Humanoid-based protocols to study social cognition: On the role of eye contact in joint attention

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ABSTRACT

Social cognition is broadly defined as the way humans understand and process their interactions with other humans. In recent years, humans have become more and more used to interact with non-human agents, such as technological artifacts. Although these interactions have been restricted to human-controlled artifacts, they will soon include interactions with embodied and autonomous mechanical agents, i.e., robots. This challenge has motivated an area of research related to the investigation of human reactions towards robots, widely referred to as Human-Robot Interaction (HRI). Classical HRI protocols often rely on explicit measures, e.g., subjective reports. Therefore, they cannot address the quantification of the crucial implicit social cognitive processes that are evoked during an interaction. This thesis aims to develop a link between cognitive neuroscience and human-robot interaction (HRI) to study social cognition. This approach overcomes methodological constraints of both fields, allowing to trigger and capture the mechanisms of real-life social interactions while ensuring high experimental control. The present PhD work demonstrates this through the systematic study of the effect of online eye contact on gaze-mediated orienting of attention.

The study presented in **Publication I** aims to adapt the gaze-cueing paradigm from cognitive science to an objective neuroscientific HRI protocol. Furthermore, it investigates whether the gaze-mediated orienting of attention is sensitive to the establishment of eye contact. The study replicates classic screen-based findings of attentional orienting mediated by gaze both at behavioral and neural levels, highlighting the feasibility and the scientific value of adding neuroscientific methods to HRI protocols.

The aim of the study presented in **Publication II** is to examine whether and how real-time eye contact affects the dual-component model of joint attention orienting. To this end, cue validity and stimulus-to-onset asynchrony are also manipulated. The results show an interactive effect of strategic (cue validity) and social (eye contact) top-down components on the botton-up reflexive component of gaze-mediated orienting of attention.

The study presented in **Publication III** aims to examine the subjective engagement and attribution of human likeness towards the robot depending on established eye contact or not during a joint attention task. Subjective reports show that eye contact increases human

likeness attribution and feelings of engagement with the robot compared to a no-eye contact condition.

The aim of the study presented in **Publication IV** is to investigate whether eye contact established by a humanoid robot affects objective measures of engagement (i.e. joint attention and fixation durations), and subjective feelings of engagement with the robot during a joint attention task. Results show that eye contact modulates attentional engagement, with longer fixations at the robot's face and cueing effect when the robot establishes eye contact. In contrast, subjective reports show that the feeling of being engaged with the robot in an HRI protocol is not modulated by real-time eye contact. This study further supports the necessity for adding objective methods to HRI.

Overall, this PhD work shows that embodied artificial agents can advance the theoretical knowledge of social cognitive mechanisms by serving as sophisticated interactive stimuli of high ecological validity and excellent experimental control. Moreover, humanoid-based protocols grounded in cognitive science can advance the HRI community by informing about the exact cognitive mechanisms that are present during HRI.

INTRODUCTION

1.1 From human-human to human-robot interaction and back

1.1.1 Social cognition research

Humans interact with other humans constantly throughout their lives. Efficient social interactions facilitate our survival and success (Gallese, Keysers, & Rizzolatti, 2004). However, social interactions are extremely complex, entailing a careful composition of self-knowledge, perception, and understanding of others, as well as interpersonal norms and motivations. This sophisticated set of cognitive processes is broadly known as social cognition (Fiske & Taylor, 1991). Social cognition research lies at the intersection between social psychology and cognitive psychology. Social psychologists have traditionally criticized the discipline of social cognition for not studying social processes during naturalistic social interactions, whereas cognitive psychologists have criticized it for not employing highly controlled paradigms grounded in strict cognitive science methods (Augoustinos, Walker, & Donaghue, 2014). Indeed, social cognition research has adopted an individualistic approach to the investigation of social processes, ignoring often that the contents of cognition originate in social life, in human interaction and communication (Augoustinos, Walker, & Donaghue, 2014). Recent endeavors, however, suggest the 'second-person social neuroscience' and state that the second-person neuroscience approach is crucial for understanding both intra- and inter-personal processes during involvement in online reciprocal social interactions (De Jaegher, 2010; Schilbach, 2013; Schilbach, 2014). This idea stresses the fact that cognitive processes are inherently different during observation and participation in interaction and activate distinct neural regions (Schilbach, 2010). However, the more naturalistic an experimental protocol becomes the more challenging it is to optimize the experimental control. Therefore, there is the need for social cognition research to accommodate paradigms of higher ecological validity where participants could employ cognitive processes similar to real interactions but at the same time respect the demands of cognitive psychology for excellent experimental control.

1.1.2 Human-robot interaction research

Humans interact with other humans most of their lifetime. However, they also often interact with non-human others, such as animals, or even technological artifacts. Due to rapid advances in artificial intelligence and engineering, one of the recent artifacts expected to enter our social lives is the so called 'social robot'. According to Darling, *"a social robot is a physically embodied, autonomous agent that communicates and interacts with humans on a social level"* (Darling, 2016, p.2). Social robots are expected to assist humans by carrying education, care or service roles. To achieve a smooth and effective interaction between humans and robots, an important challenge lies in the optimal design of social robots. Social robots need to have specific features that would allow them to perceive humans' needs, feeling, and intentions and act on them appropriately. This necessity has motivated a high degree of interest in studying human reactions towards robots and in establishing a new area of research, widely referred to as Human-Robot Interaction (HRI). As HRI research grows rapidly, there is an increasing need for robust and efficient methods of HRI assessment and evaluation. However, one issue with current HRI research is that it often lacks systematic approaches, rigorous methodology, and adequate sample sizes (Kidd & Breazeal, 2005). In addition, HRI research often uses subjective reports to evaluate human reactions. However, subjective reports require conscious awareness and are easily affected by biases, such as the social desirability effect (Humm & Humm, 1944). Furthermore, explicit measures cannot unveil certain cognitive mechanisms that are often automatic and implicit.

1.1.3 Humanoid-based protocols to study social cognition

Constructing a link between social cognition and HRI research can address recent limitations of both disciplines and can eventually advance them by providing useful insights, see Figure I1. Regarding social cognition research, artificial agents, and in particular embodied humanoid robots (robots with a body shape similar to human body) can potentially overcome the limitations of classical social cognition research by providing excellent experimental control on the one hand and allowing for increased ecological validity on the other. Related to ecological validity, it has been shown that robots that are embodied increase social presence (Jung & Lee, 2004). Additionally, an embodied agent can influence differently the interaction compared to a virtual representation of the same agent in various contexts, e.g. better temporal coordination, facilitation in learning, increased persuasiveness

(Bartneck, 2003; Kose-Bagci, 2009; Leyzberg, 2012; Li, 2015). Furthermore, humanoid agents increase the naturalness of interaction by sharing the environment and allowing for interactive paradigms requiring joint actions (e.g. manipulating objects). Such paradigms could have real-life relevance, and extend current tasks limited to 2D screen protocols. Related to experimental control, humanoids can repeat specific behaviors in the exact same manner over many trials. Moreover, humanoids allow for tapping into specific cognitive mechanisms, since their movements can be decomposed into individual parts and allow for studying their separate or combined contribution on the mechanism of interest, known as "modularity of control" (Sciutti, Ansuini, Becchio, & Sandini, 2015).

Employing embodied humanoid agents in interactive protocols that are grounded in cognitive neuroscience methods comprises also a promising avenue for HRI research. Such experimental paradigms can focus on very specific cognitive mechanisms involved in social interactions. Additionally, by employing implicit measures used in these disciplines, i.e., behavioral, physiological, and neuroscience methods (i.e., eye-tracking, electroencephalogram: EEG, functional Near-Infrared Spectroscopy: fNIRS, functional magnetic resonance imaging: fMRI), it is possible to objectively measure the cognitive processes involved. Therefore, this approach can bring credibility and validity to the HRI research and allow for designing social robots that would elicit these specific mechanisms during the human-robot interaction. In turn, designing artificial agents that can socially-attune better with humans can further improve the ecological validity of humanoid-based experimental protocols, by evoking social cognitive mechanisms on the human side which are closer to human-human interactions.

The suggested approach can particularly advance the understanding of social cognitive mechanisms (e.g. by providing cognitive models during naturalistic embodied interactions) that are crucial for human interactions, but traditional methodologies in social cognition pose various limitations in their thorough investigation. One example consists of mechanisms associated with the processing of gaze direction. Despite the vital role of eyes in human interactions (Kleinke 1986; Emery, 2000; Baron-Cohen, 1991; Baron-Cohen, Wheelwright, & Jolliffe, 1997), current methodologies in social cognition research either compromise ecological validity in favor of experimental control (screen-based experimental protocols) or vice-versa (experimental protocols in the "wild"). Instead, here it is argued that humanoid agents could be useful in investigating in-depth unexplored mechanisms associated with gaze direction by allowing for an online embodied gaze contact and excellent experimental control.

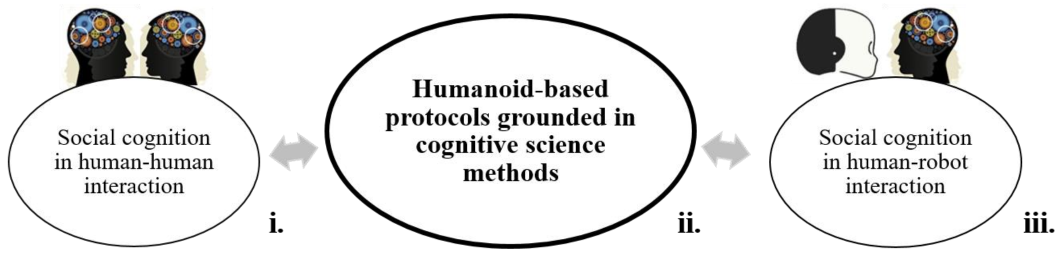

Figure I1 Bringing together social cognition in human-human interaction (i.) and social cognition in human-robot interaction (iii.) using humanoid-based protocols grounded in cognitive science methods (ii.)

1.2 Eye gaze role in human interactions

The social complexity of our environment requires us to efficiently extract relevant social information from interaction partners in order to achieve smooth and natural communication. Particularly important is processing information about eyes and gaze direction, e.g. direct or averted gaze. For example, a person looking at you would indicate that the focus of his/her attention is on you, probably with an intention of establishing a communicative context (Kleinke, 1986; Symons, Hains, & Muir, 1998). In contrast, a person looking elsewhere would mean that the focus of his/her attention is directed to somewhere else, probably indicating his/her interest in another subject/object in the environment. Gaze direction constitutes very good guidance to the focus of another's attention, their intentions or action goals (Baron-Cohen, 1991; Baron-Cohen, Wheelwright, & Jolliffe, 1997; Dovidio & Ellyson 1982; Fiebich, Gallagher, 2013).

According to Emery (Emery, 2000), there are five main social cues provided by gaze direction which may be used by a person to learn about the external (other persons, objects) or internal (emotional and intentional) states: 1. Eye contact (mutual gaze) or averted gaze, 2. Gaze following, 3. Joint attention, 4. Shared attention, 5. Theory of mind, see Figure I2. Eye contact occurs when the attention of individuals A and B is directed to each other, while averted gaze is when individual A is looking at B, but the focus of their attention is elsewhere, see Figure I2.1 (Emery, 2000). Gaze following is when individual A detects that B's gaze is not directed towards him/her and follows the gaze direction of B onto a point in space, see Figure I2.2 (Emery, 2000). Joint Attention (JA) is similar to gaze following except that the focus of attention of B is directed to a goal (such as a plate of food), so A is also looking at the same object of B, see Figure I2.3 (Emery, 2000). Adding to the complexity, shared attention is a combination of eye contact and joint attention where individuals A and B each have knowledge of the direction of the other individual's attention, see Figure I2.4 (Emery, 2000). Finally, theory of mind probably uses a combination of the previous 1-4 attentional processes, and higher-order cognitive strategies (including experience and empathy) to determine that an individual is attending to a particular stimulus because they intend to do something with the object (e.g. individual B is hungry and wants to eat the food), or believe something about the object (e.g. individual B believes that this plate belongs to a colleague), see Figure I2.5 (Emery, 2000).

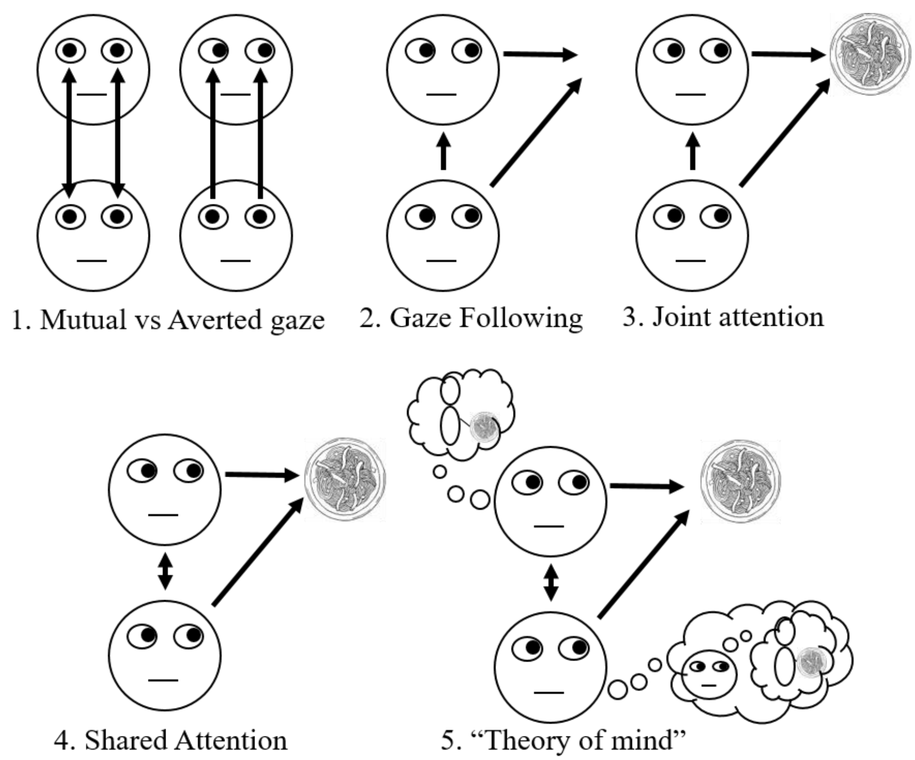

Figure I2 Processes related to social cues provided by gaze direction, redrawn from Emery (2000).

Given the pivotal role of eyes in everyday social interactions, humans are very sensitive in detecting others’ gaze direction (Anstis, Mayhew, & Morley, 1969; Gibson & Pick, 1963). Human’s sensitivity toward gaze direction is further supported by electrophysiological and neuropsychological evidence indicating the existence of specific brain regions dedicated to detecting gaze, like the Superior Temporal Sulcus (STS; Allison, Puce, & McCarthy, 2000; Hoffman & Haxby, 2000; Perrett et al., 1985). For example, STS is activated in response to averted gaze with static faces (Hoffman & Haxby, 2000), dynamic face stimuli (Hooker et al., 2003; Puce et al., 1998) but also in response to averted eyes viewed in isolation without the presence of the face (Puce, Smith, & Allison, 2000). Additionally, STS is modulated by the context of the directional information. For example, neural activity in STS is increased in response to meaningful gaze shifts compared with other gaze shifts (Hooker, Paller, Gitelman, Parrish, Mesulam, & Reber, 2003) as well as for gaze shifts directed to an object compared to an empty space (Pelphrey, Singerman, Allison, & McCarthy, 2003; for a review on gaze cueing of attention see Frischen, Bayliss, & Tipper 2007). Moreover, STS is reciprocally connected with brain areas associated to spatial attention, e.g. parietal cortex associated with orienting of attention (Harries & Perrett, 1991; Rafal, 1996) and intra-parietal sulcus (IPS) associated with spatial processing and covert orienting of attention (Corbetta, Miezin, Shulman, & Petersen, 1993; Nobre, Sebestyen, Gitelman, Mesulam, Frackowiak, & Frith, 1997). Through these connections, spatial attention systems act on the output of systems related to gaze direction discrimination and initiate orienting of attention in the corresponding direction (Bayliss, Bartlett, Naughtin, Kritikos, 2011). Among the various social signals suggested by Emery (2000), engaging to eye contact and joint attention forms a crucial foundation for the emerging skills of more complex social interactions (Jones, Gliga, Bedford, Charman, & Johnson, 2014, Striano, & Reid, 2006, Baron-Cohen, 1991, Brooks & Meltzoff, 2005; Morales et al., 2000).

1.2.1 The eye contact effect in social cognition research

Within few days after birth, infants are sensitive to eye contact and would look for a longer period of time a face with direct gaze rather than one with averted gaze or closed eyes (Farroni, Csibra, Simion & Johnson, 2002; Batki, Baron-Cohen, Wheelwright, Connellan, & Ahluwalia, 2000). Two month old human infants prefer to look at the eyes than to other regions of the face (Hainline, 1978; Haith, Bergman & Moore, 1977). Already by four months old, they can discriminate between direct and averted gaze (Johnson & Vecera, 1993; Vecera & Johnson, 1995) and show enhanced neural processing of eye contact (Farroni, Csibra, Simion, & Johnson, 2002).

In adults, the eye contact has an impact on a wide range of cognitive processes, including memory and attention (for reviews see Macrae, Hood, Milne, Rowe, Mason, 2002; Hamilton, 2016; Senju, Johnson; 2009). Relevant to the current thesis, I will focus on the impact of eye contact on attention only, which has been investigated by evaluating both covert (through manual responses) and overt orienting of attention (through oculomotor parameters), confirming that eye contact can shape attentional mechanisms. For example, direct gaze seems to have a special capacity to capture attention, which has been shown in several studies using the visual search paradigm (Böckler, van der Wel, & Welsh, 2014; Conty, Tijus, Hugueville, Coelho, & George, 2006; Doi, Ueda, & Shinohara, 2009; Palanica, & Itier, 2011; Senju, Hasegawa, & Tojo, 2005; Von Grünau, & Anston, 1995; for a critical view, see Cooper, Law, & Langton, 2013). In these studies, direct gaze captures attention in the sense that participants can locate faces with direct gaze faster and more accurate compared to targets picturing other gaze directions. Moreover, Dalmaso et al. found a greater saccadic curvature (indirect evidence of attention capture) in response to faces with open eyes acting as distractors compared to closed eyes or scrambled faces (Dalmaso, Castelli, Scatturin, & Galfano, 2017b). Direct gaze also seems to hold attention compared to other gaze directions, as disengaging from a face with direct gaze has been found to be slower than from faces with averted gaze (Senju & Hasegawa, 2005), and faces with direct gaze are looked at longer than faces with averted gaze (Palanica & Itier, 2012; Wieser, Pauli, Alpers, & Mühlberger, 2009). For example, Senju and Hasegawa presented a face on a screen with different gaze directions (direct, averted, closed eyes) followed by a peripheral target. Reaction times (RTs) for target detection were slower for direct gaze compared to averted gaze or closed eyes, suggesting that eye contact delayed attentional disengagement from the face (Senju & Hasegawa, 2005). In a modified version of Senju paradigm, Dalmaso et al. found that saccadic peak velocities to a peripheral target were lower in the presence of faces exhibiting direct gaze (reflecting attentional-holding) compared to faces with closed eyes (Dalmaso, Castelli, & Galfano, 2017a). Similarly, Ueda et al. have shown that gaze shift from averted to direct gaze (making eye contact) led to slower saccades to peripheral targets compared to gaze shifts from direct to averted gaze (breaking eye contact) (Ueda, Takahashi, & Watanabe, 2014). On the other hand, opposite to the “eye contact effect” (Senju & Hasegawa, 2005), Hietanen et al. found faster responses to a peripheral target (visuospatial discrimination task) and Stroop stimuli (selective attention) when a live confederate established eye contact with them compared to when s/he did not. They explained their results in terms of increased autonomic activation to the presence of live eye contact (see Conty, George, & Hietanen, 2016).

1.2.2 Joint attention in social cognition research

Although eye contact is crucial for sharing reciprocally affect and emotions with others (Striano, & Reid, 2006), the main boost in social-cognitive development arises when infants start engaging in joint attention. Despite the early sensitivity to the other’s gaze direction (Farroni, Massaccesi, et al., 2004;Hood, Willen, & Driver, 1998), it is only towards the end of the first year that infants use the others’ gaze direction to orient their attention reliably and flexibly (Scaife and Bruner, 1975; Flom & Pick, 2005; Brooks & Meltzoff, 2005). Effective attentional orienting constitutes the foundation for subsequent communication and cultural learning (Bruner, 1975, Cole, 1996; Rogoff, 1990), while it is essential for language acquisition, imitation (Baldwin & Moses, 2001; Brooks & Meltzoff, 2005; Morales et al., 2000) and theory of mind (Baron-Cohen, 1991; Charman et al., 2000).

