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Theory of Mind abilities predict robot's gaze effects on object preference

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***Abstract*— This study investigated the differences between human and robot gaze in influencing preference formation, and examined the role of Theory of Mind (ToM) abilities in this process. Human eye gaze is one of the most important sources of information for social interaction and research has demonstrated its effectiveness in influencing people's preference. With increasing technological development, we will interact with robots that can exhibit gaze behavior and influence people's preference. It is unclear whether there are any differences between humans and robots in this process. The present study aimed to analyze the role of the gaze of a robot and a human in influencing the ascription of a preference to the gazer and the participants' preference. Furthermore, we examined the role of ToM abilities in preference formation. The results showed that the gaze has a greater effect on the gazer preference compared to participants' preference regardless of the agent (human or robot). In addition, ToM abilities predict both gazer and individual preferences in the robot's condition only even though different socio-cognitive mechanisms are involved. The study suggests that adults are cognitively able to process the gaze of a robot similar to a human, recognizing the underlying mental state. However, only for the robot, different cognitive mechanisms are involved in the gazer (i.e., perspective taking) and participants' preference formation (i.e., advanced ToM).**

***Index Terms*—Social Robotics; Theory of Mind; Gaze Effect; Preference Formation; Attribution of Preference.**

1. INTRODUCTION

EYE gaze is one of the most important information for social interaction and monitoring another's gaze direction is unique to humans[1]. Then, how is robot eye gaze perceived? More specifically, is robot gaze understood as a gaze that incorporates mental states? This study aimed to investigate the role of gaze in influencing preference formation, comparing the effects between a human and a robot agent. Furthermore, we examined the role of Theory of Mind (ToM) abilities in this process.

Over the last two decades, numerous studies have shown that another's gaze direction affects human attention and cognition. One of the most investigated aspects is attentional shifts induced by gaze cues, known as the gaze-cueing effect[2]. Typical adults respond faster to targets that appear in cued rather than miscued locations, based on gaze cues (for a review, see[3]). A recent meta-analysis has reported that the gaze cueing effect is robust whether schematic faces, computer-generated faces, or images of real faces were used as cues[2]. The most common explanation of the gaze-cueing effect suggests that seeing an averted gaze triggers a shift of attention reflectively through the bottom-up process[4], [5]. A study examining whether the gaze cueing effect depends on mental state attributions to others has shown that the attribution of "seeing" does not necessarily modulate the gaze cueing effect[6]. In this previous study, the researchers manipulated whether the gazing agent could see the same thing as the participant or had this view obstructed by a physical barrier. In both conditions, gaze cueing effects were significantly observed, suggesting that mental state attributions to the agent's view may not be necessary for attentional shifts elicited by gaze cues.

While another's gaze direction induces attentional shifts without mental state attributions, gaze effects on more cognitive processes have been suggested to be related to another's mental states. For example, studies have shown that another's gaze direction affects preferences for objects cued by gaze in both adult[7] and infant[8], [9]. Baylis and colleagues[7] presented gaze cueing situations and asked how much the participants liked objects which were cued or miscued by gaze. They found that participants significantly preferred cued objects compared to miscued objects. In addition, this cueing effect on object preferences was absent when an arrow was used for cues. Thus, gaze effects on preferences cannot be explained by attention. Gaze direction can be a signal for liking, interest or desire[10]. If someone looks toward an object, it is interpreted she/he likes it, while if someone looks away from it, we interpret she/he does not like it. It was suggested that another's gaze information may be used to guide our own evaluative processes. To test whether another's mental states modulate gaze effects on object preferences, the same group has manipulated emotional expressions of cueing faces[11]. They found that objects

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looked at with a happy expression were liked more than objects looked at with a disgust expression. The results suggested that the gaze effects on object preferences include the process of another's mental states.

