarde, An agile framework for trustworthy AI, in: Proceedings of the First International Workshop on New Foundations for Human-Centered AI (NeHuAI)co-Located with 24th European Conference on Artificial Intelligence (ECAI 2020), 2020, pp. 1–4 [Online]. Available: http://ceur-ws.org/Vol-2659/.
[16] B. Shneiderman, Human-centered artificial intelligence: reliable, safe & trustworthy, Int. J. Hum. Comput. Interact. 36 (6) (Apr. 2020) 495–504.
[17] L.P. Robert Jr., G. Bansal, N. Melville, T. Stafford, Introduction to the special issue on AI fairness, trust, and Ethics, AIS Trans. Hum.-Comput. Interact. 12 (4) (Dec. 2020) 172–178.
[18] P.A. Hancock, D.R. Billings, K.E. Schaefer, J.Y.C. Chen, E.J. de Visser, R. Parasuraman, A meta-analysis of factors affecting trust in human-robot interaction, Hum. Factors 53 (5) (Oct. 2011) 517–527.
[19] M. Lewis, K. Sycara, P. Walker, The role of trust in human-robot interaction, in: H.A. Abbass, J. Scholz, D.J. Reid (Eds.), Foundations of Trusted Autonomy. Studies in Systems, Decision and Control, Springer International Publishing, 2018, pp. 135–159.
[20] Y. Guo, X.J. Yang, Modeling and predicting trust dynamics in human–robot teaming: a bayesian inference approach, Int. J. Soc. Robot 13 (8) (Dec. 2021) 1899–1909.
[21] T. Law, B.F. Malle, M. Scheutz, A touching connection: how observing robotic touch can affect human trust in a robot, Int. J. Soc. Robot 13 (8) (Dec. 2021) 2003–2019.
[22] D. Ullman, B.F. Malle, What does it mean to trust a robot?: steps toward a multidimensional measure of trust, in: ACM/IEEE International Conference on Human-Robot Interaction, Association for Computing Machinery, New York, United States, Mar. 2018, pp. 263–264.
[23] S. Morana, U. Gnewuch, D. Jung, The effect of anthropomorphism on investment decision-making with robo-advisor chatbots, in: Proceedings of the 38th European Conference on Information Systems (ECIS2020), Marrakech, Morocco, 2020, pp. 1–18 [Online]. Available: https://www.researchgate.net/publication/341277570_The_Effect_of_Anthropomorphism_on_Investment_Decision-Making_with_Robo-Advisor_Chatbots.
[24] A.C. Elkins, D.C. Derrick, The sound of trust: voice as a measurement of trust during interactions with embodied conversational agents, Group Decis. Negot. 22 (5) (Sep. 2013) 897–913.
[25] A.C. Elkins, N.E. Dunbar, B. Adame, J.F. Nunamaker, Are users threatened by credibility assessment systems? J. Manag. Inf. Syst. 29 (4) (Apr. 2013) 249–262.
[26] J. Foehr, C.C. Germelmann, Alexa, can i trust you? Exploring consumer paths to trust in smart voice-interaction technologies, J. Assoc. Consum. Res. 5 (2) (Apr. 2020) 181–205.
[27] V. Weistroffer, A. Paljic, L. Callebert, P. Fuchs, A methodology to assess the acceptability of human-robot collaboration using virtual reality, in: Proceedings of the 19th ACM Symposium on Virtual Reality Software and Technology (VRST '13), Association for Computing Machinery, New York, USA, 2013, pp. 39–48.
[28] E. Roesler, D. Manzey, L. Onnasch, Embodiment matters in social HRI Research: effectiveness of anthropomorphism on subjective and objective outcomes, ACM Trans. Hum. Robot Interact. 12 (115) (2023) 1–9.
[29] K.S. Button, et al., Power failure: why small sample size undermines the reliability of neuroscience, Nat. Rev. Neurosci. 14 (5) (May 2013) 365–376.
[30] R. Etzi, et al., Using virtual reality to test human-robot interaction during a collaborative task, in: Proceedings of the ASME Design Engineering Technical Conference, August 18-21, 2019, American Society of Mechanical Engineers (ASME), Anaheim, CA, USA, 2019.
[31] I. Iossifidis, C. Theis, C. Grote, C. Faubel, G. Schöner, Anthropomorphism as a pervasive design concept for a robotic assistant, in: Proceedings 2003 IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS 2003, 2003, pp. 3465–3472.
[32] K.F. MacDorman, R.D. Green, C.-C. Ho, C.T. Koch, Too real for comfort? Uncanny responses to computer generated faces, Comput. Hum. Behav. 25 (1) (May 2009) 695–710.
[33] S.A. Steckenfinger, A.A. Ghazanfar, Monkey visual behavior falls into the uncanny valley, Proc. Natl. Acad. Sci. USA 106 (43) (2009) 18362–18366.
[34] P.H. Kahn, et al., What is a Human? Toward psychological benchmarks in the field of human-robot interaction, Interact. Stud. 8 (3) (Nov. 2007) 363–390.
[35] M. Mori, K. MacDorman, N. Kageki, The uncanny valley [from the field], IEEE Robot. Autom. Mag. 19 (2) (Jun. 2012) 98–100.
[36] A. Czeszumski, et al., Coordinating with a robot partner affects neural processing related to action monitoring, Front. Neurorob. 15 (Aug. 2021).
[37] T. Farroni, G. Csibra, F. Simion, M.H. Johnson, Eye contact detection in humans from birth, Proc. Natl. Acad. Sci. USA 99 (14) (2002) 9602–9605.
[38] D.H. Lee, J.M. Susskind, A.K. Anderson, Social transmission of the sensory benefits of eye widening in fear expressions, Psychol. Sci. 24 (6) (2013) 957–965.