In order to experimentally investigate gaze-mediated attentional mechanisms, variations of Posner’s spatial cueing paradigm (Posner, 1980) have been developed and extensively employed (Driver et al., 1999; Friesen & Kingstone, 1998; for a review see Frischen, Bayliss, & Tipper, 2007). In the original version of this paradigm (Posner, 1980), covert attentional orienting was examined with respect to peripheral cues, such as a flash of light (triggering an exogenous orienting of attention) or central symbolic cues, such as arrows (triggering an endogenous orienting of attention). Studies examining the automaticity level of exogenous and endogenous orienting of attention suggest that peripheral cues trigger an automatic or reflexive shift of attention, while central cues trigger a voluntary shift of attention (Jonides, 1981; Müller & Rabbitt, 1989). In the gaze-cueing paradigm, a face is initially presented at the center of the screen with a direct gaze. Subsequently, the gaze is presented averted towards one side of the screen (left or right). After a specific time window, i.e., stimulus-to-onset ansychrony (SOA), a target appears at the same (validly-cued) or the opposite location (invalidly-cued), see Figure I3 for a classical gaze-cueing procedure. The typical finding of these paradigms is that RTs in target detection or discrimination are faster to validly-cued targets compared to invalidly ones, reflecting a gaze-cueing effect (GCE). One of the first attempts to investigate this phenomenon constitutes the gaze-cueing study with schematic faces and various SOAs conducted by Friesen and Kingstone (Friesen & Kingstone, 1998). Although the gaze was uninformative of the target location, results showed that RTs were faster in valid trials compared to invalid or neutral trials (keeping a direct gaze), thereby resembling exogenous attention for the following reasons: i. Rapid emergence (105-msec cue–target SOA) of the effect in two conditions (Cheal & Lyon, 1991), ii. Occurrence of GCE independent of the non-predictive cue (Jonides, 1981), iii. fade-outs of the effect after a relatively short period (disappearing by the 1,005-msec cue–target SOA) (Müller & Rabbitt, 1989), iv. Facilitation effect without costs (Posner & Snyder, 1975). Further evidence in favor of the reflexive nature of GCE comes from the study of Driver et al. (1999). Despite the use of a counter-predictive gaze cue (Experiment 3, 20% validity) participants' attention was guided by the cue (but only with an SOA of 300 ms) indicating that gaze cues cannot be suppressed. Additionally, Law et al. showed that GCE seems to be intact to task load (Law, Langton, and Logie, 2010) similarly to exogenous orienting of attention (Jonides, 1981).

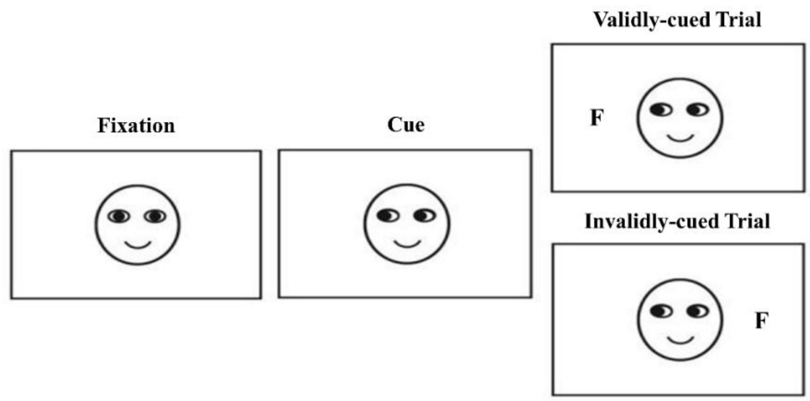

Figure I3. Example of classical joint attention paradigm: gaze-cueing paradigm with schematic faces (adapted from Friesen & Kingstone, 1998; Frischen et al. 2007).

Despite similarities in orienting of attention triggered by central gaze cues and peripheral cues, there also important differences. First, GCE is found at around 1000 ms of SOA, while the cueing effect obtained from exogenous cues results in a reverse effect (facilitation for invalid cues compared to valid cues) for SOAs longer than 250-300 ms, giving rise to the Inhibition of Return (IOR, Maylor, 1985)[1]. In contrast, gaze cues produce IOR at gazed-at locations only after around 2400 ms. Second, unlike peripheral cues but similar to central cues (endogenous orienting of attention), gaze-mediated orienting of attention is susceptible to modulation of top-down processes such as task goals (Ricciardelli, Carcagno, Vallar, & Bricolo, 2013), social or physical characteristics of the gazer (Ciardo, Marino, Actis-Grosso, Rossetti, & Ricciardelli, 2014; Bonifacci, Ricciardelli, Lugli, & Pellicano, 2008; Ohlsen, van Zoest, & van Vugt, 2013; Pavan, Dalmaso, Galfano, & Castelli, 2011; Dalmaso, Pavan, Castelli, & Galfano, 2012), context (Perez-Osorio, Müller, Wiese, & Wykowska, 2015; Wiese, Zwickel, & Müller, 2013), beliefs about the agency (Wiese, Wykowska, Prosser, & Muller, 2014; Cole, Smith, & Atkinson, 2015). Taken together, gaze-mediated attentional orienting bears similarities to both endogenous and exogenous orienting of attention, thereby suggesting a dual-component model of attentional orienting (Wiese, Zwickel, Müller, 2013). That is, in addition to a bottom-up component, gaze-mediated

[1] Inhibition of Return is a mechanism that inhibits attention to a cued location after a certain period of time in order to encourage reallocation of attention to novel locations

attentional orienting is susceptible to various factors, like socio-cognitive variables (i.e., gender, age, mind perception), see Figure I4.

Additional to a behavior signature, a neural mechanism underlying the validity effect has been identified as sensory gain control (Mangun, Hillyard, & Luck, 1990; Hillyard, Vogel, & Luck, 1998). Sensory gain control enhances the signal-to-noise ratio for stimuli at attended, compared to other locations (Müller, & Findlay, 1987; Hawkins, et al, 1990). Early sensory P1/N1 components of event related potentials (ERPs) have been identified as the ERP index of the sensory gain control. In more detail, parieto-occipital P1/N1 components have an earlier onset and increased amplitude for stimuli at cued, relative to uncued locations (Mangun, Hillyard, & Luck, 1993). The sensory gain mechanism has been studied extensively using a variety of procedures designed to modulate spatial attention: exogenous cues (Luck et al., 1994), central cueing (Mangun, & Hillyard, 1991; Eimer, 1994), sustained attention (Mangun, Hillyard, Luck, 1993), or directional gaze (Schuller & Rossion, 2001).

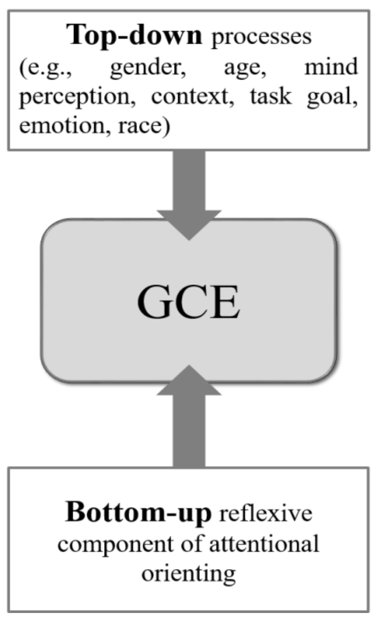

Figure I4. GCE emerges as a result of bottom-up attentional orienting and top-down processes.

Classical gaze-cueing studies advanced substantially the understanding of cognitive and neural mechanisms of joint attention, but by involving pictorial stimuli on the screen they lack the aspect of reciprocity in social interactions and ecological validity. Recently, a new account has been suggested according to which investigating mechanisms of social cognition requires “online” interactive experimental paradigms (Bolis & Schilbach, 2018; Edwards, Stephenson, Dalmaso, & Bayliss, 2015; Risko, Laidlaw, Freeth, Foulsham, & Kingstone, 2012; Risko, Richardson, & Kingstone, 2016; De Jaegher, Di Paolo, & Gallagher, 2010; Schilbach, 2014; Schilbach et al, 2013). Indeed, evidence shows that static social stimuli cannot elicit the same mechanisms of joint attention as more dynamic stimuli (for a review see Risko et al., 2012). First, Hietanen & Leppänen (2003) using static gaze cues found no modulation of emotions (happy, sad, fearful) on GCE. However, Putman and colleagues reported a modulation of complex dynamic emotions on GCE, i.e., larger cueing effect for fearful compared to happy faces (Putman, Hermans, & Van Honk, 2006). This modulation might arise from the difference in emotion processing per se when using dynamic stimuli (Sato, Kochiyama, Yoshikawa, Naito, & Matsumura, 2004; Sato & Yoshikawa, 2007). Importantly, studies have also examined the gaze-cueing paradigm using another human as a central cue, see Figure I5 (upper panel) (Cole, Smith, & Atkinson, 2015, Lachat, Conty, Hugueville, & George, 2012). For example, Cole and colleagues employed a human-human gaze-cueing study and studied the impact of mental state attribution on GCE (Cole, Smith, & Atkinson, 2015). The results showed a GCE independent of mental state ascription, i.e., even when the targets were occluded from the agent that performed the gaze-cueing procedure. This finding is in contrast with previous screen-based studies where the GCE was modulated by mental state attribution, i.e., belief regarding whether the central face can or cannot see through a pair of goggles (Teufel et al., 2010). It is worth noting that Cole and colleagues involved a whole head movement as a cue and they found a three times larger GCE compared to traditional screen-based paradigms (see Lachat, Conty, Hugueville, & George, 2012, for a gaze-cueing effect size similar to screen-based, when only eyes are used as a cue). These studies show that more dynamic and naturalistic gaze cues stimuli do not necessarily reveal the same pattern of results compared to static screen-based stimuli.

This finding is also supported by studies that involved the potential for real social interaction, i.e., studies in the “*wild*” (Risko et al., 2012). In this case, evidence suggests that experiments in more naturalistic situations might lead to different results compared to lab-based paradigms. For instance, Gallup and colleagues (Gallup, Chong, & Couzin, 2012) demonstrated that participants reacted differently depending on whether their gaze direction could be (or not) seen by the confederates, i.e., they were more likely to follow confederates' cues when walking on the same direction with them (confederates were not facing them), as compared to walking to the opposite direction (confederates were facing them). Interestingly, when the participants were seen by the confederates, they followed the gaze even less compared to a baseline condition (no gaze cue), see also (Gallup, Hale, Sumpter, Garnier, Kacelnik, Krebs, & Couzin, 2012 for similar results). More direct evidence in support of this view (i.e., the discrepancy between lab-based and real-world interactions) comes from Hayward and colleagues, who compared gaze following between lab-based and real-world situations (Hayward, Voorhies, Morris, Capozzi, & Ristic, 2017). During the real-world interaction paradigm, a confederate shifted his/her gaze on various occasions, while otherwise maintaining eye contact and having an everyday conversation with the participant, see Figure I5 (lower panel). In this part of the experiment, response to joint attention was operationalized as the proportion of confederate's gaze shifts that were followed by the participant. During the laboratory paradigm, participants executed a classical non-predictive gaze-cueing task on a computer screen. In this part of the experiment, overt and covert attentional shifts were measured. Overt shifting was measured as the proportion of gaze congruent fixation breaks, while covert shifting was operationalized as the classical GCE. In both paradigms findings of attentional shifting reflected results in the existing literature. However, there were no reliable associations for shifting functions between lab-based cueing task and the real-world interaction task. The abovementioned studies demonstrate that lab-based experiments might not always mirror key factors of real-life interactions (for a review see Risko et al, 2012).

Figure I5. Examples of novel joint attention paradigms: a human-human gaze-cueing protocol: taken form Lachat et al. 2012 (upper left panel), Cole et al., 2015 (upper right panel), real-world interaction setup: gaze shifting during an everyday conversation: adapted from Hayward et al. 2017 (lower panel).

1.2.3 The eye contact effect on joint attention

Although eye contact has been shown to affect various cognitive processes and states (Hamilton, 2016; Senju & Hasegawa, 2005; Senju & Johnson, 2009), its impact on joint attention has been scarcely studied. However, given the strong communicative content carried by eye contact (Kleinke, 1986), establishing eye contact with your interaction partner might often be a prerequisite to orient his/her attention. For example, imagine a simple everyday scenario where you are attending a party and you would like to communicate to your friend that a person that s/he is interested in has just arrived. Most probably, if your friend is busy talking to other people, you will be waiting until s/he looks at you in the eyes, and only then, you will direct their attention to the person of interest. Preliminary studies show that eye contact is either a prerequisite or facilitates joint attention. In infants, Farroni et al. (Farroni, Mansfield, Lai, & Johnson, 2003) (Experiments 2 and 3) compared infants' sensitivity to an averted gaze being preceded or not by direct gaze. Authors showed that infants were more likely to look to the gazed-at location (i.e., number of saccades towards a target) when averted gaze was preceded by direct gaze. The results indicated that eye contact was a prerequisite to engage the attention of the infants, which was then driven by the direction of the pupil's motion. In adults, Bristow and colleagues found that when a face with direct gaze (social context) preceded a gaze shift, reaction times to detection of shift direction are significantly faster compared to a preceding averted gaze (unsocial context) (Bristow, Rees, & Frith, 2007). The authors explained the result by suggesting that participants' attention was covertly attracted to the social face assisting them in the faster detection of the subsequent shift direction. Moreover, Xu and colleagues showed that a larger GCE followed a supraliminally presented direct gaze in comparison to gaze directed downwards (Xu, Zhang, & Geng, 2018).

Although preliminary studies show that eye contact facilitates joint attention, it is important to note that the impact of eye contact on joint attention has never been examined in online naturalistic protocols. There is evidence, however, that naturalistic paradigms might lead to different results compared to screen-based lab paradigms related to both eye contact and joint attention mechanisms (see paragraphs 1.2.1, 1.2.2). However, experimental paradigms involving a natural interaction with humans carries certain methodological problems. There are various aspects of the interaction that can alter participants' reactions to the examined processes, namely the velocity of the directional movement in cueing procedure (joint attention) or the exact duration and location of the eye contact. These aspects are complicated to replicate, often they are not controlled for, or not mentioned. Real-life protocols suffer from an even higher risk of achieving adequate experimental control and reproducibility. For instance, in additional to cues' controllability and reproducibility, differences in results between live and screen-based cues or between realistic and lab-based paradigms can be partially attributed to the variations in the visual stimuli that participants are exposed to (Gobel, Kim, & Richardson, 2015). Therefore, there is a need to examine social cognition mechanisms by employing protocols that would allow for high ecological validity without compromising the experimental control. For this reason, it is suggested here to use embodied humanoid robots as interaction partners, for their high ecological validity and excellent experimental control. However, to date, studies involving robots to examine the effect of eye contact and joint attention are mostly limited in using classical HRI methodologies.

1.3 Eye contact and joint attention in HRI research

Multiple studies have investigated the role of eye contact in HRI. To begin with, it has been found that people are sensitive to a robot's gaze. For instance, people notice a gaze directed towards them, but not a gaze directed to someone else nearby (Imai, Kanda, Ono, Ishiguro, & Mase, 2002). Additionally, one feels more intensely 'being looked at' with short, frequent glances compared to longer, less frequent stares (Admoni, Hayes, Feil-Seifer, Ullman, & Scassellati, 2013). Moreover, a robot exhibiting eye contact improves its social evaluation, attribution of intentionality and engagement. For example, Yonezawa and colleagues showed that participants judged more favorably and interacted more time with a stuffed animal robot who shows eye contact compared to robots without mutual gaze (Yonezawa et al., 2007). In another study, in which participants were demonstrating a robot how to recognize objects, they spent more time teaching the robot and they evaluated it is as more intentional, compared to a robot with a random gaze (Ito, Hayakawa, & Terada, 2004). Finally, it has been shown that robots with eye contact can capture the attention and initiate successfully a conversation (Satake et al., 2009). The social context of the conversation can also shape the effect of eye contact. Along this line, it has been found that a robot with eye contact was judged as more sociable and intelligent compared to a robot with gaze avoidance when it replied to a neutral question, whereas the opposite effect held for an embarrassing topic (Choi, Kim, & Kwak, 2013). Additionally, in persuasive conversation, eye contact improved a robot's persuasiveness (Ham, Cuijpers, & Cabibihan, 2015).

The majority of HRI studies on joint attention have focused on examining the impact of evoking joint attention on the quality of HRI, e.g. perceived pleasantness, task performance. It has been shown that a robot with joint attention mechanisms (e.g. responding by gazing to objects pointed to or talked about by participants) facilitates participants' task performance (Boucher et al., 2012; Huang & Thomaz, 2011; Mwangi, Barakova, Díaz-Boladeras, Mallofré, Rauterberg, 2018). For example, Boucher and colleagues (2012) employed a collaboration task in which participants were asked to select an object as quickly as possible based on the robot's instructions. Adding joint attention capabilities to the robot during the instruction phase (head and gaze directional cues) significantly improved participants' performance in the task. Additionally to facilitating participants' task performance, a robot with joint attention mechanisms was also perceived as more competent and socially interactive (Huang & Thomaz, 2011; Mwangi, Barakova, Díaz-Boladeras, Mallofré, Rauterberg, 2018).

Studies in eye contact and joint attention with classical HRI methodologies are informative regarding the impact of robot's behaviors on the quality of HRI. However, they lack a systematic approach, e.g. not mentioning parameters of robot's movements that could affect joint attention (Boucher et al., 2012; Huang & Thomaz, 2011; Mwangi, Barakova, Díaz-Boladeras, Mallofré, Rauterberg, 2018), or not including adequate sample sizes (Boucher et al., 2012). Furthermore, these studies cannot target specific components of human cognition that are at stake during the interaction and could be responsible for improving HRI quality. Therefore, such paradigms do not always contribute to the theoretical basis of social cognition.

Although the use of robot agents in classical HRI research cannot advance the theoretical knowledge of social cognition mechanisms, employing embodied humanoid agents in interactive protocols that are grounded in cognitive neuroscience methods comprises a promising avenue. To date, embodied humanoid agents have only been scarcely used in joint attention protocols grounded in cognitive science methods. For example, Wykowska et al. using a gaze-cueing paradigm with embodied iCub robot demonstrated that the GCE was not modulated by whether participants believed that iCub's behavior was 'human-controlled' or 'programmed'. This result is in slight contrast to previous studies with screen-based robot stimuli, where the authors showed that the same robot face elicited a GCE dependent on whether participants believed its behavior was pre-programmed or human-controlled (Wiese, Wykowska et al., 2012). Therefore, similar to human-human studies in joint attention research, humanoid-based protocols also show that an embodied robot might not reveal the same pattern of results compared to screen-based robot stimuli. Related to the eye contact effect, to date, no studies have addressed this topic using a structured and systematic psychology-inspired paradigm with humanoid robots.

1.4 Rationale of the project

Research presented in this PhD work aims to show that employing humanoid-based protocols can advance both social cognition and classical HRI research. This approach is demonstrated by targeting a specific process related to joint attention that is difficult to address using classical social cognition methodologies; that is the influence of online eye contact on gaze-mediated orienting of attention. Although establishing eye contact is a strong social communicative signal for human interactions (Kleinke, 1986), classical studies in social cognition research addressed the effect of eye contact on GCE using screen-based gaze stimuli (see paragraph 1.2.3), due to the need for high degree of experimental control. However, it has been shown that an online eye contact can elicit different neural, physiological and behavioral responses compared to pictorial gaze stimuli (EEG asymmetry: Hietanen, Leppänen, Peltola, Kati & Heidi, 2008; EEG symmetry, skin conductance response: Pönkänen, Peltola & Hietanen, 2011; reaction times: Hietanen, Myllyneva, Helminen, & Lyyra, 2016). Therefore, it is worth examining how the establishment of real-time eye contact with a live interaction partner could affect the processing of following social cues and thus modulate attentional orienting.

To this end, a 3-D novel gaze/head cueing paradigm is employed, in which the iCub humanoid robot is positioned between two computer screens, on which target letters appear, see Figure I6. To investigate the impact of eye contact on gaze cueing, the gaze of the robot before shifting to a potential target location is manipulated. In one condition, iCub looks towards participants' eyes, establishes eye contact with them, and then looks at one of the lateral screens. In the other condition, the robot avoids the human's gaze by looking down before looking toward one of the lateral screens. The first two studies, reported in Publication I and Publication II, systematically examine the impact of eye contact on the gaze-cueing effect depending on the cue validity and the SOA. In the following studies, reported in Publication III and Publication IV, the effect of eye contact is examined using both explicit and implicit measures but still embedded in a gaze-cueing paradigm.

Figure I6. Example of a novel protocol to study joint attention using a humanoid robot

Publication I

The first study of the PhD thesis, reported in Publication I, aims to implement a well-studied joint attention paradigm of cognitive neuroscience research in an HRI protocol involving the iCub robot. The main goal is to validate the protocol by replicating documented results in gaze-cueing studies both at behavioral (i.e., faster RTs to cued relative to uncued targets) and neural levels (i.e., enhanced event related potentials of the EEG signal for cued relative to uncued targets). Furthermore, this study investigates whether GCE is sensitive to different manipulations of the gaze direction prior to the gaze-cueing procedure. To this end, before shifting its gaze, iCub either looks straight towards participants' eyes (eye contact condition) or downwards (no eye contact gaze condition)[2]. The validity of the gaze direction is not informative with respect to the subsequent target location (validity = 50%) and the SOA is relatively short for a naturalistic gaze-cueing procedure (SOA = 500 ms), thereby providing the most neutral, unbiased gaze cueing procedure.