The relation between gaze direction and mental state attributions has been discussed in developmental and neuroscientific studies. Baron-Cohen and colleagues[10] have shown that typical 4-year-old children use another's gaze direction as a cue for reading mental states such as desire and goal, in contrast, children with autism failed to use gaze cues to infer the mental states. Children with autism have been known for their lack of gaze communication and ToM[12], [13]. Within typical children, the frequency of gaze communication predicts the ToM abilities in later development. Brooks and Meltzoff[14] conducted a longitudinal study and found that gaze following at 10.5 months predicted the use of mental-state terms at 2.5 years and use of mental-state terms at 2.5 years predicted theory of mind at 4.5 years. Thus, gaze following behaviour in early infancy is subsequently correlated with ToM.

Neuroimaging studies have shown that gaze processing and ToM share their neural substrates. Adult functional magnetic resonance imaging (fMRI) studies have shown that medial prefrontal cortex (mPFC) is implicated in this high-level component of gaze processing. For example, mPFC responded more when the participant was following a dot that was being tracked by an actor's gaze compared to when the actor's gaze did not track the dot[15], suggesting that mPFC was preferentially engaged when the actor's gaze signalled joint attention to the dot. The mPFC has been suggested as a core region of the ToM network[16], [17]. A meta-analysis of ToM studies has also shown that the mPFC was activated across different task groups, suggesting the mPFC is robustly engaged in ToM[18].

Neuroimaging studies have reported the common neural substrates to gaze processing and ToM. However, it is unknown whether the gaze effects on object preferences are related to mental state attributions. Although it has been revealed that facial expressions modulate the gaze effects on object preferences[11], it remains unclear whether gaze cueing situations with neutral faces also include mental state attributions. Bayliss and colleagues[7] used arrow cueing to control the effects of attention, however, arrow cueing is qualitatively different from gaze cues. For example, Ishikawa and colleagues[19] suggested that both cues can induce attentional shifts but only gaze cues can signal context-dependent information about the surrounding environment. Thus, arrow cues may not include information about the cued objects and not influence object preferences.

The role of the gaze in the interactions between humans and robots has been widely recognized[20]. Numerous studies have shown that the gaze of the robot is processed as a significant social signal starting as early as the second year of age[21], [22], though with specific differences compared to human gaze[21], [23]. Thus, gaze remains a salient and recognizable social signal even in adulthood[24], [25]. In this study, we used a human-like robot (Robovie) as an agent having eye features without mental states (i.e., adults cognitively know the robot does not have mental states) which has already been used with 17-month-old children to study gaze following mechanism, demonstrating that although less salient than in human, it can activate this mechanism[21]. An fMRI study has shown that the levels of mental state attributions to robots correlate with the increase of human-likeness of the interaction partner, showing increased activities in mPFC[26]. A study exploring children's mental state attribution to different robots has found that children aged 7 and 9 years attributed less mental states to the Robovie than another more human-like robot[27]. Although the Robovie has two eyes and face-like features, adults evaluate that the Robovie is mechanical rather than human-like[28] and ascribe less mental states compared to more human-like robots[29]. Thus, adults attribute few mental states to the Robovie compared to the human agent. By using the Robovie as an agent, it is possible to investigate whether the agent's mental states are necessary for gaze effects on object preferences.

Similar to human gaze, robot gaze can effectively convey spatial information in adults [24] Robot gaze behaviour affects perceptions of social presence and emotional state [30]. While no studies have examined the relationship between ToM abilities and the effects of robot gaze on adult cognition, individual differences in mental state attribution may lead to variations in how adults understand robot gaze.

To measure ToM abilities, we used two tasks of ToM: Reading Mind in the Eyes (RME) test and Perspective Taking (PT) task. RME has been used as an advanced ToM test[31], [32] across different cultures[33], [34]. In the study assessing the reliability and validity of the RME test, the positive correlation between self-reported empathy and the performance in the RME test has been shown[35]. Based on this result, it is proposed that the RME may reflect empathy functions in understanding other's emotion. On the other hand, PT has been assumed as a fundamental ability of ToM, inferring what others can see[36]. PT itself does not include understanding other's emotional states, however, studies have suggested that PT is related to the effects of gaze cueing. For example, Nuku and Bekkering[37] found that attention was not shifted at all if the gaze cue could not see the targets, suggesting gaze cueing effects are induced when the participant take another's perspective. Also, Teufel and colleagues[38] showed that the basic gaze cueing effect was significantly larger when the participant believed that the agent could see the inducing stimuli, suggesting that PT to the agent facilitates the gaze effect. Thus, RME reflects empathy functions of ToM sharing other's mental states, while PT reflects ability to inferring perceptual aspects of other's mental states focusing on what others see.