[39] E.H. Hess, J.M. Polt, Pupil size as related to interest value of visual stimuli, Science 132 (3423) (1960) 349–350.
[40] P. van der Wel, H. van Steenbergen, Pupil dilation as an index of effort in cognitive control tasks: a review, Psychon. Bull. Rev. 25 (6) (Dec. 2018) 2005–2015.
[41] M.E. Kret, A.H. Fischer, C.K.W. De Dreu, Pupil mimicry correlates with trust in in-group partners with dilating pupils, Psychol. Sci. 26 (9) (Sep. 2015) 1401–1410.
[42] L. Onnasch, C.L. Hildebrandt, Impact of anthropomorphic robot design on trust and attention in industrial human-robot interaction, ACM Trans. Hum. Robot Interact. 11 (1) (Mar. 2022).
[43] M. Abel, et al., Gender effects in observation of robotic and humanoid actions, Front. Psychol. 11 (Apr. 2020).
[44] I.H. Kuo, et al., Age and gender factors in user acceptance of healthcare robots, in: RO-MAN 2009 - the 18th IEEE International Symposium on Robot and Human Interactive Communication, IEEE, Sep. 2009, pp. 214–219.
[45] P.A. Pavlou, Consumer acceptance of electronic commerce: integrating trust and risk with the technology acceptance model, Int. J. Electron. Commer. 7 (3) (Apr. 2003) 101–134.
[46] K. Wu, Y. Zhao, Q. Zhu, X. Tan, H. Zheng, A meta-analysis of the impact of trust on technology acceptance model: investigation of moderating influence of subject and context type, Int. J. Inf. Manag. 31 (6) (2011) 572–581.
[47] S. Choi, Y. Jang, H. Kim, Influence of pedagogical beliefs and perceived trust on teachers' acceptance of educational artificial intelligence tools, Int. J. Hum. Comput. Interact. 39 (4) (Feb. 2023) 910–922.
[48] F.D. Davis, User acceptance of information technology: System characteristics, user perceptions and behavioral impacts, Int. J. Man Mach. Stud. 38 (3) (1993) 475–487.
[49] A. Pinto, S. Sousa, A. Simões, J. Santos, A trust scale for human-robot interaction: translation, adaptation, and validation of a human computer trust scale, Hum. Behav. Emerg. Technol. 2022 (Dec. 2022) 1–12.

[50] D. Coleman, I.S. ¸ Ucan, S. Chitta, N. Correll, Reducing the barrier to entry of complex robotic software: a MoveIt! Case study, Journal of Software Engineering for Robotics 5 (1) (2014) 3–16.
[51] S. Gulati, S. Sousa, D. Lamas, Design, development and evaluation of a human-computer trust scale, Behav. Inf. Technol. 38 (10) (Oct. 2019) 1004–1015.
[52] A. Pinto, S. Sousa, C. Silva, P. Coelho, Adaptation and validation of the HCTM Scale into Human-robot interaction Portuguese context: a study of measuring trust in human-robot interactions, in: *NordiCHI 2020*, Tallinn, Estonia, Association for Computing Machinery, Oct. 2020, pp. 1–4.
[53] S. Gulati, S. Sousa, D. Lamas, Modelling trust in human-like technologies, in: Proceedings of the 9th Indian Conference on Human Computer Interaction (IndiaHCI'18), Association for Computing Machinery, Dec. 2018, pp. 1–10.
[54] E. Roesler, D. Manzey, L. Onnasch, A meta-analysis on the effectiveness of anthropomorphism in human-robot interaction, Sci. Robot 6 (58) (2021).
[55] R. Etzi, M. Zampini, G. Juravle, A. Gallace, Emotional visual stimuli affect the evaluation of tactile stimuli presented on the arms but not the related electrodermal responses, Exp. Brain Res. 236 (12) (Dec. 2018) 3391–3403.
[56] O. Corneille, P. Lush, Sixty Years after Orne's American Psychologist Article: A Conceptual Framework for Subjective Experiences Elicited by Demand Characteristics, Jun. 2021.
[57] P.P. Forster, H. Karimpur, K. Fiehler, Demand characteristics challenge effects in embodiment and presence, Sci. Rep. 12 (1) (Dec. 2022).
[58] S. Bermúdez i Badia, et al., Virtual reality for safe testing and development in collaborative robotics: challenges and perspectives, Electronics 11 (1) (May 2022) 1726.
[59] E. Granholm, S.R. Steinhauer, Pupillometric measures of cognitive and emotional processes, Int. J. Psychophysiol. (Mar. 2004) 1–6.
[60] C.D.B. Luft, et al., Social synchronization of brain activity increases during eye-contact, Commun Biol 5 (1) (Dec. 2022).
[61] M. Tomasello, B. Hare, H. Lehmann, J. Call, Reliance on head versus eyes in the gaze following of great apes and human infants: the cooperative eye hypothesis, J. Hum. Evol. 52 (3) (2007) 314–320.
[62] R.K. Singh, B.J. Voggeser, A.S. Göritz, Beholden: the emotional effects of having eye contact while breaking social norms, Front. Psychol. 12 (Apr. 2021).
[63] R.M. Yerkes, J.D. Dodson, The relation of strength of stimulus to rapidity of habit-formation, J. Comp. Neurol. Psychol. 18 (1908) 459–482.
[64] A. Atabaki, K. Marciniak, P.W. Dicke, P. Thier, Assessing the precision of gaze following using a stereoscopic 3D virtual reality setting, Vis. Res. 112 (Jul. 2015) 68–82.
[65] S.P. Marshall, Identifying cognitive state from eye metrics, Aviat Space Environ. Med. 78 (5 Suppl) (2007) B165–B175.