Publication II

The aim of the study reported in Publication II (Experiment 1 and Experiment 2) is to examine whether online eye contact modulates the GCE depending on the validity of the cue and the SOA. Similar to the study in Publication I, a gaze-cueing paradigm is employed,

[2] In Publication I the gaze conditions are named as following: eye contact is named as straight-ahead and no eye contact is named as down gaze.

where iCub either establishes eye contact and then gazes to one of the screens (eye contact condition), or it looks down without establishing eye contact (no eye contact condition). This time, however, the manipulation of straight-forward vs. downwards gaze of iCub is enhanced by a face detection algorithm, which allows the humanoid robot to online detect the participants' eyes and establish real-time eye contact with them. In Experiment 1 of Publication II, the validity of the gaze direction is non-predictive with respect to the subsequent target location (validity = 50%) and the SOA is relatively long (SOA = 1000 ms). Given the increased potential to engage in an interaction initiated by an online eye contact, and similar to previous findings (Bristow, Rees, & Frith, 2007; Xu, Zhang, & Geng, 2018), it is hypothesized that the social top-down component of eye contact might enhance the gaze-related attentional orienting (i.e., larger GCE in eye contact compared to no eye contact condition). Experiment 2 of Publication II aims to examine how the top-down social component engaged by the eye contact would interact with the top-down strategic component to modulate the reflexive component of gaze-mediated attentional orienting. To this end, in Experiment 2 the gaze-cueing procedure is counter-predictive (validity = 25 %) and the SOA is shorter (SOA = 500 ms). The question of interest is whether the top-down social component of eye contact would engage participants in suppressing the unnecessary orienting of attention even when the time for top-down control over reflexive processes is limited (short SOA).

Publication III

The aim of the study presented in Publication III (Experiment 1 and Experiment 2) is to examine how a humanoid robot is evaluated by participants, depending on established eye contact or not. Similar to previous studies, the manipulation of eye contact is embedded in a gaze-cueing procedure. The predictivity of the gaze is altered between experiments to create two types of "social context", i.e., a 1) non-predictive (Experiment 1) and 2) a counter-predictive referential gaze (Experiment 2). The sensitivity to eye contact, the engagement level and the attribution of human-likeness are examined through the collection and analysis of subjective reports.

Publication IV

The final study, presented in Publication IV aims to investigate how eye contact established by a humanoid robot can affect participants' engagement by comparing implicit (i.e, joint attention, gaze fixation patterns) and explicit measures (i.e., subjective evaluations). To this end, a similar gaze-cueing paradigm to Publication II-Experiment 1 is employed (i.e., validity = 50 %, SOA = 1000 ms) combined with an eye-tracking methodology to investigate the patterns of fixations on the robot face in the context of eye contact and no eye contact. The engagement level with the robot is also measured through subjective reports. Apart from a comparison between explicit and implicit measures of engagement, this study provides insights to cognitive mechanisms that could be responsible for the modulatory effect of eye contact on GCE.

All studies reported here have been published, and Publication I - Publication IV consist in accepted version of manuscripts, respectively.

Publication I is constituted by a manuscript of the paper: "Kompatsiari, K., Pérez-Osorio, J., De Tommaso, D., Metta, G., & Wykowska, A. (2018, October). Neuroscientifically-grounded research for improved human-robot interaction. *In 2018 IEEE/RSJ International Conference on Intelligent Robots and Systems* (IROS) (pp. 3403-3408). IEEE".

Publication II is the manuscript of the paper: "Kompatsiari, K., Ciardo, F., Tikhanoff, V., Metta, G., & Wykowska, A. (2018). On the role of eye contact in gaze cueing. *Scientific reports*, 8(1), 17842".

Publication III constitutes the manuscript of the paper "Kompatsiari, K., Ciardo, F., Tikhanoff, V., Metta, G., & Wykowska, A. (2019). It's in the Eyes: The Engaging Role of Eye Contact in HRI. *International Journal of Social Robotics*, 1-11".

Publication IV is the manuscript of the paper: "Kompatsiari, K., Ciardo, F., de Tommaso D., & Wykowska, A. (accepted, 2019). Measuring engagement elicited by eye contact in Human-Robot Interaction. *In 2019 IEEE/RSJ International Conference on Intelligent Robots and Systems* (IROS), Macau. IEEE".

PUBLICATIONS

2.1. Publication I: Neuroscientifically-grounded research for improved human-robot interaction

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2.1.1 Abstract

The present study highlights the benefits of using well-controlled experimental designs, grounded in experimental psychology research and objective neuroscientific methods, for generating progress in human-robot interaction (HRI) research. More specifically, we aimed at implementing a well-studied paradigm of attentional cueing through gaze (the so-called "joint attention" or "gaze cueing") in an HRI protocol involving the iCub robot. Similarly to documented results in gaze-cueing research, we found faster response times and enhanced event-related potentials of the EEG signal for discrimination of cued, relative to uncued, targets. These results are informative for the robotics community by showing that a humanoid robot with mechanistic eyes and human-like characteristics of the face is in fact capable of engaging a human in joint attention to a similar extent as another human would do. More generally, we propose that the methodology of combining neuroscience methods with an HRI protocol, contributes to understanding mechanisms of human social cognition in interactions with robots and to improving robot design, thanks to systematic and well-controlled experimentation tapping onto specific cognitive mechanisms of the human, such as joint attention.

2.1.2 Introduction

The advanced technological capabilities of robotic systems bear a promise of integration of robots in society in the role of companion and/or assistive technology. This, however, calls for intensified research in Human-Robot Interaction (HRI), as integration into society means not only that the robots need to have advanced skills, but also that the humans shall feel comfortable with their future social interaction partners. Therefore, to understand how the human brain reacts to the robot's social presence, and how it processes information conveyed by a robotic agent, it is crucial to employ (neuro-) scientific methods and experimental designs that would bring valid, reproducible and generalizable results to HRI research (Bartneck, Kulić, Croft, Zoghbi, 2009; Bethel & Murphy, 2010). Two common present limitations of HRI consist in often relatively small number of test persons, and the lack of experimental protocols where specific mechanisms of the human cognition are targeted systematically with the use of neuroscientific methods, or methods of experimental psychology (Bethel & Murphy, 2010; Wiese, Metta, & Wykowska, 2017). Drawing from psychological or social sciences, Bethel et al. proposed guidelines for human studies methods in HRI, using combination of various measures such as self-assessments, interviews, behavioral measures, psychophysiology measures, and task performance metrics (Bethel & Murphy, 2010). However, most evaluations of robotic systems by human users consist in self-assessments and behavioral methods (Bethel & Murphy, 2010), and they often lack systematicity (Wiese, Metta, & Wykowska, 2017). In general, even when other measures are included, the studies lack proper adaptation of psychological paradigms, experimental control, or statistical power in the sample.

A. Investigating Joint Attention in HRI

Here, we focus on one specific experimental paradigm (attentional cueing), which targets a fundamental mechanism of social cognition, namely joint attention (JA). JA occurs when two individuals share their focus on the same object/event, creating a triadic interaction between the self, the other person and the object/event of interest (Moore, 2014). It constitutes a basis for higher-level mechanisms of human communication (Emery, Lorincz, Perrett, Oram, & Baker, 1997; Grossmann & Johnson, 2010; Tomasello, 2010; Moore, 2014). JA has been extensively studied in cognitive science using gaze-cueing paradigms (Friesen & Kingstone, 1998; Driver et al., 1999; Frischen, Bayliss, & Tipper, 2007). Traditionally, in such paradigms, a face is presented centrally on a computer screen, and then its gaze is shifted towards a location on the screen. Subsequently, a target appears at the gazed-at location (validly-cued target) or at the opposite location (invalidly-cued target). Response times (RTs) for detection or discrimination of validly-cued targets are typically faster than for the invalidly-cued targets, a phenomenon termed as the gaze-cueing effect (GCE). This is explained in terms of attentional orienting: when the gaze of the centrally presented face stimulus shifts towards a location, attentional focus of the observer moves to that location as well, and therefore processing sensory information at that location is facilitated, as compared to a situation when attentional focus needs to be switched to a location that has not been attended (i.e., it has not been cued by the gaze direction). Interestingly, in case of directional cues provided by gaze, orienting of attention appears to be reflexive, as the validity effect occurs even when the gaze is not informative with respect to target location, or is even more likely to cue invalidly (Friesen & Kingstone, 1998; Driver et al., 1999).

Although the gaze-cueing effects have been long investigated in cognitive psychology with the use of stimuli on computer screens, implementations of the gaze cueing paradigm in more naturalistic HRI scenarios have been scarce, and results have not been entirely consistent. On the one hand, a study by Admoni et al., examining the effect of anthropomorphism on GCE, showed that directional gaze of two different robots did not elicit reflexive GCE (Admoni, Bank, Tan, Toneva, & Scassellati, 2011). Similarly, Okumura et al. demonstrated that human gaze towards a location elicited anticipatory gaze shifts of 12-year-old infants, while robots gaze did not have the same effect (Okumura, Kanakogi, Kanda, Ishiguro, & Itakura, 2013). On the other hand, Wiese, Wykowska et al. showed that a robot face induced a GCE, but to a smaller extent compared to a human face (Wiese, Wykowska, Zwickel, & Müller, 2012). Furthermore, in a gaze-cueing paradigm involving an embodied humanoid agent (the iCub robot (Metta et al. 2010)), Wykowska et al. showed GCE, independent of whether participants perceived behavior of the robot as human-like or more mechanistic (Wykowska, Kajopoulos, & Ramirez-Amaro, 2015). In the light of these somewhat mixed results, we proceeded to investigate and later implement human-like gaze behavior on the iCub robot, with the use of neuroscience methods. Our measure of success is whether the robot elicits the same behavioral and neural responses of a human interaction partner.

B. Aim of study

The aim of the present study was to examine whether the behavioral responses (reaction times) and neural correlates (EEG) typically observed on the gaze-cueing paradigm could be observed also in an HRI setup. This posed a substantial challenge, given that the experimental paradigm needed to be adapted to a naturalistic interaction with an embodied robot, while EEG, behavioral measures, stimulus presentation and robot behaviors needed to be integrated in one setup, and synchronized with excellent temporal resolution.

In addition, we aimed at examining how reflexive/ automatic is the gaze-cueing effect in an interactive HRI setup. That is, whether GCE occurs although the validity of the gaze direction (50%) is not informative with respect to subsequent target location, and whether GCE is stable across different manipulations of the gaze direction prior to the gaze-cueing procedure. In more detail, we introduced two conditions prior to the shift of gaze to one of the potential target locations. In one condition, the robot gazed straight ahead (similarly to standard design in experimental psychology), and in another, it looked down (cf. Table 1). We were interested in whether GCE would be observed not only in a typical scenario of the agent gazing straight ahead, but also in a slightly different condition, namely when the robot looks down prior to gazing to one of the sides.

C. Motivation

Replicating the GCE and its neural correlates in a realistic HRI paradigm constitutes a good example of linking cognitive neuroscience with robotics (Wykowska, Chaminade, & Cheng, 2016). This approach is grounded in cognitive neuroscience due to implementation of a classical gaze-cueing paradigm and the use of neuroscience methods, while its anchoring in robotics occurs through the use of the humanoid robot iCub in an HRI setting. The results are of significant contribution to both fields of research. In social/cognitive neuroscience, this approach allows for examining the mechanisms of social cognition in ecologically valid, yet well-controlled experimental protocol. Humanoid robots, being embodied agents, increase the naturalness of interaction due to their social presence and sharing joint environment, for reviews on the use of embodied robot to studying human cognition see (Wykowska, Chaminade, & Cheng, 2016; Wiese, Metta, & Wykowska, 2017; Admoni & Scassellati, 2017). At the same time, using a humanoid robot rather than another human interaction partner allows for excellent experimental control, as the robot's behavior can be modified in a controlled and modular way, allowing for a systematic investigation of the impact of subtle behavioral cues on social cognitive mechanisms of humans (Sciutti, Ansuini, Becchio, & Sandini, 2015). Furthermore, a robot can reproduce the exact same behavior over many trials of an experiment – a task impossible for a human.

In terms of contribution to robotics, such approach allows for targeting very specific and well-isolated components of human cognition that are at service during interaction with humanoid robots. This should enable progress in designing robots that are well tuned to the workings of the human brain. Only through understanding such well-defined and specific processes of the human brain, will we be able to target them with an adequate design of robot behavior and appearance. To give an example, if our aim is to design robots that are to assist in therapy for children with autism spectrum disorder (ASD), the best strategy is to understand what specific cognitive mechanisms we are aiming to address (responding to or initiating JA, spatial perspective taking, mentalizing, etc.), and depending on which of them is the focus of the therapy, a robot's behavior (together with training protocol) can be designed to address specifically that mechanism. If the aim of training (for the specific impairment) is predominantly based on JA, the robot should be engaging a child in JA, but not necessarily be additionally too expressive, as this might be overwhelming for a child diagnosed with ASD. In other words, in order to engage in JA, we need to understand the optimal conditions and isolate behavioral parameters of the robot to evoke JA in the user, presumably reducing other characteristics of the robot (in the case of training specifically JA, it could mean reducing e.g., emotional expressiveness), which could evoke other – perhaps interfering – mechanisms of social cognition (e.g., emotional reactions), unless it is demonstrated experimentally that emotional expressions positively influence JA.

In general, thanks to the methods and approach proposed here, it is possible to isolate specific parameters of the robot's design that are best suited for evoking specific mechanisms of human cognition in an HRI scenario.

D. Experimental Design

In order to replicate JA and its EEG correlates in HRI, we developed a proof-of-concept study with a variation of gaze-cueing paradigm using the embodied humanoid iCub with a 3D experimental setting. We focused the design and later analyses on the event-related potentials (ERPs) of the EEG signal, related to the behavioral GCE. ERP "components" (shortly, ERPs) are obtained by averaging over multiple trials EEG activity locked to a given event in the trial sequence (here, we focus on the event of stimulus onset). ERPs provide information about the time dynamics of the brain, as the peaks and troughs of an ERP waveform (ERP components) reflect cognitive processing, as it unfolds over time. In particular, we focused on the early sensory P1/N1 components, locked to the onset of the target (Schuller & Rossion, 2001). P1 is the first positive-amplitude component around 100 ms post stimulus onset, while N1 is the first negative-amplitude component peaking around 150-200 ms. Both P1 and N1 are related to sensory processing of the stimulus material, and reflect potential attentional modulations of the sensory processes.

ERP correlates of the GCE have been reported on the early sensory P1/N1 components, locked to the onset of the target (Schuller & Rossion, 2001), and reflect the impact of attentional modulation of the sensory gain mechanism (Mangun & Hillyard, 1990; Luck, Woodman, & Vogel, 2000), which is thought to increase the signal-to-noise ratio (SNR) for stimuli at attended locations, relative to other locations (Müller & Findlay, 1988; Hawkins et al., 1990). In more detail, parieto-occipital P1/N1 components have an earlier onset and increased amplitude for stimuli at cued, relative to uncued locations (Mangun, Hillyard, & Luck, 1993). While the P1 component reflects a perceptual suppression for ignored locations, the N1 indexes enhanced discriminative processing of stimuli within the focus of attention (Hillyard, Vogel, & Luck, 1998; Luck, Woodman, & Vogel, 2000). Fedota et al. suggest that the N1 effect also reflects top-down modulation of discriminative processing in areas of the ventral visual stream (Fedota, McDonald, Roberts, & Parasuraman, 2012), which is in line with evidence also in more social contexts (Wykowska, Wiese, Prosser, & Müller, 2014; Perez-Osorio, Müller, Wiese, & Wykowska, 2015). In summary, for the purposes of our study, we focus on the P1/N1 components to understand if the iCub robot is capable of inducing similar attentional mechanisms as another human would do, in a social interaction setup. If the robot were to be perceived akin to a human, then we would expect to find a gaze cue-related modulation of the P1/N1 complex locked to target onset in a (e.g. a letter) discrimination task embedded in an interactive HRI protocol.

2.1.3 Methods

A. Participants

To define the sufficient statistical power of our sample, we conducted an a-priori power analysis (Faul, Erdfelder, Lang, & Buchner, 2007) for the validity effect, using (i) the effect size (dz= 0.7) calculated from a previous study of a similar setup with iCub and a gaze-cueing procedure (Wykowska, Kajopoulos, & Ramirez-Amaro, 2015), (ii) an alfa error equal to .05, and (iii) a power level of .85. This analysis yielded an adequate sample size of 21. In total, 24 healthy right-handed (self-reported handedness) volunteers (mean age = 26.16 ± 4.02, 16 women) were recruited and reimbursed for their participation. 3 of the initial participants were excluded due to artefacts higher than 30%. All had normal or corrected-to normal vision and provided their informed written consent prior to participation. The data were collected at the Istituto Italiano di Technologia, IIT, Genova. The study was approved by the local ethical committee (Comitato Etico Regione Liguria).

B. Stimuli and Apparatus

The experiment was performed in an isolated and noise-attenuating room. Participants were seated in front of a desk, 125 cm away from the robot. iCub's eyes were aligned with participants' eyes at 122 cm from the floor. Two screens, used for stimulus presentation (27 inches), were positioned laterally on the desk (75 cm apart centre-to-centre) at a distance of 105 cm from the participant's nose apex. The screens were slightly tilted back (by 12° with reference to the vertical position) and were rotated to the right (right screen) or left (left screen) by 14° with reference to the lateral position, see Figure 1. The target stimuli were letters V or T (3° 32' high, 4° 5' wide, the degrees of stimuli refer to visual angle from the human perspective). iCub was looking at five different locations during the experiment: (1) "rest" – towards a point between the desk and participants' body, (2) "straight-ahead" gaze – towards participants' eyes, (3) "down" – towards the table, (4) "left" – towards left screen, and (4) "right" – towards right screen (exact xyz coordinates (in m) are provided in Table 1, measured from the robot frame of reference, i.e., waist).

iCub moved both its eyes and its neck to indicate the respective screen. The eyes and the neck of iCub were controlled by the YARP Gaze Interface, iKinGazeCtrl (Roncone, Pattacini, Metta, & Natale, 2016). The vergence of the robot's eyes was set to 5 degrees and maintained constant. The trajectory time for the movement of eyes and neck was set to 200 ms and 400 ms respectively, to maintain the impression of a smooth and naturalistic movement. iCub's movements, triggers sent to the EEG recording system, presentation of stimuli, and data collection were controlled in OpenSesame (an open-source, graphical experiment builder for social sciences) (Mathôt, Schreij, & Theeuwes, 2012) in combination with the iCub middleware YARP (Yet Another Robot Platform) (Metta, Fitzpatrick, & Natale, 2006), using the Ubuntu 12.04 LTS operating system.

Table 1. Positions of robot gaze (measures in m)

Positions of robot gaze	x	y	z
Rest	-0.78	0.0	0.16
Down	-0.78	0.0	0.04
Left	-0.78	-0.35	0.16
Right	-0.78	0.35	0.16
Straight-ahead	-0.78	0.0	0.28

EEG was recorded with Ag-AgCl electrodes from 64 electrodes of an active electrode system (ActiCap, Brain Products, GmbH, Munich, Germany). Horizontal and vertical EOG were recorded bipolar from the outer canthi of the eyes and from above and below the observer's left eye, respectively. All electrodes were referenced to AFz and re-referenced offline to the average of all electrodes. Electrode impedances were kept below 10 kΩ. Sampling rate was 500 Hz, and the EEG activity was amplified with a band-pass filter of 0.1-250 Hz, BrainAmp amplifiers (Brain Products, GmbH).

C. Procedure

The whole session, including EEG preparation, lasted around 2.5 hours. Every trial consisted of the following steps: The trial started with the robot having its eyes closed, see Figure 1A. After 2s, the robot opened its eyes for 500 ms looking at the same position ("rest"), see Figure 1B. Following this delay, iCub looked either down ("down" gaze) or up towards the eyes of the participant ("straight-ahead" gaze), see Figure 1C. The whole duration of this phase was 2s. The experiment was divided on 20 blocks of 16 trials, pseudo-randomly assigned to the "straight-ahead" or "down" condition. Subsequently, the robot shifted to gaze to the left or right screen, see Figure 1D. After 500 ms delay from the initiation of this movement (Stimulus Onset Asynchrony, SOA= 500 ms), the letter V or T appeared on the same or the opposite screen (50% probability) for 200 ms, see Figure 1E. Participants were asked to respond as fast and as accurate as possible to the target identity by pressing the V button with their left hand for V, and the T button with their right hand for T (Group 1), and the opposite stimulus-response mapping for Group 2. The screens remained blank (Figure 1F) until participant's response was executed, and the next trial started with robot closing its eyes at "rest" position. If participants did not respond within 1500 ms, a new trial started, and the participant's response was registered as incorrect. At the end of every block, participants received feedback about their mean reaction time (RT) and accuracy. The order of the gaze blocks (straight-ahead or down) was counterbalanced between participants. The direction of the robot gaze, the identity of the letters and the screen of stimulus presentation were counterbalanced and randomly selected within each block. Participants had a practice session of two blocks (10 trials each) of both gaze conditions but with a random order. Participants had self-paced breaks after every block (1-2 mins), short breaks every 4 trials (3-5 mins) and a longer pause at the middle of the experiment (~10 minutes), in order to reduce fatigue.

D. Analysis

1) Behavioral data

For behavioral data, error trials (4.02%), RTs <100 ms, or 2.5 SDs above- or below an individual's mean for each condition were removed (2.53% of correct trials). We conducted analyses on the correct RTs of target discrimination. In order to determine whether there were any statistically significant differences between the means of the conditions, following standard statistical procedures, a repeated-measures analyses of variance (ANOVA) (Field, 2013) were conducted on mean RTs, with gaze type (straight-ahead, down) and validity (valid, invalid) as within-subjects factors. T-tests were conducted to compare RT means between valid and invalid conditions for the different gaze type conditions.