In this study, we compared the effects of the gaze of a human and a robot on the gazer preference and participants' preference. We postulated that the score of gazer preference indexes the understanding of agents' gaze information (i.e., the interest of the gazer), while the participants' preference score reflects how much another's gaze information affects participants' preference formation. Furthermore, we examined whether ToM abilities (i.e., perspective taking and advanced ToM) are associated with the understanding of gazer's information and individual preference formation. We hypothesised a positive correlation between perspective taking and understanding of gazer's information and a positive correlation between RME and participant preference formation.

2. METHODS

2.1. Participants

Seventy-nine Italian adult participants (F = 40, Mean age = 23.83 years, SD = 3.17, age-range = 19-30 years) took part in the study. Inclusion criteria for all participants were age of majority and being a native Italian speaker. All participants gave written informed consent in accordance with the requirements of the Research Ethics Review Board of Department of Psychology, Kyoto University in Kyoto, Japan, which approved this study (ethical proof number: 28-P12). The study was conducted in accordance to the Declaration of Helsinki between October 2020 and December 2020.

2.2. Reading the Mind in the Eyes

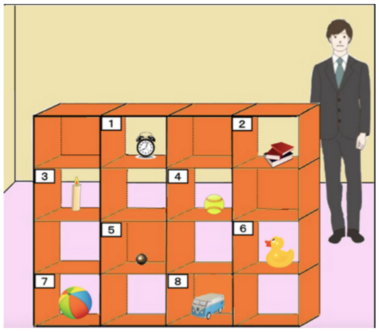
The Reading the Mind in the Eyes[32], [35] is composed of 36 images depicting the eye area of various human faces. Participants must choose what the depicted character is feeling or thinking from four options (one target, three distractors) written under each picture. The scores are calculated as the total number of correct answers for all 36 items (range 0-36). Higher RMET scores are correlated with better ability to infer others' emotional states from subtle social cues.

2.3. Perspective Taking task

A task inspired by Dumontheil and colleagues[39] was used to analyse Perspective Taking (PT; see Figure 1). In this study, PT is defined as the ability to infer what another person can or cannot see in a given context. It specifically evaluates participants' capacity to adopt another individual's visual perspective by accurately identifying the object that falls within the other person's line of sight or focus of attention. As a fundamental component of ToM, PT enables individuals to interpret and predict others' behaviour based on their visual access to the environment.

This task is widely used with adults [40], [41]. Specifically, participants are shown a picture of a bookcase consisting of several shelves on which various objects are placed. Behind the bookcase is a person who, with respect to the frontal (participant) perspective, cannot see all the objects in the bookcase as some shelves are not visible from behind the bookcase. The participant is shown the picture of the bookcase only from the front, i.e. not from the perspective of the person behind the bookcase. The participant is asked to indicate which object (i.e., the target) from the perspective of the person behind the bookcase is smaller or bigger. Specifically, there are several objects in the bookcase, some of which are not part of the target's class of objects while other objects are part of the same class of the target but have different shapes and sizes. The task consists of five trials with five different object classes (e.g., balls, bottles, candles) and the shelves visible in the bookcase from the perspective of the person behind it are different for each trial. An answer is considered correct when the participant indicates the target from the perspective of the person behind the bookcase (for example, the smallest candle). The scores are calculated as the total number of correct answers for the five items (range 0-5). Higher PT scores are correlated with better ability to take the other's perspective.

Figure 1. The image represents one of the five trials of the perspective taking task. In this specific trial, the participants have to indicate which ball is smaller from the perspective of the person behind the bookcase (correct answer: object number four). In this figure, the smallest ball is the object number five from the participant's perspective, thus participants need to take another's perspective to choose the correct answer.



2.4. Design and gaze preference task.

The design was a 2x2 repeated measures model, with 2 levels of *Agent* (Human, Robot) and 2 levels of *Question* (Gazer Preference, Participant Preference) as the within-subject factors. The dependent variables were the attribution of the gazer preference and the individual preference. Each participant watched 10 short videos (10 seconds each) in which either a human (5 videos) or a robot (5 videos) looked towards one of two objects on a screen. The order of the video presentation was randomized between participants. Specifically, on a black background at the top of the screen was a white square showing the face of either the human or the humanoid robot Robovie and at the bottom were two objects, the target (i.e., object gazed by agents) and the distractor (see Figure 2 A-B). Initially, the agent looked straight at the participant (4 seconds) to engage s/he, then moved their gaze towards the target and, finally looked at it (6 seconds). The position – left and right – of the target and the distractor on the screen and the direction of the gaze – left and right – towards the target were randomised. For each trial the pair of objects were different (e.g., flag and brush or scoop and shuttlecock; see [7]). At the end of each video the participant saw the two objects again (their position, left and right, was randomised) and asked randomly two questions: 1) "*Which object does the robot/girl like?*" (Gazer Preference) and 2) "*Which object do you like?*" (Participant Preference). If the participants' response matched the object gazed by the agent (i.e., the target), it was considered a consistent choice (score 1), choosing the distractor was considered inconsistent (score 0). The score for the Human condition and Robot condition was then calculated by summing the responses from the five trials (range 0-5). The higher the score on the gaze preference task, the greater the effect of gaze on the

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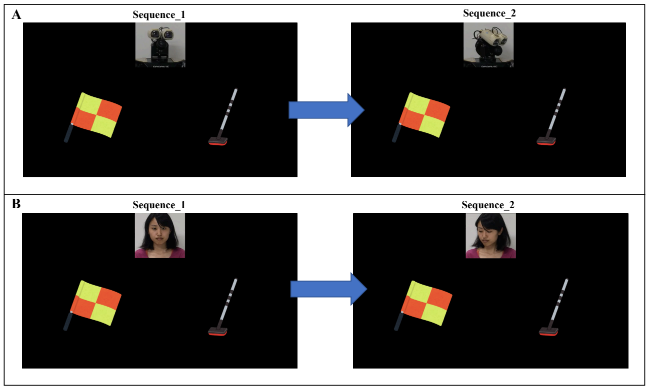
preference attribution.

Fig. 2 A–B. The figure represents two examples of the video stimuli: A) In Sequence-1 the robot gazer looked at the camera (4 seconds) and in Sequence-2 looked at the target (6 seconds); B) In Sequence-1 the human gazer looked at the camera (4 seconds) and in Sequence-2 looked at the target (6 seconds). The actress has provided consent to publish the images in all formats i.e. print and digital.



2.5. Procedure and Measures

Data were collected through an online survey hosted on the Qualtrics platform. The participants were recruited via Prolific and paid 7.50€ per hour. Prolific is an online platform specifically designed for research participant recruitment. It offers access to a diverse participant pool and enables researchers to screen for specific demographic criteria, ensuring a representative sample. Participants were informed about the experimental procedure, the measurement items, and the materials. With respect to the study, after the participants provided sociodemographic information (i.e., age, gender, residence, occupation, and level of study), they randomly completed: The Gaze Preference task, the Reading the Mind in the Eyes and the Perspective Taking task.

3. RESULTS

3.1. Gaze Preference task

Because the distributions of evaluations for objects were not normal, we used generalised linear mixed models (GLMM) for the analysis of the gaze preference task.

We used the scores in the gaze preference task as the dependent variable. In the GLMM, we implemented *Agent*, *Question*, and *Gender* as fixed effects, *Agent* × *Question*, *Agent* × *Gender*, and *Question*× *Gender* as interaction terms and participant ID as random effects. In addition to the independent factors in our experimental design, we incorporated gender as a factor in our main analysis. This decision was guided by literature reporting gender differences in gaze effects; specifically, females' attention is more influenced by another's gaze direction compared to males (Bayliss et al., 2005). The results showed that the participants evaluated other's preference higher than own preference when an agent is looking at an object (see Figure 3). There were no other significant effects. The results are reported in Table 1, Table 2 and Table 3.