2) EEG data pre-processing

For the ERP analysis, we first filtered the raw data offline using a 30 Hz high-cutoff filter. Then we averaged the data over 1000-ms epochs including a 200 ms pre-stimulus baseline, time-locked to the target onset. For eye-movement artefacts, we inspected the F10, F9, and Fp1 channels using an automatic artefact-rejection procedure. We excluded trials with eye movements and blinks on either of these channels prior to averaging. Artefacts were defined as any absolute voltage difference in a segment exceeding 50 µV or voltage steps between two sampling points exceeding 80 µV. We also excluded individual channels with other artefacts (all channels considered) if amplitude exceeded ± 80 µV or activity was lower than 0.10 µV for a 100 ms interval. The epochs were baseline-corrected with 200 ms period prior to stimulus onset.

3) ERP analyses of the EEG signal

To examine the ERP correlates of the behavioral gaze-cueing effect, we focused on the P1/N1 components, locked to the target onset. For the P1 and N1 mean amplitude analyses, we selected a time window based on the average latency of the grand-average peak for all conditions over the P3, P4, PO3 and PO4 channels (pooled). For P1, we selected the time window of 105–145 ms (± 20 ms, relative to the peak latency), while for the N1 component we selected the time window of 150–230 ms (± 40 ms relative to the peak latency). For peak latency analyses on the P1/N1 components, we followed analogous procedure (and same time windows) as for the mean amplitude analyses. The mean amplitudes and peak latencies were subjected to separate 2 × 2 repeated-measures ANOVAs with gaze type (straight-ahead vs. down) and validity (valid vs. invalid) as within-subject factors. Planned comparisons (t-tests) were conducted for the valid versus invalid conditions for the different gaze type conditions. Where appropriate, statistics were corrected according to Greenhouse-Geisser for potential nonsphericity.

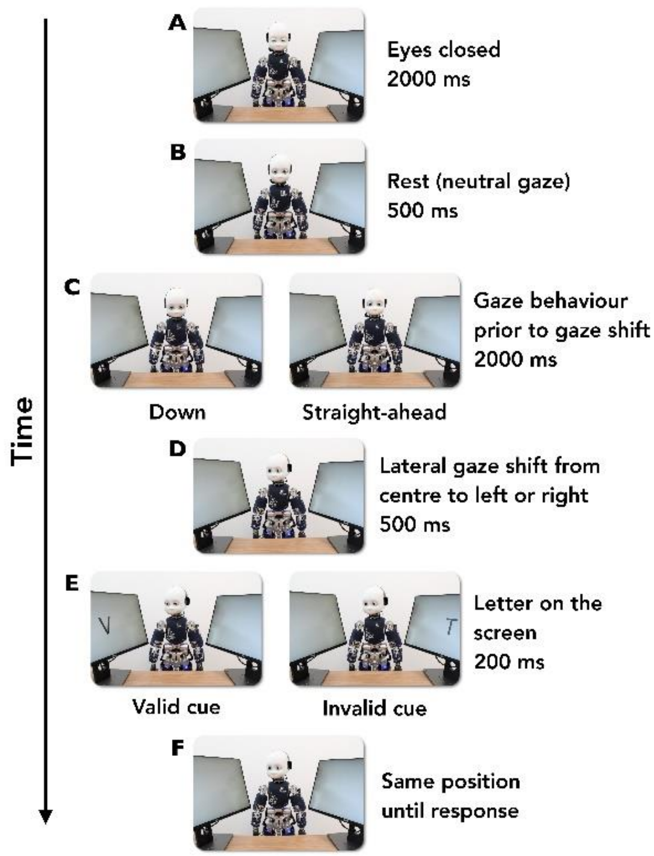

Figure 1. Experimental sequence.

The experiment had 80 repetitions per condition. After rejection of eye movement artefacts and incorrect-response trials, 71 trials (on average) remained in each experimental condition (straight-ahead valid: 70.8, invalid: 70.4; down valid: 72.3, invalid: 70.9). Letter ("V"/"T") and side of presentation (left/right) were averaged together.

2.1.4 Results

A. Behavioral

The 2×2 ANOVA with the factors gaze type (straight-ahead vs. down) and validity (valid vs. invalid) on RTs revealed a significant main effect of validity, F (1, 20) = 34.0, p < .001, η_p^2 =.63. This means that participants followed the gaze of the robot and were faster in valid (Mvalid = 438.05, SEM = 12.11) relative to invalid trials (Minvalid = 452.86, SEM

= 10.88). There was no significant main effect of gaze type, F (1, 20) = 2.85, p = .11, η_p^2 =.12, or interaction, F (1, 20) < 1. This indicates that there was no difference between straight and down gaze condition. However, we conducted pairwise comparisons to evaluate the validity effect within each gaze type condition. These analyses showed significant differences between valid and invalid trials, both in the straight-ahead gaze, t (20) = 4.51, p < .001 (Mvalid = 435, SEM = 10.41; Minvalid = 450.5, SEM = 11.21) and the down-gaze condition, t (20) = 5.21, p < .001 (Mvalid = 441.1, SEM = 11.7; Minvalid = 455.3, SEM = 13.2), cf. Figure 2. This means that participants followed the gaze of the robot in both gaze type conditions.

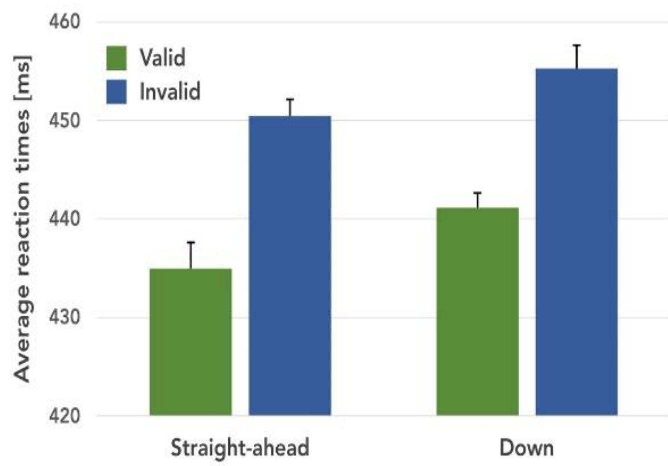

Figure 2. Average RTs. Left: straight-ahead gaze, right: down. Green bars: valid trials, blue bars: invalid trials. Error bars represent standard error of the means adjusted to within-participant designs according to Cousineau (Cousineau, 2005).

B. EEG data

1) P1 component

Analysis of mean amplitudes in the P1 time window between 105–145 ms post-target onset revealed no main effect of validity, F (1, 20) = 1.14, p = .3, η_p^2 = 0.05. There was no significant main effect of gaze type, F (1, 20) = 1.8, p = .19, η_p^2 = 0.08, or interaction, F (1, 20) = 3.89, p = .06, η_p^2 = 0.16. Also, peak latency analyses did not reveal any significant effect or interaction for P1 (p > .25), cf. Figure 3. Thus, results on the P1 component reveal that there was no attentional suppression observed for uncued locations.

2) N1 component

Mean amplitudes in the N1 time window (150-230 ms) post-target onset revealed a main effect of validity, F (1, 20) = 5.21, p = 0.034, η_p^2 = 0.21 (Mvalid = -1.21, SEM = 0.38; Minvalid = -0.92, SEM = 0.43). N1 is a typical EEG correlate of behavioral GCE, and suggests enhanced discriminative processing of stimuli within the focus of attention. There was no main effect of gaze type, F(1, 20) = <1, or interaction, F (1, 20) <1. Peak latency showed main effect of validity, F (1, 20) = 18.33, p<.001, η_p^2 = 0.48 and no interaction, F(1, 20) < 2.6, cf. Figure 3, suggesting that the cued targets evoked not only enhanced processing at the attended location, but that the cued target was also processed faster.

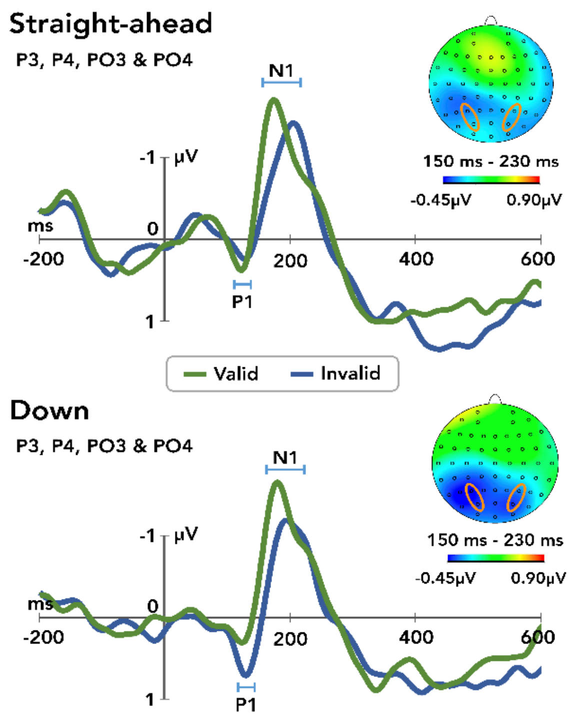

Figure 3. Grand-averaged ERP waveforms time-locked to target onset (left), and voltage distribution of the differential effect (right) for the straight-ahead gaze condition (top) and down condition (bottom). Green lines: validly cued trials, blue lines: invalidly cued trials. Time windows: P1, 115-135 ms; and N1, 150-230 ms. Red ovals mark the electrodes of interest (PO3/4, P3/4)

2.1.5 Discussion

The present study replicated, in an HRI setup the effect of gaze cueing at a neural and behavioral level. GCE is a phenomenon well established in cognitive neuroscience. This study is novel in showing that an embodied humanoid robot with mechanistic eyes and human-like face evokes similar attentional mechanisms as another human would do. The study also served as a proof-of-concept of integrating cognitive neuroscience methods, with an interactive HRI paradigm.

Furthermore, the results showed that the GCE induced by the robot generalize across different types of gaze conditions, namely gaze straight-ahead and gaze-down, prior to directional gaze cueing. It is important to note, however, that this might be the case only under the condition of 50% validity and specific parameters of the experimental design (for example, the length of the SOA). Future research needs to examine all potential factors that might contribute to evoking the GCE in HRI.

In more detail, our results show that reaction times were faster, the N1 ERP component peaked earlier and had higher amplitude on validly cued trials, relative to invalidly cued trials. Faster reaction times in valid, compared to invalid, trials (GCE) indicate that participants engaged in JA with iCub, although the gaze was not predictive of target location. At the neural level, the amplitude and latency effects of the N1 component paralleled the behavioral results, and indicate that processing of stimuli at locations at which attention is focused due to gaze of the robot is enhanced (Hillyard, Vogel, & Luck, 1998). Additionally, an earlier peak of N1 for valid vs. invalid trials indicates that stimuli at the attended trials are processed also faster, perhaps due to a lesser cognitive load (Callaway & Halliday, 1982).

In general, our findings suggest that participants followed the gaze of the robot in a reflexive and automatic manner, regardless lack of predictivity in the gaze and independent of the robot's gaze behavior prior to the directional shifts. This suggest that a humanoid robot iCub in a natural HRI scenario is capable of effectively orienting attention of observers towards the direction of its gaze, similarly to a human agent (Driver et al., 1999). In the context of previous studies (Wiese, Wykowska, Zwickel, & Müller, 2012) which showed reduced GCE for robot faces on the screen, as compared to human faces, this provides a strong evidence that embodiment of a robotic agent plays a crucial role in engaging in JA (Wykowska, Chaminade, & Cheng, 2016).

In general, our study is a prime example of an approach linking neuroscience and robotics in order to establish properly scientifically-grounded HRI solutions. It can provide guidelines to robot designs on how the robot should behave in order to elicit well-defined and specific –but fundamental and crucial– brain mechanisms involved in social interactions. It is the very same mechanisms that are evoked in human-human social encounters. If robots are to co-exist with humans in the day-to-day social environment, they need to evoke those automatic and often implicit mechanisms of the human brain, in the exact same ways as other humans do. However, many present approaches in HRI research lack systematicity, and, with self-reported measures, do not tap on those fundamental (and often implicit) mechanisms of social cognition. To advance in HRI research we should first understand and measure (with well-controlled (neuro-)scientific or psychological methods) how humans respond to robots, then take these insights and translate them into improved robot design. In the present study we showed that it is feasible to (i) implement an experimental paradigm of cognitive neuroscience in an HRI protocol, and integrate all the necessary components, such as EEG, stimuli presentation, behavioral measures, (ii) obtain well documented effects from human-human interaction in HRI; (iii) observe fundamental mechanisms of social cognition being evoked by a humanoid robot. This is a promising avenue to design robots properly attuned to the workings of the human brain.

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2.2. Publication II: On the role of eye contact in gaze cueing

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Author Contributions. K.K. conceived, designed and performed the experiments, analyzed the data, discussed and interpreted the results, wrote the manuscript. F.C. conceived, designed and performed the experiments, analyzed the data, discussed and interpreted the results. V.T programmed the experiment, discussed and interpreted the results. G.M discussed and interpreted the results. A.W. conceived the experiments, discussed and interpreted the results, wrote the manuscript. All authors reviewed the manuscript.

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2.2.1 Abstract

Most experimental protocols examining joint attention with the gaze-cueing paradigm are “observational” and “offline”, thereby not involving social interaction. We examined whether within a naturalistic online interaction, real-time eye contact influences the gaze cueing effect (GCE). We embedded gaze cueing in an interactive protocol with the iCub humanoid robot. This has the advantage of ecological validity combined with excellent experimental control. Critically, before averting the gaze, iCub either established eye contact or not, a manipulation enabled by an algorithm detecting position of the human eyes. For non-predictive gaze-cueing procedure (Experiment 1), only the eye contact condition elicited GCE, while for counter-predictive procedure (Experiment 2), only the condition with no eye contact induced GCE. These results reveal an interactive effect of strategic (gaze validity) and social (eye contact) top-down components on the reflexive orienting of attention induced by gaze cues. More generally, we propose that naturalistic protocols with an embodied presence of an agent can cast a new light on mechanisms of social cognition.

Keywords: eye contact, joint attention, interactive gaze, gaze cueing, human-robot interaction, social interaction

2.2.2 Introduction

Joint attention (JA) is an important mechanism of non-verbal communication for social interactions. JA occurs when two or more individuals direct their attention to the same event or object in the environment (Tomasello, 2010) and it can be induced by directional (social) gestures, such as gaze shifts. In order to experimentally investigate gaze-related mechanism of JA, variations of the Posner paradigm (Posner, 1980) have been developed and extensively employed (Friesen, & Kingstone, 1998; Driver et al., 1999; Frischen, Bayliss, & Tipper, 2007). In such paradigms, a face (often schematic) is typically presented centrally on a screen, first with gaze straight-ahead, and then with gaze averted towards a lateral location on the screen. Subsequently, a target typically appears either at the location where the gaze was directed (validly cued target), or at a different location (invalidly cued target). Response times (RTs) in target detection or discrimination are typically faster for validly cued targets compared to invalidly cued targets, reflecting the *gaze-cueing effect* (GCE). The GCE is observed even when the gaze is counter-predictive (i.e., the target is more likely to appear in the invalidly cued locations), indicating that directional gaze elicits a reflexive attentional shift towards the gazed-at location (Friesen, & Kingstone, 1998; Driver et al., 1999; Frischen, Bayliss, & Tipper, 2007). However, recent studies suggest that gaze following can be top-down modulated through task demands and goals, inferred goals of the observed agent, or beliefs about their agency (Teufel, Alexis, Clayton, & Davis, 2010; Wiese, Zwickel, & Müller, 2013; Wiese, Wykowska, & Müller, 2014; Wykowska, Wiese, Prosser, & Müller, 2014; Ciardo, Ricciardelli, Lugli, Rubichi, & Iani, 2015; Martini, Buzzell, & Wiese, 2015; Perez-Osorio, Müller, Wiese, & Wykowska, 2015).

Despite the limited amount of gaze-cueing studies using another human as a central cue (Lachat, Conty, Hugueville, & George, 2012; Cole, Smith, & Atkinson, 2015), the majority of studies examine JA through *offline* protocols with social stimuli presented statically on a screen (Schilbach, 2014). However, screen-based offline paradigms lack ecological validity, and they might fail to capture true social cognitive mechanisms evoked in natural social interactions (Schilbach, 2014). One of crucial mechanisms is real-time eye contact (Kleinke, 1986), which informs about readiness to engage in interaction. Eye contact has been shown to affect various cognitive processes and states, like attention, memory, and arousal (Macrae, Hood, Milne, Rowe, & Mason, 2002; Senju, & Hasegawa, 2005; Bristow, Rees, & Frith, 2007; Hietanen, Leppänen, Peltola, Linna-aho, & Ruuhiala, 2008; Senju, & Johnson, 2009; Pönkänen, Peltola, & Hietanen, 2011; Ueda, Takahashi, & Watanabe, 2014; Hamilton, 2016; Hietanen, Myllyneva, Helminen, & Lyyra, 2016; Dalmaso, Castelli, & Galfano, 2017; Dalmaso, Castelli, Scatturin, & Galfano, 2017; Xu, Zhang, & Geng, 2018). For instance, Senju and Hasegawa presented a face on a screen with different gaze directions (direct, averted, closed eyes) followed by a peripheral target (Senju, & Hasegawa, 2005). RTs were slower for direct gaze compared to averted gaze or closed eyes, suggesting that eye contact delayed attentional disengagement from the face. Similarly, Bristow et al. measured behavioral and neural responses to gaze shifts directed or not to a target as a function of the social context (social: eye contact, non-social: averted gaze) and the goal-directedness (i.e., toward the target or not) of the gaze shift (Bristow, Rees, & Frith, 2007). Authors found that an eye contact preceding gaze shift facilitated gaze shift detection, suggesting that participants' attention was covertly attracted to the social context of the face. Moreover, authors reported greater activation in the medial prefrontal cortex and precuneus with respect to goal directed and social gaze shift compared to non-goal directed and non-social shift, suggesting that this activity may reflect the experience of JA associated with these gaze shifts (Bristow, Rees, & Frith, 2007). More recent studies investigated the effect of eye contact on attentional processes, by employing either oculomotor behavior for screen based paradigms (Ueda, Takahashi, & Watanabe, 2014; Dalmaso, Castelli, & Galfano, 2017; Dalmaso, Castelli, Scatturin, & Galfano, 2017) or even during real-time social interactions (Hietanen, Myllyneva, Helminen, & Lyyra, 2016). In a series of screen-based studies, Dalmaso et al. reported that eye contact can modulate spatial and temporal parameters of goal-directed saccades (i.e., greater saccadic curvature, decreased peak velocity) (Dalmaso, Castelli, & Galfano, 2017; Dalmaso, Castelli, Scatturin, & Galfano, 2017). Finally, a very recent study by Xu and colleagues revealed a larger GCE following a supraliminally presented direct gaze in comparison to gaze directed downwards (Xu, Zhang, & Geng, 2018).

Previous studies have found that real-time direct gaze enhance EEG asymmetry (i.e., less power alpha band from left-sided frontal channels) and skin conductance responses (an index of arousal) compared to a direct gaze presented on a screen (Hietanen, Leppänen, Peltola, Linna-aho, & Ruuhiala, 2008; Pönkänen, Peltola, & Hietanen, 2011). Additionally, Hietanen et al. (Hietanen, Myllyneva, Helminen, & Lyyra, 2016) found that a real-time eye contact can shape attentional mechanisms differently than pictures (Senju, & Hasegawa, 2005; Ueda, Takahashi, & Watanabe, 2014). Hietanen et al. reported that real-time eye contact with a confederate enhanced performance (i.e., faster responses) in both discrimination and Stroop tasks (Hietanen, Myllyneva, Helminen, & Lyyra, 2016). The authors proposed that real-time eye contact might have increased autonomic activation (Hietanen, Myllyneva, Helminen, & Lyyra, 2016). Therefore, it is plausible to assume that real-time mutual gaze embedded in a gaze-cueing paradigm might affect the processing of socially relevant sensory information, thereby modulating JA effects.

Recent approaches to the study of the mechanisms of social cognition propose that more interactive experimental protocols are crucial for understanding cognitive and social mechanisms elicited by social interaction (De Jaegher, Di Paolo, & Gallagher, 2010; Risko, Laidlaw, Freeth, Foulsham, & Kingstone, 2012; Schilbach et al., 2013; Risko, Richardson, & Kingstone, 2016; Bolis, Balsters, Wenderoth, Becchio, & Schilbach, 2017). In line with this approach we used a novel method of involving an embodied humanoid robot in an online interactive experimental manipulation. More specifically, we embedded a face detection algorithm, which allowed the humanoid robot to detect online the participants' eyes and establish a real-time eye contact with them (for the output of the algorithm see Figure 1, panel i). Using humanoid robots to examine human social cognition allows for excellent experimental control and, at the same time, ecological validity. Robots allow for manipulation of behavioral parameters in a controlled and modular way (Sciutti, Ansuini, Becchio, & Sandini, 2015), and can be programmed to behave contingently on the human behavior (Admoni, & Scassellati, 2017). At the same time, embodied humanoid robots allow for a higher ecological validity relative to screen-based stimuli, as they increase social presence (Wykowska, Chaminade, & Cheng, 2016; Admoni, & Scassellati, 2017). A humanoid robot compared to a virtual agent shares our environment and can make changes in the environment by, for example, manipulating objects. Humanoid robots can elicit the mechanisms of social cognition in a similar way as human-human interaction (Wykowska, Chaminade, & Cheng, 2016; Admoni, & Scassellati, 2017; Wiese, Metta, & Wykowska, 2017). Moreover, eye contact with a robot increases its subjective social evaluation, attribution of intentionality and engagement, for a review see (Admoni, & Scassellati, 2017).