Figure 3. Mean scores of preferences in each condition.

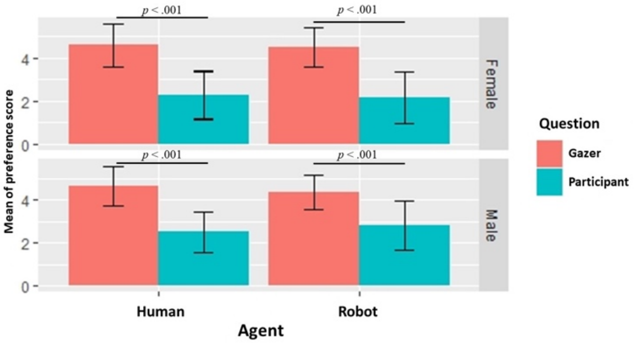


Table 1. The fixed effects showing the effect of each variable.

Fixed Effect	*Estimate*	*Std. Error*	*Z value*	*P value*
Intercept	1.51573	0.04802	31.564	< 2e-16 ***
Agent[Robot]	0.02714	0.03090	0.878	0.379842
Question[Own]	-0.63284	0.03816	-16.583	< 2e-16 ***
Gender[Male]	0.06262	0.06016	1.041	0.297931
Agent[Robot]: Question[Own]	0.07918	0.05375	1.473	0.140666
Question[Own] : Gender[Male]	0.01694	0.05375	0.315	0.752606
Agent[Robot]: Gender[Male]	-0.02439	0.04369	-0.558	0.576610

Significance levels: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Table 2. The random effects table showing the variance between participants. The Type II Wald chi-square tests evaluate the overall significance of each effect.

Effect	*Chi-square*	*Df*	*p value*
Agent	0.7714	1	0.3798
Question	275.0118	1	< 2.2e-16 ***
Gender	1.0831	1	0.2980
Agent:Question	2.1703	1	0.1407
Question:Gender	0.0994	1	0.7526
Agent:Gender	0.3117	1	0.5766

Significance levels: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Table 3. The multiple comparison results show the difference between the levels of Question (Own and Other).

Comparison	*Estimate*	*Std. Error*	*Z value*	*P value*
Participant - Gazer	-0.59289	0.02707	-21.904	< 1e-04 ***

Significance levels: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

3.2. Predicting gaze effects by ToM abilities

To investigate whether the individual differences in ToM abilities predict gaze effects of each agent, we conducted generalised linear modelling (GLM) predicting gaze effects in each condition by the PT and RME scores (see Table 4). The results showed a significant effect of the RME scores on Participant preference in the Robot condition (estimate ± s.e. =

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-0.086 ± 0.039, *Z* = -2.182, *p* = .032). Higher RME scores negatively predicted Robot gaze effect of Robot on Participant preference (coefficient of determination (R^2) = 0.059). Also, we found that higher PT scores positively predicted the Robot gaze effect on Robot preference (estimate ± s.e. = 0.155 ± 0.078, *Z* = 1.987, *p* = .05; coefficient of determination (R^2) = 0.049).

Table 4. Coefficient of determination and *p* value in each condition.

	RME	*PT*
Human-Participant	R^2 = 0.002, *p* = 0.69	R^2 = 0.001, *p* = 0.73
Human-Gazer	R^2 = 0.004, *p* = 0.55	R^2 = 0.031, *p* = 0.12
Robot-Participant	R^2 = 0.059, *p* = 0.032*	R^2 <0.001, *p* = 0.852
Robot-Gazer	R^2 < 0.001, *p* = 0.837	R^2 = 0.049, *p* = .05*

Significance levels: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

4. DISCUSSION

The aim of the study was to analyse the effects of the gaze of a human and a robot on the gazer preference and participants' preference. Furthermore, we examined whether ToM abilities (i.e., perspective taking and advanced ToM) are associated with the understanding of gazer's information and individual preference formation. In general, the results showed that the gaze has a greater effect on the gazer preference compared to participants' preference regardless of the agent (human or robot). As for the role of ToM abilities, regression analyses showed only for the robot that higher perspective taking abilities positively predicts the attribution of the gazer preference, whereas a greater advanced ToM ability negatively predicts the effect of gaze on participants' preference. ToM abilities predict neither human gazer preference nor the effect of human gaze on participants' preference.

The main finding of our study is the lack of differences in the preference attribution to the gazers, human and robot. This suggests that the gaze is a strong social signal to induce preference attribution for both agents. The literature have shown that the human gaze already from early childhood can influence gazer preference inference[42], [43] and this is also effective in adulthood[44]. Our findings extend previous research on the effects of human gaze to include robotic gaze, showing that gaze direction similarly influences preference attribution to a robot. This is in line with the literature showing that robot gaze is effective already in early childhood in directing attention to a target[21] and in influencing human decision-making in adults[25]. A possible explanation could relate to the Intentional Stance theory[45], according to which the observation of human-like behaviour influences the attribution of intentionality to an agent and, consequently, the ascription of a mental state to it. In the context of our study, the behaviour performed by the robot is perceived as a social signal (i.e., the gaze) influencing the attribution of intentionality to it[46], [47]. In other words, the robot prefers one object over another, showing an attribution of mental states by participants to it (i.e., the robot desires an object). This suggests that there is an understanding of the robot's actions in psychological terms, i.e. people interpret the robot's "mind" by attributing mental contents to its actions. This interpretation is consistent with studies showing that adults attribute some mental states to robots[27], [48], [49], [50], [51], [52], [53]. In the present study, we found similar gaze effect between human and robot in participants' preference, indicating again a similarity in preference formation between the two agents. However, in comparison to the gazer's preference attribution, participants' preferences are only weakly influenced by the gaze of the agent, whether human or robot. This could be explained by a relatively weak valence of the gaze on the intrapersonal level [11]. In other words, although the gaze is informative of the gazer's desire, at the socio-cognitive level (i.e., the gaze) seems to preclude an intrapersonal preference accommodation to the preference of the social partner. In addition, the weaker effect of gaze on individual preference formation could be related by a socio-cognitive explanation, i.e. a single gaze is not enough to influence the individual preference independent of the gazer's identity, human or robot[54].

To our knowledge, the present study suggests for the first time that individual differences in ToM abilities predict the effect of the robot gaze on gazer preference and participants' preference. In particular, the attribution of the gazer preference (or desire) correlates with PT score rather than the RME index. As claimed by Baron Cohen and colleagues[10] and supported by further studies, taking the other's perspective is crucial for understanding others' communicative intentions and feelings[55], [56], [57], [58]. To infer the robot's preference (i.e., attribute a mental state to it, a desire) requires higher-performance perspective taking abilities as the person has to accommodate the gazer's unfamiliarity. This hypothesis is supported by the lack of similar results with the human gazer for whom the interference of unfamiliarity does not occur as the gazer is a conspecific. On the one hand, in the Human condition in which a person has to attribute a preference to a conspecific, identification with the gazer is more immediate given the ontological similarity and, consequently, no particularly sophisticated perspective-taking skills are required. In other words, humans spontaneously attribute mental states to another person in social situation[59], [60]. On the other hand, when the gazer is a robot, greater perspective taking abilities are required to identify the underlying mental state of the gazer and, consequently, attribute a preference to it, as the ontological distance with the robot requires greater cognitive effort than that of a conspecific. Humans do not spontaneously attribute mental states to robots but it can be facilitated by social cues[61].