The aim of our study was to examine whether real-time eye contact modulates the GCE depending on the validity of the cue. In two experiments, we employed a gaze/head cueing paradigm, where the iCub (Metta et al., 2010) was positioned between two lateral screens (Figure 1, panel ii), on which targets were presented. In one condition, iCub established eye contact and then gazed to one of the lateral locations (eye contact condition), while in the other condition, the robot looked down without establishing eye contact (no eye contact condition, see Figure 2). The eye contact was manipulated across blocks. In order to check if eye contact differently engaged participants in the task, at the end of each block, participants were requested to answer the following question: "How much did you feel engaged with the robot?". In Experiment 1 cue-target validity was 50% and the stimulus-onset-asynchrony (SOA) was 1000 ms. We hypothesized that given the pivotal role of eye contact in social interaction (Kleinke, 1986), and previous findings supporting a larger GCE in direct gaze compared to non-direct gaze (Bristow, Rees, & Frith, 2007; Xu, Zhang, & Geng, 2018), the eye contact might act as a source of top-down enhancement of the bottom-up reflexive component, in line with the dual-component of gaze-related attentional orienting (Wiese, Zwickel, & Müller, 2013). Therefore, we expected a larger GCE in eye contact compared to the no eye contact condition. Experiment 2 aimed at examining whether the social top-down component, exerted by eye contact, would interact with the other top-down component, namely the strategic one, which might also modulate reflexive mechanism of attentional orienting in response to directional gaze cues. To achieve this, we designed a task in which cue-target validity was counter-predictive (25%), and SOA was reduced to 500 ms. By using counter-predictive cues, we made sure that *strategically* it would be beneficial to avoid orienting attention towards the direction of the gaze (Friesen, & Kingstone, 1998; Wiese, Zwickel, & Müller, 2013). In addition, we reduced the SOA to make little time available for top-down control over reflexive processes. We hypothesized that under these experimental conditions, any gaze-cueing effect that would potentially be observed would be due to a reflexive component of attentional orienting (Friesen, & Kingstone, 1998; Driver et al., 1999). On the other hand, lack of gaze-cueing effects would suggest that top-down control penetrated the reflexive mechanism. The question of interest was whether the postulated top-down component related to social signal of the mutual gaze would be powerful enough to have an impact on the reflexive component, even when little time is allowed. That is, whether the top-down component would reduce (or eliminate) the gaze cueing effects resulting from the reflexive mechanism, as following the gaze of the robot under 25% validity would not be not an efficient strategy.

Figure 1. Panel i.: Example of the output of the face detector algorithm drawn from the left robot eye. Panel ii.: Experimental setup from participant's point of view.

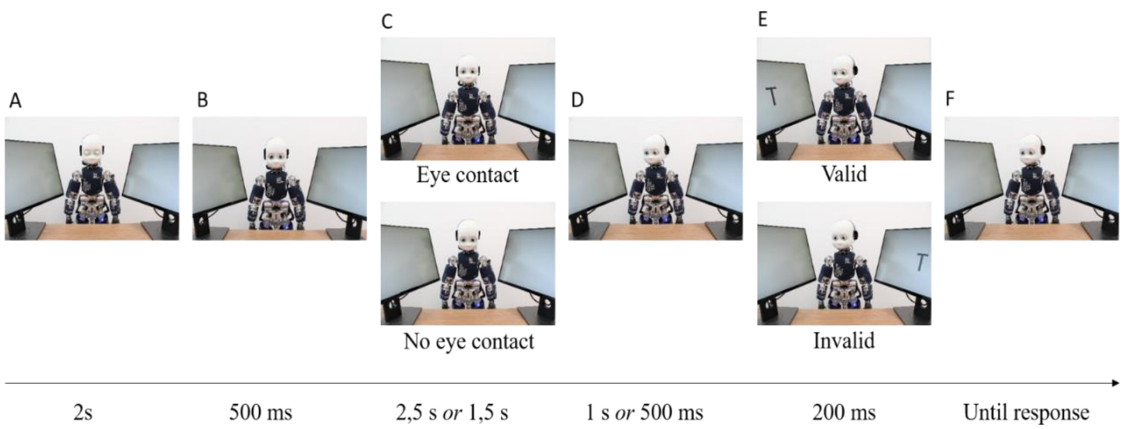

Figure 2. Experimental procedure. The robot (iCub) starts with its eyes closed for 2 s, Figure 2A. Subsequently, it opens the eyes for 500 ms (without moving the head), Figure 2B. Then, iCub looks either down (no eye contact) or towards the participants' eyes (eye contact) for 2.5 s (Experiment 1) or 1.5 s (Experiment 2), Figure 2C. After this, iCub moves its head laterally to gaze towards a potential target location, Figure 2D. After 1s (Experiment 1) or 500 ms (Experiment 2), the letter V or T appears randomly on one of the screens for 200 ms, Figure 2E. The participant (not shown) identifies the target by pressing the mouse button (left or right), Figure 2F.

2.2.3 Results

Experiment 1.

One participant with a number of errors exceeding 3 standard deviations (SD) from the overall mean (3.84% ± 3.52) was excluded from further analyses. Error trials (3.44%), RTs slower than 2000 ms, or 2.5 SDs above- or below an individual's mean for each condition were removed (2.2% of remaining trials). The mean number of the trials after removing the outliers was similar across conditions and equal to 37.75 ± 1.54 trials on average. For each participants, we computed the GCE as the difference in RTs between invalid and valid trial for the eye contact and the no eye condition separately. A positive GCE means that participants responded faster to validly- compared to invalidly-cued targets, indicating that participants oriented their attention to the location gazed at by the robot. A negative value of the GCE reflects, on the other hand, faster responses to invalidly- compared to validly-cued targets, suggesting that participants oriented their attention to the opposite direction than that of iCub's gaze. GCEs were submitted to a repeated-measures analysis of variance (ANOVA) with gaze type (eye contact, no eye contact) as within-participants factor. Furthermore, one-sample t-tests were applied in order to calculate if the average GCE in both condition statistically differed from a normal distribution with a zero mean. Since the validity was randomized across the entire experiment and thus it was not constant in each block, an additional analysis was conducted according to validity rate per block. More specifically, a linear regression was run to investigate if GCE magnitude was predicted by the rate of validity of the block. For this analysis, the GCE was computed for each participant in each block. Then, the blocks were categorized according to the validity rate into three categories: low (valid trials < 50%), middle (valid trials = 50%) and high (valid trials > 50%). Furthermore, mean ratings for social engagement were analyzed using a Wilcoxon signed-rank test in order to compute the statistical difference between eye contact vs. no eye contact blocks. Spearman's rank-order correlation coefficient was computed to assess the relationship between GCE and ratings of engagement.

Gaze-cueing effect. The analysis revealed a significant main effect of gaze type, $F(1, 32) = 7.38$, $p = .01$, $\eta_p^2 = .19$ indicating a larger GCE for the eye contact ($M_{eye\ contact} = 29.5$, SEM =

7.02) compared to the no eye contact condition ($M_{no\ eye\ contact}$ = 6.17, SEM = 7.8). One-sample t-tests showed that GCE in eye contact condition was statistically larger than 0, t (32) = 4.2, p <.001, 95% CI [15.2, 43.8] while the GCE in no eye contact condition did not significantly differ from 0, t (32) <1, 95% CI [-9.8, 22.14], see Figure 3. The multiple regression analysis indicated that gaze condition and validity rate significantly predicted the GCE magnitude, F (2,195) = 11,071, p < .001, R^2 =.102. However, only gaze condition (eye contact vs. no eye contact) added significantly to the prediction, β = -40.46, t (195) = -4.57, p < .001.

Error analysis. A paired sample t-test showed that the percentage of error trials did not significantly differ between the eye contact and no eye contact conditions, t(32) = 1.1 , p =.29 ($M_{eye\ contact}$ = 3.67 %, $SEM_{eye\ contact}$ = 0.59, $M_{no\ eye\ contact}$ = 3.22 %, $SEM_{no\ eye\ contact}$ = 0.43). The percentage of error trials in valid condition was subtracted from the percentage of error trials in invalid condition for both gaze conditions. A paired sample t-test showed that the percentage of error trials did not significantly differ between the eye contact and no eye contact conditions, t(32) < 1 , p =.42 ($M_{eye\ contact}$ = 0.68 %, $SEM_{eye\ contact}$ = 0.79, $M_{no\ eye\ contact}$ = 1.44 %, $SEM_{no\ eye\ contact}$ = 0.57).

Engagement rating. Participants rated the eye contact condition as more engaging than no eye contact, Z = -4.54, p <.001 ($M_{eye\ contact}$ = 7.10, SEM = 0.27, $M_{no\ eye\ contact}$ = 5.84, SEM = 0.21). The mean ratings of each gaze condition overall and across blocks are presented in Figure 4. No correlation between the engagement ratings and the mean GCE emerged both for the eye contact, *r* = .07, n = 33, p = .70, and the no eye contact condition, *r* = .21, n = 33, p = .23.

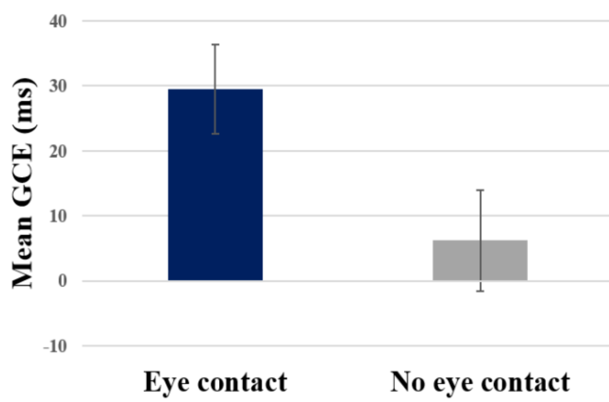

Figure 3. GCE (ms) as a function of gaze condition (eye contact vs. no eye contact). Error bars represent standard error of the means.

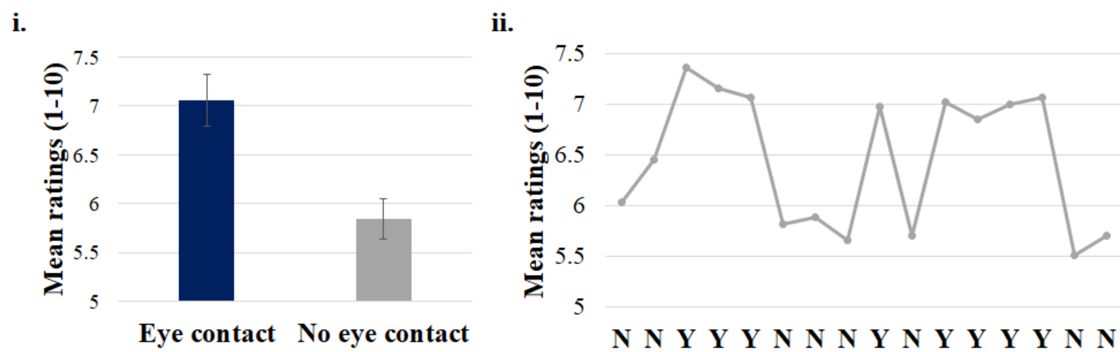

Figure 4. Panel i.: Engagement ratings averaged across conditions (eye contact, no eye contact). Panel ii: Mean engagement ratings across blocks (Y= eye contact; N= no eye contact). Error bars represent standard error of the means.

Discussion. Experiment 1 examined the impact of eye contact on orienting of attention driven by non-predictive gaze cues. GCE occurred in the eye contact condition, but not when there was no eye contact. Validity rate did not predict GCE magnitude, suggesting that the GCE was not related to the short-term variations in cue predicitivity, when the task was overall non-predictive (50% validity). Participants rated the eye contact condition more engaging, as compared to the condition with no eye contact. This is also reflected in the engagement ratings in each block, where participants repeatedly rated higher the blocks with eye contact (see Figure 4, panel ii), as compared to the no eye contact condition.

Interestingly for the purposes of this paper, our results showed no GCE in the condition with no eye contact. It was a striking result, given that the directional cue of the robot's head movement was a very salient signal. Therefore, a reflexive component should have also been present in the condition with no eye contact, in line with the idea of dual-component of attentional orienting in gaze cueing (Wiese, Zwickel, & Müller, 2013) and the dual-model of spatial orienting of attention (Müller, & Rabbitt, 1989). In line with these accounts, the reflexive component is a fast-acting mechanism with a transient facilitatory period, elicited by salient signals. A voluntary orienting component emerges slower and has a sustaining effect of attention orienting towards cued locations (Müller, & Rabbitt, 1989; Frischen, Bayliss, & Tipper, 2007). In Experiment 1, the SOA of 1000 ms might have caused the reflexive component to fade away. We set out to examine the more reflexive component of gaze-related attentional orienting in Experiment 2; and address the question if eye contact would have an impact on the reflexive orienting of attention.

Experiment 2.

One participant with a number of errors exceeding 3 standard deviations (SD) from the overall mean (4.68% ± 3.35) was excluded from further analyses. Error trials (4.2%), RTs slower than 2000 ms, or 2.5 SDs above- or below an individual's mean for each condition were removed (2.4 % of all remaining trials). The mean number of the trials after removing the outliers was: 119.7 ± 3.15 for the eye contact and 119.5 ± 3.64 for the no eye contact condition. The average percentage of valid and invalid trials was similar across gaze condition and equal to: M = 23.45 ± 0.99 (%) for valid trials and M = 70 ± 2.05 (%) for invalid trials.

The GCE was computed as in Experiment 1. In order to evaluate the effect of eye contact, the GCE was submitted to a repeated measures ANOVA with gaze type (eye contact, no eye contact) as within-participants factor. In addition, one-sample t-tests were conducted in order to calculate if the average GCE in both condition statistically differed from a normal distribution with a zero mean. Mean ratings for social engagement were analyzed using a Wilcoxon signed-rank test in order to compute the statistical difference between eye contact vs. no eye contact blocks. Finally, Spearman's rank-order correlation coefficient was computed to assess the relationship between GCE and ratings of engagement.

Gaze-cueing effect. The analysis reveal a significant main effect, F (1, 32) = 4.87, p =.035, η_p^2 =.13, indicating a larger GCE in the no eye contact ($M_{no\ eye\ contact}$ = 9.16, SEM = 3.9) compared to the eye contact condition ($M_{eye\ contact}$ = -4.69, SEM = 5.25). One-sample t-test showed that only in the no eye contact condition the GCE was significantly different from 0, t(32) = 2.33, p =.03, 95% CI [1.15, 17.17], while the GCE in the eye contact condition did not significantly differ from 0, t(32) <1, 95% CI [-15.38, 6.0], see Figure 5.

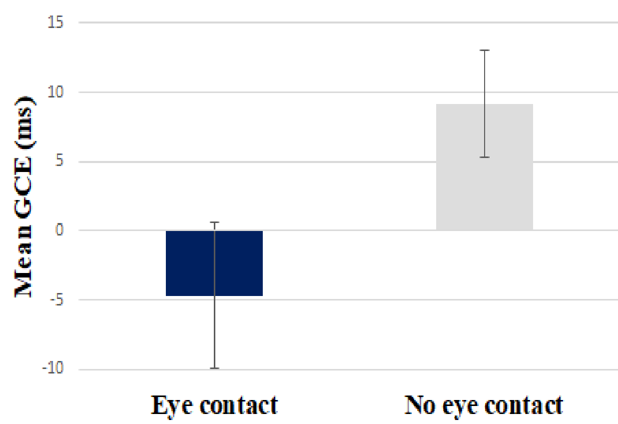

Figure 5. GCEs (ms) as a function of gaze condition (eye contact, no eye contact). Error bars represent standard error of the means.

In order to check if the results of Experiment 2 were not affected by the lower number of valid trials (25%) compared to invalid (75%), we conducted an additional analysis on a randomly selected subset of invalid trials (randperm function in Matlab). We repeated the main analysis on such a subset of trials. We computed the GCE, in a similar fashion as for the main analysis, and we submitted GCE to a repeated-measures ANOVA with gaze type (eye contact, no eye contact) as within-participants factor. The analysis reveal a stable pattern of results as indicated by the significant main effect, F (1, 32) = 7.1, p =.012, ηp^2 =.18, indicating a larger GCE in the no eye contact (M = 11.92, SEM = 4.3) compared to the eye contact condition (M = -8.9, SEM = 6.23). Moreover, in line with the results of the main analysis, one-sample t-test showed that only in the no eye contact condition the GCE was significantly different from 0, t(32) = 2.77, p =.01, 95% CI [3.16, 20.7], while the GCE in the eye contact condition did not differ significantly from 0, t(32) =-1.43, p=.16, 95% CI [-21.6, 3.8]. Results of this additional analysis mirror the pattern of the main analysis.

Error analysis. A paired sample t-test showed that the percentage of error trials did not significantly differ between the eye contact and no eye contact conditions, $t(32) < 1$, $p = .78$ ($M_{eye\ contact} = 4.3$ %, $SEM_{eye\ contact} = 0.42$, $M_{no\ eye\ contact} = 4.2$ %, $SEM_{no\ eye\ contact} = 0.52$). Similar to Experiment 1, the percentage of error trials in valid condition was subtracted from the percentage of error trials in invalid condition for both gaze conditions. A paired sample t-test showed that the percentage of error trials did not significantly differ between the eye contact and no eye contact conditions, $t(32) < 1$, $p = .9$ ($M_{eye\ contact} = 0.22$ %, $SEM_{eye\ contact} = 0.58$, $M_{no\ eye\ contact} = 0.32$ %, $SEM_{no\ eye\ contact} = 0.56$).

Engagement ratings. Overall, participants rated the eye contact condition as more engaging $Z = -2.69$, $p = .007$ ($M_{eye\ contact} = 6.14$, $SEM = 0.28$, $M_{no\ eye\ contact} = 5.65$, $SEM = 0.31$). The mean ratings for each gaze condition for the whole experiment and across blocks are presented in Figure 6. There was no correlation between the rating scores and the mean GCE across participants for the eye contact condition, $r = -.22$, $n = 33$, $p = .22$ and also for the no eye contact condition, $r = .16$, $n = 33$, $p = .39$.

Discussion. Experiment 2 examined the effect of eye contact on the reflexive orienting of attention that is when following gaze cues is not strategically efficient for the task. To this end, we reduced the SOA from 1000 ms (Experiment 1) to 500 ms, and the gaze validity from 50% to 25% (i.e., the gaze cue was counter-predictive in the 75% of the trials). Results showed that a GCE statistically different from 0, was observed only in the no eye contact condition. Given the counter-predictive design of the task and the relatively short SOA, the observed GCE can be interpreted as being due to reflexive orienting of attention. This effect was not observed in the eye contact condition, suggesting an active top-down suppression in this case. Interestingly, despite the lack of GCE in the eye contact condition, participants rated the eye contact condition as more engaging then the no eye contact one.

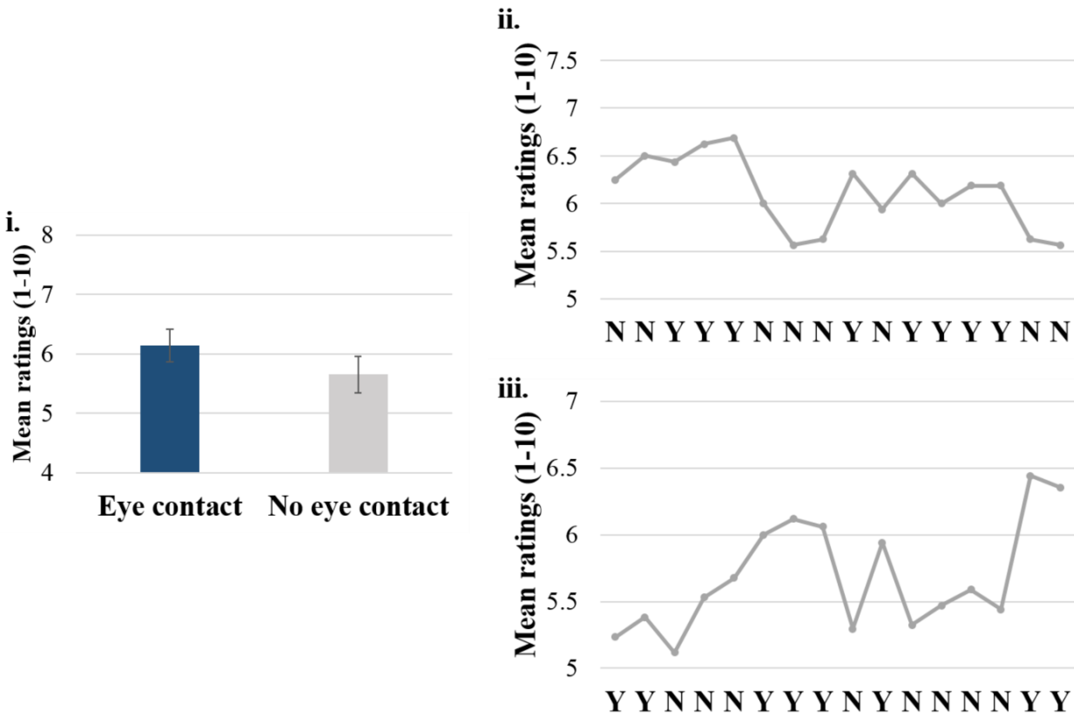

Figure 6. Panel i: Engagement ratings averaged across conditions (eye contact, no eye contact). Panel ii & iii: Mean engagement ratings across block types (Y= eye contact; N= no eye contact) and the two block sequences that were counterbalanced across participants (panel ii: Sequence type *a*, panel iii: Sequence type *b*). Sequence type *a* starts with two blocks of no eye contact condition (N), while Sequence *b* starts with two blocks of eye contact condition (Y) and consists of the opposite gaze blocks compared to Sequence type *a*.