Considering the other ToM ability measured by RME index, the understanding of emotions could be important in robot gaze effect. With respect to the effect of the robot gaze on participants' preference, people require more sophisticated advanced ToM abilities to understand the mental state underlying the robot gaze. Specifically, high RME scores are usually related to a greater ability to read subtle signals indicating the emotional state of another person[32]. Therefore, people's ability to attribute emotions to the human gaze is an important psychological component in attributing communicative meaning to the robot gaze and, consequently, attributing a mental state to it, which influences (although only slightly) participants' preference negatively. The difference between human and robot agents in the correlation between RME scores and participants' preference for the human supports the hypothesis that the robot is evaluated as an entity ontologically different from the human[62], [63]. People with more advanced mind-reading abilities, as assessed through eye cues, tend to diverge from the robot's preference, often attributing a different preference to themselves. While previous studies have shown that robots can serve as social partners for humans from childhood[21], [48], [61], [64], individual differences in ToM abilities suggest that those with higher mind-reading skills are less influenced by a robot's gaze when evaluating their own preferences.

Based on the correlations between ToM skills and gaze effects, we hypothesize that distinct mechanisms are involved in understanding gaze preference and forming participant preferences. Since adult participants can naturally attribute mental states to other humans, our study did not find significant correlations between ToM skills and gaze effects in the human condition. However, in the robotic condition, the ToM components examined—specifically, the ability to take another's perspective and the ability to understand mental states through the eyes—predicted the effects of gaze in opposite directions. This divergence likely arises because the study measures different dimensions of ToM: cognitive ToM, which involves perspective-taking, and affective ToM, which involves understanding mental states through gaze. As originally defined by Brothers and Ring[65], cognitive ToM—referred to as the "cold" aspect—concerns the inference of others' mental states, such as knowledge and beliefs. Meanwhile, affective ToM—the "hot" aspect—involves the empathetic understanding of others' emotional states and feelings[66]. In our study, the Perspective-Taking (PT) score represents cognitive ToM abilities, while the Reading the Mind in the Eyes (RME) score reflects affective ToM capabilities. Given our earlier findings, cognitive ToM predicts robot preference attribution, suggesting that attributing preference to a robot requires more cognitive effort ('cold' ToM). In contrast, affective ToM predicts aversion toward the robot in individual preference formation, indicating that this process is influenced by emotional factors ('hot' ToM).

5. CONCLUSIONS

The present study show that adults interpret the robot's gaze in mentalistic terms, ascribing desires (such as preferring one object over another) to the robot in a manner similar to how they do with humans. However, gaze alone is not sufficient to influence participants' preferences, regardless of whether the gaze comes from a human or a robot. Furthermore, the results reveal that mentalistic components predict both the participants' and the gazer's preferences in the robot condition.

The implications of these findings may have a twofold perspective, psychological and robotic. From a psychological perspective, the study shows that adults cognitively process the social signals (i.e., the gaze) of a robot similarly to those of a human, recognising the underlying mental state (i.e., a desire towards an object). However, our findings suggest that gaze alone may not be sufficient to significantly influence individual preference formation. This highlights the potential for future studies to explore integrating additional components with gaze, such as explicit emotional cues (e.g., a smile), to exert a greater influence on preference formation. To improve their social communication effectiveness, robots could integrate emotional signals with gaze behaviour in practical ways. For example, a robot could combine gaze with facial expressions to convey emotional states more effectively. When fixating on an object to indicate a preference, a robot could smile to suggest approval or interest, or frown to signal disinterest. This combination of gaze and emotional expression could clarify the robot's intentions to human partners, especially in ambiguous social scenarios. These possible integrations are in line with recent studies in which the association between gaze and emotion can influence adults' sharing behaviours toward a robot [51]. These examples highlight the importance of designing robots that can convey multimodal social signals. Future research could further investigate the combination of these signals to improve social communication in various applications.

Furthermore, as our study involved agents presenting only a single gaze toward the object, future research could explore whether multiple gazes might have a stronger impact on the formation of individual preferences. Additionally, the data suggest that the effect of the robot gaze on gazer preference and participants' preference are based on different socio-cognitive mechanisms. Specifically, robot preference is influenced by perspective-taking skills, whereas participants' preference is influenced by advanced ToM skills. These differences in socio-cognitive mechanisms are not observed with the human, likely because familiarity with a conspecific requires less cognitive effort. Mirroring with another human is more immediate and intuitive compared to a robot, which is perceived as an ontologically distinct entity. This suggests a further exploration into how mentalistic abilities affect preference formation in human-robot interactions. Furthermore, given that different components of ToM abilities are involved in gaze processing, and considering that ToM develops with age, it would be interesting for future research to examine the association between ToM and gaze effects across different age groups.