2.2.4 General Discussion

In the present study, we examined whether real-time eye contact influences GCE in a more ecologically valid scenario than classical screen-based paradigms. To this aim, we designed a gaze-cueing paradigm involving an embodied humanoid robot iCub. In Experiment 1 (non-predictive cueing procedure, 1000 ms SOA) we observed GCE for the eye contact condition, but not for the no eye contact condition. Experiment 2 (counter-predictive cueing procedure, 500 ms SOA) showed a reverse pattern. In both experiments, participants rated as more engaging the eye contact condition, compared to no eye contact condition.

Our results suggest that the GCE is a result of an interaction of a bottom-up reflexive orienting of attention, with top-down modulatory mechanisms related to strategic control and social engagement. In the case of non-predictive cues and relatively long SOA (Experiment 1), for the eye contact condition, the observed GCE might have been a combination of bottom-up mechanism and a top-down social enhancement, in line with previous literature (Wiese, Zwickel, & Müller, 2013; Wiese, Wykowska, & Müller, 2014; Wykowska, Wiese, Prosser, & Müller, 2014). This enhancement might have occurred because the eye contact condition was more engaging and/or rewarding, which was supported by the subjective ratings of engagement. Furthermore, it has been previously shown that eye contact positively modulates reward-related neural circuitry, as indicated by the activation of dopaminergic systems when pleasing faces are presented with a direct gaze compared to averted (Kampe, Frith, Dolan, & Frith, 2001). Similarly, Schilbach and colleagues showed that other contingent behaviors, such as initiating a contingent gaze sharing, can also activate reward-related brain regions, i.e., the ventral striatum (Schilbach et al., 2010). Since eye contact was more engaging, participants might have been more prone to follow the gaze of iCub when it engaged them in a more social context of eye contact.

In the no eye contact condition, no GCE was observed. This might have been due either to active suppression of the bottom-up reflexive component, or due to that the bottom-up component was not enhanced further by the social/engaging/rewarding context, and thereby it faded away with time. Although the present data cannot conclusively support one of the two interpretations, we speculate that it is more likely that the bottom-up mechanism simply faded away for the no eye contact condition, in line with literature showing that the bottom-up mechanisms of attention orienting are transient and short-lived (Müller, & Rabbitt, 1989). This reasoning is further supported by another study (Kompatsiari, Pérez-Osorio, De Tommaso, Metta, & Wykowska, 2018) in which GCE effects were found for both eye contact and no eye contact in non-predictive cueing procedure with 500 ms. In this case, it might be argued that the reflexive bottom-up mechanism was still observed (not yet faded away) due to 500 ms SOA.

One might argue that top-down active suppression of reflexive attentional orienting needed 1000 ms to develop, and hence it was observed in the present Experiment 1 but not in the other study with 500 ms SOA. However, Experiment 2 of the present study speaks against this interpretation, as in Experiment 2, in the eye contact condition, top-down suppression of reflexive component was already present at 500 ms SOA. Taken together, we argue that it is more likely that in Experiment 1, lack of GCE in no eye contact condition was due to temporal fading away of the reflexive component, rather than active suppression thereof.

On the other hand, in the case of counter-predictive cueing (Experiment 2), where GCE is most likely the signature of reflexive orienting of attention, we observed the reflexive mechanism in the no eye contact condition. Interestingly, for the eye contact condition, the GCE was not observed, suggesting top-down influence. Since in the counter-predictive cueing procedure, following the direction of gaze was very inefficient for the task (most of the times, following gaze direction led to focusing on the wrong location in terms of subsequent target appearance), it was strategically better to suppress orienting of attention in the direction of the gaze. Hence, due to a more engaging social signal in the eye contact condition, top-down control might have already been activated, while in the no eye contact condition, the reflexive component was still pronounced, resulting in significant GCE.

Taken together, our results suggest that when a socially rewarding/engaging signal is detected (as evidenced by engagement ratings), strategic top-down control might be more likely to be activated – which either enhances or suppresses activation of the attentional network, dependent on predictivity of the cue, and the best strategy to efficiently solve the task. When following the gaze is strategically equally sensible as not following the gaze, as in the case of our Experiment 1 (50% validity), the reflexive component of attentional orienting might be enhanced due to socially engaging eye contact). This allows the attention-related activity to be larger and/or last longer than the default reflexive component. This is in line with the idea that the top-down mechanisms of attentional orienting have a longer-lasting effect than the transient, reflexive component (Müller, & Rabbitt, 1989; Friesen, & Kingstone, 1998; Frischen, Bayliss, & Tipper, 2007). On the other hand, when following the gaze would be inefficient, and thus strategically would not make sense, as in Experiment 2 (25% validity), the engaging condition of eye contact presumably induces active suppression of the reflexive component of attentional orienting. Indeed, when a context is more engaging or socially rewarding (as in the case of our eye contact condition), top-down control can be potent enough to suppress the reflexive component of attentional orienting in response to directional gaze. However, in the case of no (socially) rewarding/engaging signal (i.e., no eye contact), the strategic top-down control might be less likely to be activated. Therefore, the default reflexive attentional orienting mechanism, related to gaze direction might be more prominent. This mechanism enhances processing of the target at the cued, relative to uncued, location, but the enhancement – being bottom-up – is likely transient (Müller, & Rabbitt, 1989). Therefore, GCE are observed for a short SOA (500 ms), both for non-predictive (Kompatsiari, Pérez-Osorio, De Tommaso, Metta, & Wykowska, 2018) and counter-predictive cues (Experiment 2). However, this enhancement fades away in cases where SOA is longer (1000 ms, Experiment 1).

In sum, results of the present study showed that using more interactive protocols with embodied presence of a humanoid robot allow for more ecological validity whilst maintaining experimental control. Such approach provides novel insights into the mechanisms of social cognition. In the case of our study, we showed that social signals such as gaze contact have an impact on the reflexive mechanism of gaze-related orienting of attention through activation of top-down strategic control processes.

As a final remark, we highlight the importance of the dissociation that we observed between subjective reports of engagement and the GCE. This is of relevance not only for social cognitive neuroscience and experimental psychology but mainly for the research field of human-robot interaction (HRI). In this field, most of studies rely on subjective reports. However, our results showed that self-reports do not reveal all the information about the underlying cognitive mechanisms. More specifically, we showed that the impact of eye contact on engagement ratings was similar, independently of cue predictivity. That is, eye contact always elicited higher engagement ratings, as compared to no eye contact. Interestingly, the GCE did not follow the same pattern, indicating a dissociation between subjective ratings and the objective measure of social engagement (i.e., the GCE), which is in line with previous findings of Martini et al. (Martini, Buzzell, & Wiese, 2015). These findings suggest that in order to target the entire spectrum of cognitive mechanisms involved in HRI (or any other social interaction), one needs to supplement subjective reports with objective measures.

2.2.5 Methods

Participants. The sample size was estimated via a priori power analysis using G*Power (Faul, Erdfelder, Lang, & Buchner, 2007). The analysis yielded a sufficient number of 30 participants, adopting the effect size of a similar previous study (Wykowska, Kajopoulos, Ramirez-Amaro, & Cheng, 2015): dz= 0.53, $\alpha = .05$, and $1-\beta = 0.80$. In total, thirty-four healthy participants (mean age= 26.74 ± 6.45, 4 left handed, 17 female) took part in the Experiment 1 and thirty-four new participants (mean age= 26.18 ± 4.03, 5 left handed, 19 female) took part in Experiment 2. Participants received honorarium (15 €) for their participation. All had normal or corrected-to normal vision, and were debriefed about the purpose of the study at the end of the experiment. Both Experiment 1 and Experiment 2 were conducted in accordance with the ethical standards laid down in the 2013 Declaration of Helsinki and were approved by the local ethical committee (Comitato Etico Regione Liguria). The experiments were performed at the Istituto Italiano di Technologia. All participants provided written informed consent prior to participation. Data were stored and analyzed anonymously.

Stimuli and Apparatus. The apparatus and stimuli were constant across experiments. The experiments were carried out in an isolated and noise-attenuated room. Participants were seated face-to-face with the iCub robot placed at the opposite side of the desk at a distance of 125 cm. iCub was mounted on a supporting frame and its eyes were aligned with participants' eyes at 124 cm from the floor. iCub's gaze shifts were always embedded in a head movement, in order to make them more naturalistic. The gaze could be directed (together with the head movement) to five different positions: "resting" - towards a location in space between the desk and participants' upper body, "eye contact" - towards participants' eyes (based on the output of face extraction algorithm, see subsection "iCub and algorithms"), "no eye contact" - towards the table, "left" - towards the location of the target on the left screen, and "right" - towards the location of the target on the right screen (see Table 1 for the x, y, and z coordinates of the robot gaze from the robot frame of reference, i.e., robot's waist). The z-coordinate of "resting" and "no eye contact" positions were calculated starting from z-coordinate of "eye contact" gaze, in order to maintain the z-value for the resting condition equally distanced from the z-value of "eye contact" and "no eye contact" conditions (see Table 1). Importantly, the height of robot's gaze prior to directional shift was equally distanced from the "left"/"right" position for both eye contact and the condition with no eye contact. Similarly, the amplitude of the gaze shift on the horizontal axis (y coordinate) was equal for left-and right- directed gaze shift (see Table 1). These coordinates were predetermined in order to ensure that the distance required to reach the end point (left or right) was the same both for the eye contact and for condition with no eye contact. Two screens (21.5 inches) were used for stimuli presentation and were situated laterally on a desk at a viewing distance of 105 cm from the participant's nose apex, see Figure. 1. The screens were both tilted back approximately by 12° from the vertical position and were rotated by 76° to the right or left. The screens were positioned 75 cm apart (center-to-center) and the stimuli were letters V or T (3° 32' high, 4° 5' wide). iCub, stimulus presentation, and data collection were controlled by an experiment programmed in C++ using the Ubuntu 12.04 LTS operating system.

Table 1. Positions of robot gaze from robot frame of reference (in m).

Positions of robot gaze	x	y	z
Resting	-0.78	0.0	0.16
No eye contact	-0.78	0.0	0.04
Left	-0.78	0.35	0.16
Right	-0.78	0.35	0.16
Eye contact	-0.78	0.0	0.28

iCub and algorithms. iCub is a humanoid robot (size: 104 x 34 cm), with 3 degrees of freedom in the eyes (common tilt, vergence, and version) and three additional degrees of freedom in the neck (roll, pitch, yaw). YARP (Yet Another Robot Platform) is used as the iCub middleware (Metta, Fitzpatrick, & Natale, 2006). YARP is a multi-platform open-source framework, which comprises a set of libraries, protocols, and tools, supporting modularity and interoperability. To control the eyes and the neck of iCub, we used the YARP Gaze Interface, iKinGazeCtrl, from the available open source repository [https://github.com/robotology/iCub-main/tree/master/src/modules/iKinGazeCtrl], which allows the control of iCub's gaze through independent movement of the neck and eyes following a minimum-jerk velocity profile (Roncone, Pattacini, Metta, & Natale, 2016). In our gaze-cueing procedure, iCub moved its entire head to one of the sides, not only its eyes, to make its behavior more naturalistic (see Supplementary Material). The vergence of the eyes was set to 5 degrees and maintained constant. The vergence was locked because the combined movement of neck and eyes using the iKinGazeCtrl controller produces an overshooting in the position of the eyes which would result in a very unnatural cueing procedure, see Roncone et al. for a qualitative comparison of the velocity profiles between typical gaze shifts in humans and iCub's using iKinGazeCtrl (Roncone, Pattacini, Metta, & Natale, 2016). Additionally, previous studies have reported similar attentional effects produced by head and gaze cueing (Langton, Watt, & Bruce, 2000; Langton, & Bruce, 2000), thereby encouraging us to use the entire head movement of the iCub. The trajectory time for the movement of eyes and neck was set for this experiment to 200 ms and 400 ms respectively, to maintain the impression of a smooth and naturalistic movement. The human eyes were detected using the face detector of the [https://github.com/robotology/human-sensing] repository, which uses the dlib library [http://dlib.net], see Figure 1- panel i. Informed consent for publication of Figure 1-panel i was obtained.

Procedure. In both experiments, participants were instructed to keep their eyes fixated on the face of the robot and to not move their eyes towards the screens. The latter requirement was also the best possible strategy for the task, as the letters on the screen were presented in peripheral vision, so moving the eyes toward one screen would mean missing the target, if it appeared on the opposite one. The experimenter monitored online eye movements of participants through the iCub cameras in order to check that at the beginning of each trial they were following the instructions and fixated at the robot's face. Participants were asked to hold a mouse with their thumbs placed on the buttons and to identify the target as fast and as accurate as possible. Half of the participants pressed the left key to the V stimulus and the right key for the T (stimulus-response mapping 1). The other half was assigned an opposite stimulus–response mapping (mapping 2). At the end of each block, participants were requested to answer aloud to the following question: "How much did you feel engaged with the robot (1-10)”? The answer was noted down by the experimenter and the participant continued to the next block by pressing the middle mouse button.

Experiment 1. A full experimental session lasted about 25 minutes. The duration of all events include the robot movement which lasted for 400 ms, equivalent to the neck trajectory time. The sequence of events (cf. Figure 2) was the following. Each trial started with the robot having its eyes closed at the resting position. After 2 s, the robot opened its eyes for 500 ms. During this time, the robot extracted information related to the position of the face and the eyes of the participant without making any movement. Then, it looked either to the predefined position: down, for the condition with no eye contact, or direct to the eyes of a participant in the eye contact condition. The whole duration of this phase was 2,5 s (actual eye contact duration : ~ 2s). Subsequently, the robot’s head and eyes shifted to either the left or the right screen. Head direction was uninformative with respect to target location (i.e., cue-target validity = 50%). Following the onset of the robot’s gaze shift, after 1 s, a letter appeared on one of the lateral screens for 200 ms. After 200 ms, the screens turned blank until the participants responded. Target duration was defined following the gaze-cueing procedure with iCub applied in Wykowska et al. study (Wykowska, Kajopoulos, Ramirez-Amaro, & Cheng, 2015; Kompatsiari, Pérez-Osorio, De Tommaso, Metta, & Wykowska, 2018). Experiment 1 consisted of 160 pseudo-randomized trials, divided into 16 blocks of 10 trials each. The blocks were randomly assigned to one of the gaze condition: eye contact or no eye contact. The order of block was constant across participants. Cue-target validity was randomized across trials, both for eye contact and no eye contact conditions, throughout the experiment.

Experiment 2. A full experimental session lasted 40 minutes. The procedure was the same as in Experiment 1 with only three exceptions. First, a 75% ratio of invalid trials were included in each block, in line with the counter-predictive nature of the cueing procedure. Second, we reduced the SOA from 1000 ms to 500 ms to address the more reflexive component of gaze-related attentional orienting[3]. It is important to note here that the SOA in a naturalistic scenario with an entire head movement is not comparable to classical gaze cueing paradigms where there is no gradual transition of the gaze shift. Therefore, what seems to be a relatively long SOA in classical paradigms (500 ms) appears much shorter when the entire head movement is displayed, given that the SOA is counted from the onset of the movement to its final position. Finally, in order to compensate for the shorter SOA (half the duration of the SOA in Experiment 1), the whole phase of gaze manipulation (including eye contact/gaze down) was also reduced to 1.5 (actual eye contact duration : ~1s) so that the ratio of duration between eye contact/no eye contact and SOA would remain similar. Indeed, several studies showed that long time of direct gaze is an ostensive signal (Nichols, & Champness , 1971; Argyle, & Cook, 1976; Frischen, Bayliss, & Tipper, 2007). This combined with the counter-predictive nature of the task might have led to the robot have been perceived as aggressive or competitive, therefore yielding to a completely different social context compared with Experiment 1. In total, 256 pseudo-randomized trials were presented, divided into 16 blocks of 16 trials each. The order of the blocks was counter-balanced across participants, using either the same randomized sequence of Experiment 1 (Sequence type a) or the opposite (Sequence type b). We counterbalanced the Sequence of Eye contact/No-eye contact blocks in order to control for any potential effect of block order. Moreover, given the counter-predictive nature of the task in Experiment 2 we wanted to ensure that the strategical top-down component was not affected by the condition of the first block (i.e., eye contact or no-eye contact). A preliminary analysis on GCE as a function of block sequence showed that block sequence did not affect the GCE (all Fs < 1), thus it was not included in the in our analyses as a factor.

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2.3. Publication III: It's in the eyes: The engaging role of eye contact in HRI

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2.3.1 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 Experiment 1 the gaze direction was non-predictive, in Experiment 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 design of robot behaviors for social HRI.

2.3.2 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 (Tapus, Matarić, 2006; Takayama, Ju, Nass, 2008; Cabibihan, Javed, Ang, & Aljunied, 2013; Martín et al., 2013; Mubin, Stevens, Shahid, Al Mahmud, & Dong, 2013). Moreover, robots might become a new form of social companions, for example, for elderly people (Tapus, Mataric, & Scassellati, 2007; Birks, Bodak, Barlas, Harwood, & Pether, 2016). 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 (Dovidio, & Ellyson, 1982; Baron-Cohen, Campbell, Karmiloff-Smith, Grant, & Walker, 1995; Baron-Cohen, Wheelwright, & Jolliffe, 1997). In humans, eye contact is one of the powerful social signals as it is used to initiate communication and covey interpersonal signals (Kleinke, 1986; Kampe, Frith, & Frith, 2003).

Eye contact modulates a wide range of cognitive processes in humans (Argyle, & Cook, 1976; Macrae, Hood, Milne, Rowe, & Mason, 2002; Senju, & Johnson, 2009; Hamilton, 2016), including social attention and memory (Batki, Baron-Cohen, Wheelwright, Connellan, & Ahluwalia, 2000; Farroni, Csibra, Simion, & Johnson, 2002; Farroni, Mansfield, Lai, & Johnson, 2003; Hood, Macrae, Cole-Davies, & Dias, 2003; Senju, & Hasegawa, 2005; Senju, & Csibra, 2008). Early in development, humans are sensitive to eye contact (Farroni, Csibra, Simion, & Johnson, 2002). For instance, it has been shown that newborns prefer direct rather than averted gaze or closed eyes (Batki, Baron-Cohen, Wheelwright, Connellan, & Ahluwalia, 2000). 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 (Farroni, Mansfield, Lai, & Johnson, 2003; Senju, & Csibra, 2008). Eye contact captures attention in two ways: either resulting in a delayed attentional disengagement from the gaze, or by enhancing other cognitive processes

(Macrae, Hood, Milne, Rowe, & Mason, 2002; Hood, Macrae, Cole-Davies, & Dias, 2003; Senju, & Hasegawa, 2005). On the one hand, Senju and 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 (Senju, & Hasegawa, 2005). On the other hand, there is evidence that faces with eye contact, compared to faces with averted gaze, improved identity recognition (Hood, Macrae, Cole-Davies, & Dias, 2003) and gender discrimination (Macrae, Hood, Milne, Rowe, & Mason, 2002). Direct gaze does not only have an impact on cognitive processes but also on affectional aspects as arousal and likeability (Brooks, Church, & Fraser, 1986; Kuzmanovic et al., 2009). 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) (Kuzmanovic et al., 2009). 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 (Argyle, & Cook, 1976; Brooks, Church, & Fraser, 1986; Knackstedt, & Kleinke, 1991; Droney, & Brooks, 1993). 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 (Mason, Tatkow, & Macrae, 2005; Conty, Tijus, Hugueville, Coelho, & George, 2006).

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 (Yonezawa, Yamazoe, Utsumi, & Abe, 2007). 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 (Ito, Hayakawa, & Terada, 2004). The authors argue that all these cues imply an increase in the feeling of intentionality towards the “eye contact” robot [p. 477, 30]. 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 (Choi, Kim, & Kwak, 2013). 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 (Zhang, Beskow, & Kjellström, 2017), see Admoni & Scasselatti (2017) for an extensive review on social eye gaze in HRI.

Previous studies have examined the effect of eye contact using a screen-based agent (Choi, Kim, & Kwak, 2013), a non-humanoid agent (Yonezawa, Yamazoe, Utsumi, & Abe, 2007) or a robot head (Ito, Hayakawa, & Terada, 2004; Zhang, Beskow, & Kjellström, 2017). 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.

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 (Metta, et al., 2010; Natale, Bartolozzi, Pucci, Wykowska, & Metta, 2017). 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 Figure.1), or to the opposite screen (incongruent trial, see right panel of Figure.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 (Experiment 1: 50% congruency between gaze direction and target location) or counter-predictive (Experiment 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 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.

Figure 1. Congruency between gaze direction and target location. Left panel: Congruent trial. Right panel: incongruent trial

2.3.3 Experiment 1

2.3.3.1 Methods

Participants

The experiment was carried out at the Italian Institute of Technology (IIT). Twenty-four participants (mean age = 26.71 ± 6.39; 11 female; 3 left-handed) took part in the study, and each participant received an honorarium for participation. Both experiments (Experiment 1:

non-predictive referential gaze and Experiment 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.

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).

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 (Metta, Fitzpatrick, & Natale, 2006; Natale, Bartolozzi, Pucci, Wykowska, & Metta, 2017). To control the eyes and the neck, we used the iKinGazeCtrl (a YARP Gaze Interface), from the available open source repository[3], which allows the control of iCub's gaze through independent movement of the neck and eyes in a biologically-inspired way (Roncone, Pattacini, Metta, & Natale, 2016). 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.

The human eyes were detected using the face detector of the "human sensing" module[4], which uses the Dlib library[5]. Dlib is a modern C++ toolkit containing image

[3] [https://github.com/robotology/iCub-main/tree/master/src/modules/iKinGazeCtrl]
[4] [https://github.com/robotology/human-sensing]
[5] [http://dlib.net]

processing and machine learning algorithms and tools, used in robotics, embedded devices, and large high-performance computing environments[6](Kazemi, & Sullivan, 2014; Sharma, Shanmugasundaram, & Ramasamy, 2016; Feng, Kittler, Awais, Huber, & Wu, 2017). 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 (Gould, 2012; Portalska et al., 2012; Matsuyama et al., 2016; Nasir, Jati, Shivakumar, Nallan Chakravarthula, & Georgiou, 2016; Valstar et al., 2016; Wood, Baltrušaitis, Morency, Robinson, & Bulling, 2016; Martinez, Valstar, Jiang, & Pantic, 2017; Zhang, Sugano, & Bulling, 2017), 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.

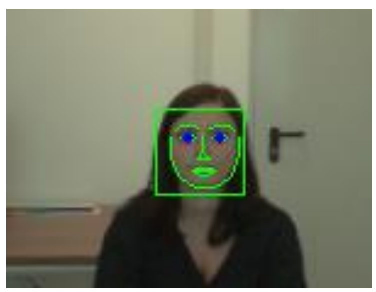


Figure 2. Output of the left robot eye camera depicting the result of the face detector algorithm. Blue circles indicate the position of the detected eyes.

Procedure

Every trial started with the robot having its eyes closed for 2s. 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

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

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 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 was kept constant within block, see Figure 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 minutes. For a more detailed description of the experimental procedure see the video provided as Supplementary material.

Figure 3. Gaze conditions. Left panel: Eye contact. Right panel: No eye contact

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.

Table 1. Questionnaire (Experiment 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.

2.3.3.2 Questionnaire evaluation

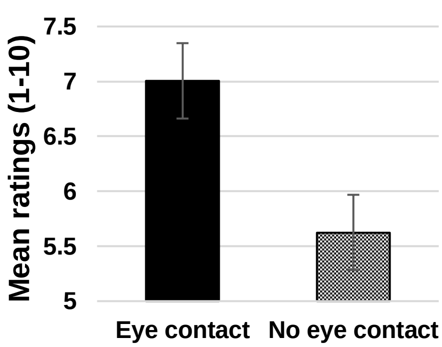
Two independent evaluators rated the responses to the questionnaires and categorized them into four categories, see Table 2. More specifically, Category 1 included replies related to the establishment of eye contact with the robot. Category 2 involved statements about robot behavior that we did not manipulate, 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".

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

2.3.3.3 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.



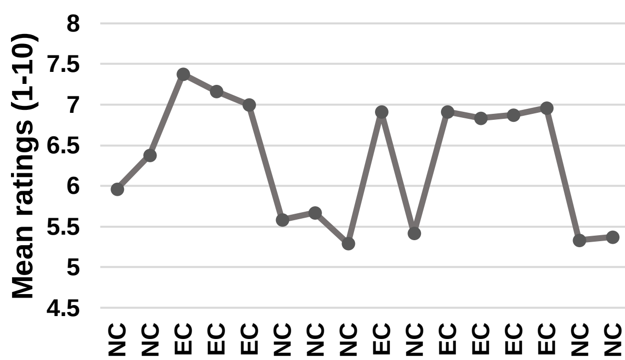


Figure 4. Engagement ratings per gaze condition and across blocks **4.a** Mean engagement ratings averaged per condition (eye contact condition, no eye contact condition). Error bars represent standard error of the means. **4.b** Mean engagement ratings averaged per block (EC= eye contact block; NC=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

The mean familiarity rating (answers to Question 1) was: M = 2.16, SD = 0.92. 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 difference 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 (Figure 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 (0.25). 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 response was not clear. The responses of 22 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 (Figure 5, middle bars). According to the results of chi-square 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 their 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 (Figure 5, upper bars).

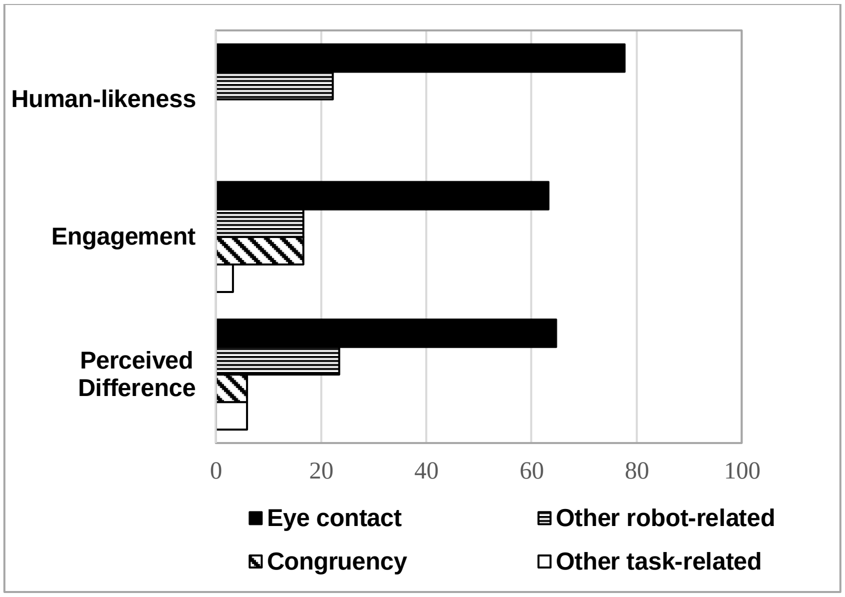


Figure 5. Responses of the participants (in percentages) plotted as a function of four different categories: Eye contact (filled bars), Other robot-related (horizontally striped bars), Congruency (diagonally striped bars), Other task-related (empty bars). The lower bars refer to the responses to Question 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).

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 Experiment 1, show that establishing eye contact is a crucial factor impacting on the quality of human-robot interaction.

2.3.4 Experiment 2

Experiment 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.

2.3.4.1 Method

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.

Apparatus, materials and procedure

The apparatus, stimuli and procedure were the same as in Experiment 1. Methods and algorithms for programming iCub's behavior were the same as in Experiment 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 Experiment 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 Experiment 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 minutes.

After the completion of the task, participants filled out a questionnaire similar to the one used in Experiment 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 Experiment 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 (Bartneck, Kulić, Croft, & Zoghbi, 2009) 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 (Experiment 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?

2.3.4.2 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.

2.3.4.3 Results

The level of engagement with the robot across the blocks averaged to M = 5.82, SD = 1.8. Similarly to Experiment 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 = 0.004, see Figure 6a.

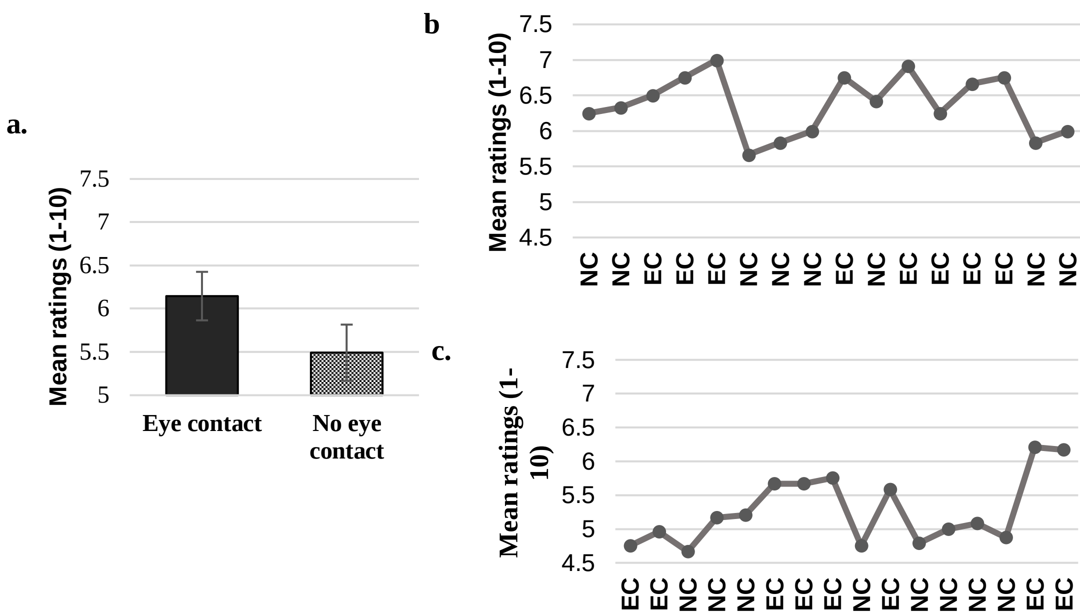


Figure 6. Engagement ratings per gaze condition and across blocks. **6.a** Mean engagement ratings averaged per condition (eye contact condition, no eye contact condition). Error bars represent standard error of the means. **6.b** Mean engagement ratings averaged per block (EC= eye contact block; NC=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

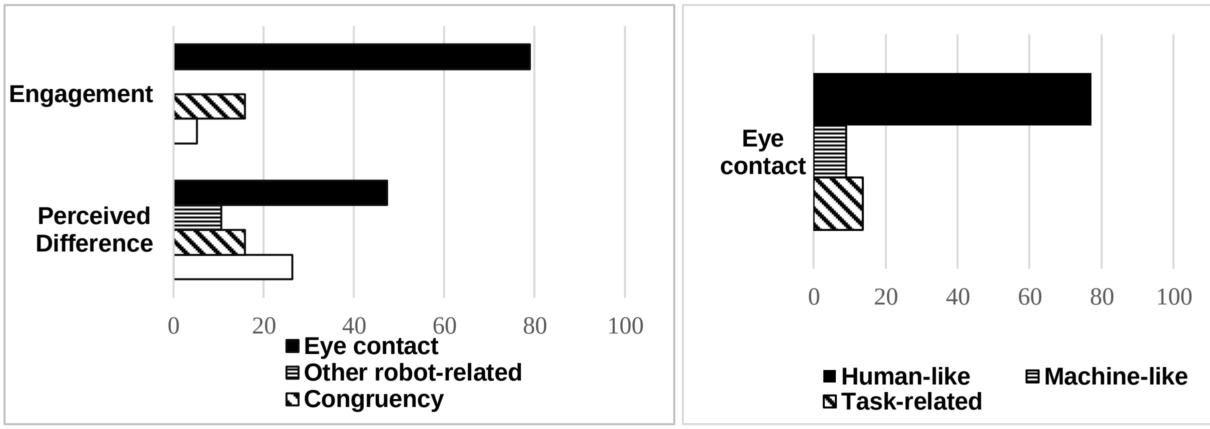
The mean familiarity rating (Question 1) was: M = 1.6, SEM = 0.78. Regarding the question about differences during the experiment (Question 2), 22 participants responded “yes”. 4 people were not included in further analysis, because they did not refer to the difference itself, their responses were unclear or were classified into different categories by the two raters. The remaining 18 participants gave 19 answers in total, and were categorized in the five 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 Figure 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 Figure 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 Figure 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 ($M_{eye\ contact}$= 3.32, SD = 0.78; $M_{no\ eye\ contact}$=3.07, SD = 0.91). Similarly, participants rated the eye contact as more likeable in comparison with the no eye contact condition, Z = -3.5, p <.001($M_{eye\ contact}$= 4.15, SD = 0.71; $M_{no\ eye\ contact}$= 3.58, SD= 0.78).



a. b.

Figure 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). **7.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).

2.3.4.4 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 Experiment 2 was categorized as robot-related. Again, no significant association emerged between experiment and engagement factor, χ^2 (2) = 0.16, p=.93.

2.3.5 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 Experiment 1, iCub either looked toward participant's eyes or downwards and then gazed randomly at one of the peripheral screens where a target appeared (Experiment 1: non-predictive referential gaze, 50% congruency). In the second experiment, iCub after establishing (or not) the eye contact gazed most frequently at the screen that would not contain the target (Experiment 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 attributions of human-likeness to the robot.

The results of both Experiment 1 and 2 showed that in the majority of the given responses 64.7% (Experiment 1) and 47.4% (Experiment 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 Experiment 2, it did not differ from the level of engagement for eye contact reported in Experiment 1. It should be noted that participants rated higher the eye contact condition compared to the no eye contact condition repeatedly across Experiment 1. In Experiment 2, the same effect is clear for Sequence A (same sequence with Experiment 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

Experiment 1 and 79.8% in Experiment 2. No significant difference between experiments emerged regarding social engagement with iCub.

The responses regarding attribution of human-likeness in Experiment 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 Experiment 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 Experiment 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 the design of robots' behavior. 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 (Kajopoulos et al. 2015). 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 (Schilbach et al., 2103, Schilbach, 2014). Our approach of using robots in interactive experimental paradigms increases ecological validity of paradigms used in social cognitive neuroscience, and allows also high degree of controllability, relative to human-human interactions. Therefore, embodied robots provide an efficient tool for studying human cognition, see (Wykowska, Chaminade, & Cheng, 2016; Wiese, Metta, & Wykowska, 2017) 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 (Wykowska, Chellali, Al-Amin, & Müller, 2014; Wykowska et al., 2015; Wykowska, Kajopoulos, Ramirez-Amaro, & Cheng 2015).

2.3.6 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.

2.3.7 References

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2.4. Publication IV: Measuring engagement elicited by eye contact in Human-Robot Interaction

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2.4.1 Abstract

The present study aims at investigating how eye contact established by a humanoid robot affects engagement in human-robot interaction (HRI). To this end, we combined explicit subjective evaluations with implicit measures, i.e., reaction times and eye tracking. More specifically, we employed a gaze cueing paradigm in HRI protocol involving the iCub robot. Critically, before moving its gaze, iCub either established eye contact or not with the user. We investigated the patterns of fixations of participants' gaze on the robot's face, joint attention and the subjective ratings of engagement as a function of eye contact or no eye contact. We found that eye contact affected implicit measures of engagement, i.e., longer fixation times on the robot's face during eye contact. Moreover, we showed that joint attention was elicited only when the robot established eye contact, whereas no joint attention occurred when it did not. On the contrary, explicit measures of engagement with the robot did not vary across conditions. Our results highlight the value of combining explicit with implicit measures in an HRI protocol in order to unveil underlying human cognitive mechanisms, which might be at stake during the interactions. These mechanisms could be crucial for establishing an effective and engaging HRI, and provide guidelines to the robotics community with respect to better robot design.

2.4.2 Introduction

A. Measuring engagement in HRI

Engagement with a robot partner affects the initiation, maintenance, and end of the interaction and thus, it is a crucial factor in successful and natural human-robot interaction (HRI) (Sidner, Lee, Kidd, Lesh, & Rich, 2005). Therefore, it is imperative to address the issue of engagement in HRI research. As stated in (O'Brien, & Toms, 2008, p.1): "Engagement is a category of user experience characterized by attributes of challenge, positive affect, endurability, aesthetic and sensory appeal, attention, feedback, variety/novelty, interactivity, and perceived user control". Studies that have examined the aspect of engagement in HRI used both explicit (e.g., Nomura, Kanda, Suzuki, & Kato, 2008; Rousseau, Ferland, Létourneau, & Michaud, 2013; Ben-Youssef et al., 2017) and implicit measures (Sidner, Kidd, Lee, & Lesh, 2004; Mower, & Feil-seifer, 2007; Rich, Ponsler, Holroyd, & Sidner, 2010; Hall et al., 2014; Baxter, Kennedy, Vollmer, de Greeff, & Belpaeme, 2014; Anzalone, Boucenna, Ivaldi, & Chetouani, 2015; Ivaldi et al., 2017; Székely, & Michael, 2018). Explicit measures and questionnaires – while providing valuable hints regarding the phenomenon of interest, suffer from several limitations. First, they rely on explicit reports, meaning that participants need to be able to consciously assess their inner states. Furthermore, explicit measures are dependent on introspective abilities and interpretation of the questions and can be prone to various biases, such as social desirability effect (Humm, & Humm, 1944). Finally, explicit responses are not sufficiently informative with respect to specific cognitive mechanisms involved, which are implicit and automatic, and thus not necessarily accessible to conscious awareness. In natural interactions, people are often not aware that their brains employ certain mechanisms and processes. However, thanks to the careful design of experimental paradigms inspired by research in cognitive science that target specific cognitive mechanisms, we can collect objective implicit metrics and draw conclusions about what cognitive processes are at stake (Wykowska, Wiese, Prosser, & Müller, 2014; Wykowska et al, 2015; Kompatsiari, Ciardo, Tikhanoff, Metta, & Wykowska, 2018). Typically, psychologists use performance measures (e.g., reaction times, and error rates) to study mechanisms of perception, cognition, and behavior, and also the social aspects thereof: for example, joint attention (e.g., Friesen, & Kingstone, 1998; Driver, Davis, Ricciardelli, Kidd, Maxwell, & Baron-Cohen, 1999; Wiese, Wykowska, Zwickel, & Müller, 2012; Wykowska, Wiese, Prosser, & Müller, 2014; Ciardo, Ricciardelli, Lugli, Rubichi, & Iani, 2015; Perez-Osorio, Müller, Wiese, & Wykowska, 2015; Wykowska et al, 2015; Kompatsiari, Ciardo, Tikhanoff, Metta, & Wykowska, 2018), or visuospatial perspective taking (Samson, Apperly, Braithwaite, Andrews, & Bodley Scott 2010; Zwickel, White, Coniston, Senju, & Frith, 2010). As such, these measures have informed researchers about the respective cognitive processes with high reliability, and without the necessity of participants being aware of the processes under investigation. In addition to performance measures, researchers have also widely used other implicit measures – behavioral (e.g., eye tracking or motion capture) or neurophysiological/neuroimaging: for example, electroencephalogram (EEG), Galvanic skin response (GSR) or functional magnetic resonance imaging (fMRI) (Gazzaniga, & Ivry, 2013). Those measures provide a valuable source of information regarding neural and physiological correlates of behavior.

B. Joint attention as a measure of engagement in HRI

One implicit measure of engagement in social interactions is joint attention (JA). JA occurs when two agents direct their focus of attention to the same object or event in the environment. This fundamental mechanism is a basis for many other complex processes involved in social interactions (Tomasello, & Farrar, 1986; Baron-Cohen, 1991; Baldwin, 1995; Charman et al., 2000; Fiebich, & Gallagher, 2013), like referential communication. In fact, an impaired ability to engage in JA has been reported in the case of individuals diagnosed with autism spectrum disorder (Baron-Cohen, 1997). In human-computer interaction (HCI) and HRI research, JA has been postulated to be a marker of engagement (Peters, Asteriadis, & Karpouzis, 2010; Anzalone, Boucenna, Ivaldi, & Chetouani, 2015). For instance, Anzalone et al. used JA among other dynamic metrics (synchrony, imitation) to evaluate engagement in HRI (Anzalone, Boucenna, Ivaldi, & Chetouani, 2015). Peters et al defined the level of engagement between a user and virtual agent by measuring JA (Peters, Asteriadis, & Karpouzis, 2010)- i.e., how much the user has been looking at objects looked at or pointed by the virtual agent. Moreover, Kasari et al. showed that JA mediated interventions increased engagement of toddlers during interaction with caregivers (Kasari, Gulsrud, Wong, Kwon, & Locke, 2010).

Researchers in cognitive psychology have operationalized JA in the form of the gaze cueing paradigm (Friesen, & Kingstone, 1998; Driver, Davis, Ricciardelli, Kidd, Maxwell, & Baron-Cohen, 1999). This is an attentional task in which participants are presented with a face on the computer screen. The face initially has either eye closed or directed straight ahead. Subsequently, the direction of the gaze is shifted to one of the sides of the screen the gazed-at or a different location. Participants' task is to determine either target's identity or simply respond to its presence. When participants "engage" in JA with the "gazer" they attend to where the gazer shifts their eyes. Therefore, detection/discrimination of any target at the gazed-at location is faster and more accurate than at the other locations, this effect is known as the cueing effect (GCE), and it is considered a behavioral index of JA. Recent studies showed that the GCE can be elicited in naturalistic and ecologically valid paradigms and that it is reflected, apart from performance measures, also in EEG (Schuller, & Rossion, 2001; Perez-Osorio, Müller, & Wykowska, 2017; Kompatsiari, Pérez-Osorio, De Tommaso, Metta, & Wykowska, 2018), fMRI (Kingstone, Tipper, Ristic, & Ngan, 2004; Hietanen, Nummenmaa, Nyman, Parkkola, & Hämäläinen, 2006; Özdem et al., 2017), and eye tracking measures (Pfeiffer, Vogeley, & Schilbach, 2013; Ciardo, Marino, Actis-Grosso, Rossetti, & Ricciardelli, 2014).

Here, we would like to additionally focus on eye tracking as an implicit measure of engagement (Sidner, Kidd, Lee, & Lesh, 2004; Baxter, Kennedy, Vollmer, de Greeff, & Belpaeme, 2014; Anzalone, Boucenna, Ivaldi, & Chetouani, 2015), as eye movements are particularly informative with respect to attentional processes (Deubel, & Schneider, 1996). In the context of social interaction, eye movements not only are informative with respect to the individual's attentional focus, but they are also signaling to others where attention is oriented. As such, they are one of the most important social signals with which we convey our inner mental states (Baron-Cohen, 1991). Despite our sensitivity to gaze shifts, the contribution of other cues to our attentional orienting should not be downplayed, e.g., head orientation and body posture (Perrett & Emery, 1994; Langton, Watt, & Bruce, 2000).