From a robotics perspective, the study confirms that the robot gaze is a particularly powerful social signal to convey the robot's communicative intentions and desires. However, as for the human, it is not sufficient to influence individual preference formation. These results support the idea that in the human-robot interactions the robot gaze needs to be associated to another social signal (e.g., an emotion) to be effective in influencing people preference formation. This could be an important behavioural feature to be implemented in a robot in sensitive context in which influencing the other preference is fundamental, as for example in healthcare. An additional consideration is the individual psychological differences. Our results show that ToM abilities have an influence on how adults process robot social signals. However, we do not know whether the ToM abilities of the human partner can mediate interactions in more complex social situations such as in trust games. Future studies should consider the ToM abilities of human partners to better understand how a robot can influence a human's behaviour and, conversely, how mentalistic abilities can affect and/or mediate interactions with the robot.

Our study offers valuable insights into the field of emotional computation by examining how gaze, a fundamental social signal, influences both cognitive and emotional aspects of preference formation. While the primary focus was on the cognitive processing of gaze, the emotional impact of gaze cannot be overlooked. In psychological terms, gaze not only directs attention but also carries emotional weight, influencing how individuals develop preferences and perceive the desires of others. By analysing the role of gaze in both personal preference formation and the attribution of others' preferences, our research sheds light on how an agent's gaze can affect emotional states and desires. Additionally, our findings demonstrate that different components of ToM—both cognitive and affective—play distinct roles in how gaze shapes preferences. This distinction is crucial for the development of more sophisticated computational models in robotics, where understanding and replicating human-like gaze interactions can enhance the emotional responsiveness and personalization of robots. The study underscores the importance of considering individual differences in human-robot interactions, suggesting that these variations can lead to diverse effects of gaze on users. In other words, a robot capable of acquiring information about an individual's ToM abilities could potentially adapt its gaze behaviour to better meet the specific needs of the human. This adaptability could hold particular significance in pathological conditions, such as neurodegenerative diseases, where either the emotional or cognitive component of ToM may be impaired. By tailoring its behaviour based on the individual's abilities, the robot could provide more effective support and interaction. However, it is important to note that these considerations remain theoretical at this stage and require further empirical exploration. Future studies are essential to investigate the feasibility and efficacy of such adaptive mechanisms and to determine how they can be implemented effectively in real-world contexts.

One limitation of the study is the cultural homogeneity of our sample, which consisted of Italian participants. Cultural factors can influence social cognition and behaviour, including gaze processing and ToM abilities (for review see [67]). Previous research has shown that cultural differences can impact gaze-following behaviour and the interpretation of social cues [68], [69]. These cross-cultural differences have also been identified in human-robot interaction, where Eastern cultures (i.e., Japan and Singapore) seem to respond more easily to the gaze of social robots than Western ones (i.e., Italy, Germany, UK) [70], [71]. This is probably in line with the reflection regarding the greater exposure and acceptance of robotic technologies in Eastern cultures. In fact, societies with higher exposure to advanced technologies and frequent interactions with robots may foster greater familiarity and acceptance, potentially leading to a higher likelihood of attributing mental states to robotic agents. On the other hand, in cultures where robots are less integrated into daily life or predominantly framed as tools rather than social entities, the tendency to attribute mental states may be more limited. Moreover, public and general narratives about robotics—whether they emphasize robots as collaborative partners or mechanical tools—can shape individuals' expectations and cognitive biases in interpreting robot behaviour. It is important to note that these considerations derive from existing literature and were not directly investigated in the present study. Given that our study was conducted with a culturally homogeneous sample, future research should consider replicating the study with participants from diverse cultural backgrounds to empirically examine how cultural differences in exposure, acceptance, and narratives about robots influence the attribution of mental states and responses to robotic gaze in human-robot interaction.

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