C. Aim of study and related work

In this study, we aimed at examining whether eye contact established by the iCub robot (Metta et al., 2010; Natale, Bartolozzi, Pucci, Wykowska, & Metta, 2017) would influence engagement in HRI, measured by two implicit objective markers: JA (by means of the GCE) and patterns of fixations on the face of the robot during eye contact. Eye contact is one of the most important social signals communicating the intention to engage in an interaction. Indeed, eye contact between humans has been shown to affect various cognitive processes such as attention or memory, and also physiological states, for example, arousal (Senju & Hasegawa, 2005; Hamilton, 2016; Dalmaso, Castelli, & Galfano, 2017).

In the context of HRI, research examining the effect of eye contact mainly focused on subjective evaluations of the robot (Imai, Kanda, Ono, Ishiguro, & Mase, 2002; Yonezawa, Yamazoe, Utsumi, & Abe, 2007; Admoni, & Scassellati, 2017; Kompatsiari, Tikhanoff, Ciardo, Metta, & Wykowska, 2017; Zhang, Beskow, & Kjellström, 2017; Kompatsiari, Ciardo, Tikhanoff, Metta, & Wykowska, 2019), and how it is related to engagement (Rich, Ponsler, Holroyd, & Sidner, 2010). In the present study, we address for the first time the impact of eye contact on two different implicit measures of engagement: the GCE and patterns of fixations on the robot face. Such measures should allow for more in-depth analysis of the cognitive mechanisms that are affected by eye contact in HRI.

Kompatsiari et al. showed that eye contact established by a robot influences JA in the sense that larger GCE has been observed for eye contact condition, as compared to no eye contact condition (Kompatsiari, Ciardo, Tikhanoff, Metta, & Wykowska, 2018). However, it remains to be examined and understood what specifically causes this effect. Is it because eye contact has a “freezing” effect on attentional focus, thereby causing longer disengagement times from the robot face and longer time to reallocate attentional focus to a different location? Or perhaps there are some other attention mechanisms at stake? In the current study, we address this question by employing an eye tracking methodology and investigating the patterns of fixations on the robot face in the context of eye contact and no eye contact. Answering the question of precisely what cognitive mechanisms are affected by eye contact is not only of theoretical interest, but it has also implications for robot design. If eye contact attracts attention to the face of the robot to the point that it creates delays in disengagement, it might be a positive factor for social interaction and engagement, but might impair performance in other tasks where a reallocation of attentional focus is critical.

2.4.3 Methods

A. Participants

In total, twenty-four healthy adults (mean age = 25.25 ± 4.01, 9 female, 2 left-handed) took part in the experiment. All had normal or corrected-to-normal vision, and they received an honorarium of 15 euros for taking part in the experiment. They were all naive with respect to the purpose of this study, and they were debriefed at the end of the experimental session. The experiment was conducted at the Istituto Italiano di Tecnologia (Genoa, Italy). Written consent was taken from each participant before the experimental session. The study was approved by the local ethical committee (Comitato Etico Regione Liguria).

B. Stimuli and Apparatus

The experiment was performed in an isolated and noise-attenuated room. Participants were seated opposite of iCub, at the other side of a desk, while their eyes were aligned with iCub’s eyes. The target stimuli were letters V or T (3° 32' high, 4° 5' wide) and they were presented at two screens (27 inches), laterally positioned on the desk (75 cm apart, centre-to-centre).

The screens were tilted back (by approximately 12° from the vertical position) and were rotated to the right (right screen) or left (left screen) by 76°. iCub's gaze was directed to five different Cartesian coordinates: resting– towards a point between the desk and participant's upper body, eye contact– towards participants' eyes, no eye contact – towards the desk, left – towards the left screen, and right – towards right screen, see for a similar procedure (Kompatsiari, Ciardo, Tikhanoff, Metta, & Wykowska, 2017; Kompatsiari, Ciardo, Tikhanoff, Metta, & Wykowska, 2018).

We used the iCub's gaze controller for controlling the robot's gaze, specifically the eyes and the neck (Roncone, Pattacini, Metta, & Natale, 2016). The controller uses inverse kinematics to find the eyes' and neck's poses for looking at desired Cartesian coordinates in the robot's frame. In addition, it produces joints' movements that follow a minimum-jerk velocity profile. The trajectory time for the movement of eyes and neck was set to 200 ms and 400 ms respectively. The vergence of the eyes was set to 3.5 degrees and maintained constant. The participants' eyes were detected by the robot stereo cameras using a face detector algorithm[7]. When the eyes were not detected by the algorithm, the robot was programmed to look straight. Since participants were seated face-to-face with iCub and their eyes were aligned with iCub's eyes, this procedure ensured the establishment of eye contact even in the rare case of the algorithm's failure. The Cartesian coordinates of the target positions were defined according to predefined values of pitch, roll, and yaw of the neck's joints. These angles were selected adequately in order to ensure balanced joints' displacements between conditions, i.e., a displacement of 12° in the pitch between resting->eye contact and resting->no eye contact, a displacement of 27° in the yaw, 12° in the pitch and 7° in the roll between eye contact-left or right and no eye contact-> left or right. Table 1 shows the desired and measured angles of the neck.

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

Table 1. Robot's gaze positions. EC represents eye contact, no EC represents no eye contact

Desired			
Positions	**roll**	**pitch**	**Yaw**
Resting	0.0	-12.0	0.0
EC	0.0	0.0	0.0
No EC	0.0	-24.0	0.0
Left	-7.0	-12.0	27.0
Right	7.0	-12.0	-27.0
Measured			
Positions	**roll**	**pitch**	**Yaw**
Resting	0.09 ± 0.05	-12.75± 0.02	-0.02 ± 0.08
EC	0.14 ± 0.08	-0.28 ± 0.59	-0.19 ± 0.86
No EC	-0.04 ± 0.03	-24.01 ± 0.05	-0.002 ± 0.01
Left	-7.18 ± 0.08	-12.13 ± 0.08	27.56 ± 0.12
Right	6.93 ± 0.03	-12.05 ± 0.05	-27.65 ± 0.11

C. Procedure

A full experimental session lasted about 40 minutes. Participants were instructed to fixate at the robot's face while performing the task. The sequence of events was the following: Each trial started with the robot having its eyes closed at the resting position. After 2 s, the robot opened its eyes for 500 ms. During this time, the robot extracted information related to the position of the face and the eyes of the participant without making any movement. Then, it looked either to the predefined position: down, for the condition with no eye contact, or direct, to the eyes of a participant in the eye contact condition. After the movement was completed, iCub fixed its gaze to the same position for 2 s. This means that the eye contact/no eye contact duration was 2 s. Subsequently, the robot's head and eyes shifted to either the left or the right screen. Head direction was not predictive with respect to target location (i.e., cue-target validity = 50%). After 1000 ms of the onset of the robot's gaze shift, a letter appeared on one of the lateral screens. After 200 ms, the screens turned blank until the participants' response. The trial expired if participants did not reply within 1500 ms. The experiment consisted of 16 blocks of 16 trials each. A block was assigned to eye contact or no eye contact condition. The order of the blocks was counterbalanced across participants, starting either with a no eye contact block or with an eye contact block. Cue-target validity was randomized across blocks (i.e., cue-target validity = 50% in each block). At the end of each block, participants were asked to rate their engagement level with the robot on a 10-point Likert scale (1 = Strongly not engaged; 10 = Strongly engaged).

D. Eye Tracker recordings

Eye movements were recorded using a wearable eye tracker Tobii pro glasses 2[8] at 100 Hz. The head unit of Tobii pro glasses comprises of two eye cameras per eye, allowing for the recording of pupil positions binocularly. The eye tracking technology is based on pupil center corneal reflection (PCCR) and dark pupil tracking. A full-HD scene camera (1920 x 1080 pixels at 25 fps) is embedded in the head unit with a field of view of 90°, 16:9.

E. Analysis

1) Exclusion Criteria

Three participants were excluded from the analysis due to eye movement recording issues, i.e two recordings could not be opened with the Tobii pro lab software, and in one recording the iCub's face was not fully inside the field of view of the participant. One participant was excluded from the analysis, as s/he failed to follow task instructions (i.e., % of fixation on iCub's face was at the chance of level). The analysis was run on a final sample size of N=20.

2) Eye Tracker

Firstly, we defined our Area of Interest (AOI) as iCub's face. The AOI was defined independently for data collected across the two experimental conditions since the image of iCub's face is different (eye contact: looking straight, no eye contact: looking down). Participants' raw gaze data were mapped inside or outside the desired AOI using the default mapping algorithm of Tobii Pro lab. Fixations were extracted using the default parameters

[8] https://www.tobiipro.com/product-listing/tobii-pro-glasses-2/

of the fixation filter in Tobii Pro lab for the majority of the parameters (Tobii I-VT fixation filter: Olsen 2012). Specifically, the gap fill-in interpolation was not applied, the noise was removed by a moving median filter of 3 samples, the window length of the velocity calculator was set to 20 ms, the velocity threshold was set to 30°/s, and adjacent fixations were not merged. However, we lowered the threshold of the default value regarding the minimum fixation duration from 60 ms to 30 ms in order to extract also very short fixations.

For each trial, we extracted the number of fixations within the AOI and their duration in ms for the gaze condition phase (i.e., the time between resting and lateral movement equal to 2000 ms). If the trial belonged to the eye contact condition, the data were mapped to the AOI of iCub looking straight. In the same way, if the trial belonged to the no eye contact condition, the data were mapped to the AOI of iCub looking down. Paired sample t-tests were performed to test the statistical difference between eye contact and no eye contact conditions regarding the percentage of fixations and the fixations' duration inside our AOI, i.e., iCub's face.

3) Behavioral Data

The errors were 3.2% ± 2.1% of the administered trials, and they were not further analyzed. Reaction times (RTs) faster than 100 ms or 2.5 SDs above or below an individual's mean for each experimental condition were removed (2.34% of the correct trials). After removing all outliers, the experimental conditions (eye contact-valid, eye contact-invalid, no eye contact-valid, no eye contact-invalid) consisted of a similar number of trials on average, equal to 60.5 ± 1.94. Paired sample t-tests were conducted separately for the eye contact and no eye contact conditions between valid and invalid trials.

4) Self –report ratings

Mean engagement ratings for eye contact and no eye contact blocks were analyzed using a Wilcoxon signed-rank test.

2.4.4 Results

1. Robot's performance

The eyes detection algorithm produced valid results for 92.26 ± 16.04 % of the administered trials. The measured mean trajectory times for the gaze positions were very close to the specified trajectory time for the neck movement (400 ms), see Table 2.

Table 2. Mean robot's gaze trajectory times and standard deviations (SD). EC represents eye contact, no EC represents no eye contact, Lateral represents both left and right positions

Positions	Mean (ms)	SD
Resting- EC	401.12	0.37
Resting-No EC	400.65	0.28
EC-Lateral	404.61	2.34
No EC-Lateral	405.54	1.43

2) Eye Tracker

Paired sample t-tests showed significant differences in the fixation durations between the eye contact and no eye contact condition, $t(19) = -2.3$, $p= .03$, 95% CI [-390.51, -18.73]. Specifically, fixation durations were longer for the eye contact (M = 1450.31 ms, SEM = 225.93 ms) compared to the no eye contact condition (M = 1245.69 ms, SEM = 158.7 ms), see Figure 1, lower panel. No difference between eye contact and no eye contact conditions was found for the percentage of fixations inside the AOI; $t(19) < 1$ (eye contact: M = 95.03%, SEM = 1.1%; no eye contact: M = 95.3%, SEM = 1.3%).

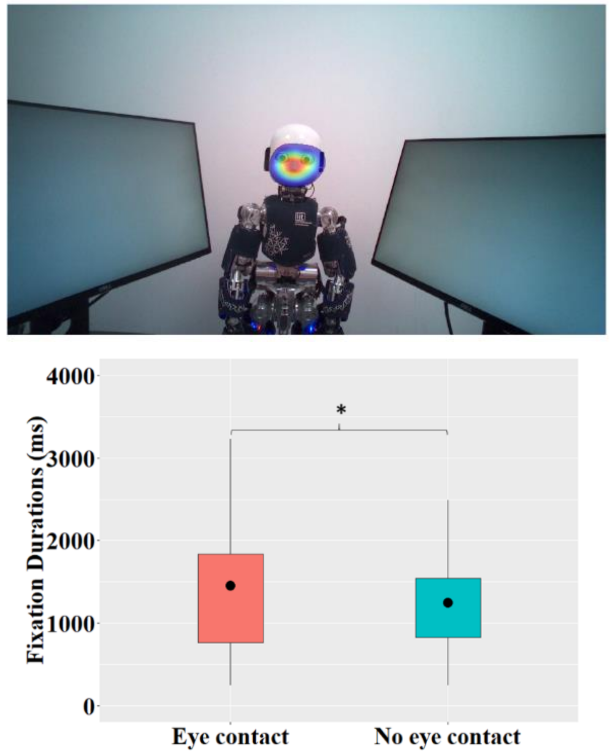

Figure 1. Upper panel: Heat map based on fixation duration values of all participants in the eye contact condition performed with PyGaze (Dalmaijer, Mathôt, & Van der Stigchel, 2014). 'Red zone' represents areas to which participants performed the longest fixations. ‘Blue zone' represents areas to which participants performed the shortest fixations. Lower panel: Mean fixation durations across gaze conditions. The dots represent the mean of the data. End of the whiskers represent the lowest and maximum data point within 1.5 interquartile range of the lower and upper quartile respectively. Asterisk represents significant differences between conditions.

3) Behavioral data

Pairwise comparisons showed a significant difference between valid and invalid trials (the classical GCE) for the eye contact condition, $t(19) = 2.37$, $p = .03$, 95% [CI 1.58, 24.19], with RTs faster for valid (M = 500.11 ms, SEM = 12.74 ms) than invalid trials (M = 512.99 ms, SEM = 15.62 ms), see Figure 2. No differences in RTs between valid and invalid trials were found for the no eye contact condition; $t(19) = 1.6$, $p = .11$, 95% CI [-1.61, 13.3] (Valid: M = 504.9 ms, SEM = 14.75 ms; Invalid: M = 510.73 ms, SEM = 15.2 ms).

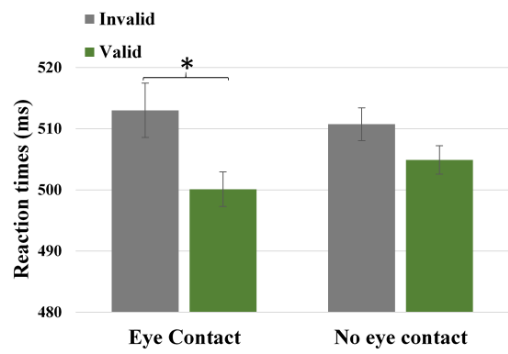

Figure 2. Means RTs across gaze conditions. Grey bars: invalid trials, green bars: valid trials. Error bars represent standard error of the means adjusted to within-participant designs according to Cousineau (Cousineau, 2005). Asterisk represents significant differences between conditions.

4) Self –report ratings

Participants' mean engagement ratings did not differ between the eye contact and the no eye contact conditions, Z = -1.72, p = .09 (eye contact: M = 6.52, SD = 1.96; no eye contact: M = 6.17, SD = 1.98), see Figure 3.

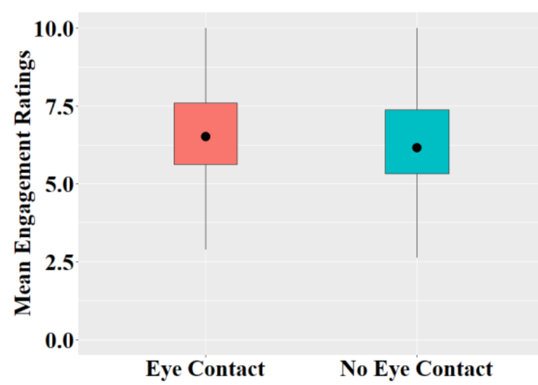

Figure 3. Mean engagement ratings across gaze conditions. The dots represent the mean of the data. End of the whiskers represent the lowest and maximum data point within 1.5 interquartile range of the lower and upper quartile respectively.

2.4.5 Discussion

In the present study, we examined what cognitive mechanisms are at stake during eye contact established by the iCub humanoid robot in HRI. To this end, we combined explicit (subjective reports) and implicit measures of engagement (GCE and fixations' patterns on iCub's face). Results showed that objective measures of engagement differed between the eye contact and the no eye contact conditions. First, our results showed that participants fixated longer to iCub's face during eye contact compared to no eye contact condition. Second, we found a statistically significant GCE (i.e., faster responses to validly- compared to invalidly-cued targets), a behavioral index of JA, only when the robot established eye contact before shifting the gaze. Such a result indicates that participants engaged in JA with iCub only when the robot established eye contact with them (eye contact condition), while there was no JA when iCub looked downwards before the gaze shift (no eye contact condition). It should be noted that the magnitude of the GCE in eye contact condition is comparable to what has been reported in screen-based paradigms in experimental psychology (Friesen, & Kingstone, 1998; Driver, Davis, Ricciardelli; Wiese, Wykowska, Zwickel, & Müller, 2012; Ciardo, Ricciardelli, Lugli, Rubichi, & Iani, 2015; Perez-Osorio, Müller, Wiese, & Wykowska, 2015).

Results from objective measures extend recent findings related to the influence of eye contact on JA (Kompatsiari, Ciardo, Tikhanoff, Metta, & Wykowska, 2018), and they give more insights into the cognitive mechanisms associated with this mechanism in HRI (Admoni, & Scassellati, 2017). Specifically, the longer fixations duration reported in the eye contact condition suggests that when the robot established eye contact participants looked longer at its face. This might have increased the amount of attentional resources allocated at robot's face resulting in a difficulty to "disengage" from the task-irrelevant information, i.e., the head/eyes. Thus, as a consequence, when the robot shifted the head/gaze laterally, participants could not disengage from its face and oriented their attention in the same direction. This resulted in faster reaction times when the target appeared at the gazed-at location compared to when it occurred in the opposite location. On the other hand, when no eye contact was established, participants looked shorter to the robot's face. Shorter fixations at iCub's face may have facilitated participants to allocate their attentional focus to the relevant target letter.

The impact of eye contact on social interaction by holding attention to the robot's face is presumably a facilitating factor in engagement and social interaction with the robot. Indeed, knowing that eye contact keeps or "freezes" attentional focus on the robot face is crucial when designing behaviors in which the robot has to grab users' attention. For instance, imagine a robot designed to give directions to the users, according to our findings it should be designed to establish eye contact with the users in order to attract their attention. However, in other tasks, for example, when moving a heavy object together with the robot, focusing attention on the robot's face/eyes could impair the user's performance by delaying shift of attention toward, for example, a potential obstacle.

Although the present study consists in a lab-based controlled paradigm which does not involve engaging natural ativities, the findings can be informative for future extensions into more naturalistic environments. For example, a paradigm could be developed where participants are engaged in a conversation with a robot. During the conversation, the robot would establish eye contact or not with the participant, while additionally, it would turn its head to look at distracting stimuli in the environment at random instances. In this setup, participants could be free to move their eyes. One could evaluate implicit measures of engagement during eye contact/no eye contact phase (percentage of fixations in the eyes, fixations duration), and also measures of engagement during the joint attention phase initiated by the robot (percentage of gaze following, saccadic times). Additionally implicit and explicit measures (subjective feelings of engagement in the interaction) could be compared.

Interestingly, explicit measures of engagement were not affected by eye contact in this study, which is in contrast to findings of Experiment 1 in (Kompatsiari, Ciardo, Tikhanoff, Metta, & Wykowska, 2018), where results from subjective and objective measures were aligned. A disassociation between explicit and implicit measures found here has been also found in Experiment 2 of (Kompatsiari, Ciardo, Tikhanoff, Metta, & Wykowska, 2018). In that experiment, the results showed that when the head/gaze direction of the robot was counter-predictive with respect to the target location (25% validity) GCE and subjective ratings of engagement showed an opposite pattern. Specifically, while no GCE occurred in the eye contact condition (given to the counter-predictive nature of the head/gaze cue), participants rated their engagement lower than in the no eye contact condition. A dissociation between objective and subjective measures was also reported in Martini, Buzzell, & Wiese, 2015). These findings suggest – as argued earlier – that subjective measures are sometimes not sensitive enough to capture various (often implicit) cognitive processes involved in a task, and that effective evaluation of engagement in HRI needs to supplement subjective reports with objective measures.

In conclusion, our study highlights the necessity of using objective measures to target implicit social cognitive mechanisms that are evoked during HRI. This approach is essential for designing robot behaviors which would need to elicit or inhibit these mechanisms dependent on the specific context of the human-robot interaction.

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GENERAL DISCUSSION

3.1. Synopsis of results

The work described in this thesis aimed to show that creating a link between social cognition and HRI fields can provide useful insights and overcome current methodological limitations of both disciplines. To show this, the current thesis focused on an unexplored topic of social cognition, i.e., the effect of real-time eye contact on gaze-mediated attentional orienting. More specifically, the study presented in **Publication I** aimed to adapt the gaze-cueing paradigm to an objective neuroscientific HRI. Furthermore, it aimed to examine whether the GCE is sensitive to the establishment of eye contact prior to the gaze-cueing procedure. The study replicated classic GCE findings both at the behavioral level (i.e., faster RTs to validly- relative to invalidly-cued targets) and the neural level (i.e., enhanced N1 component of parieto-occipital EEG signal for validly- relative to invalidly-cued targets). GCE was present in both gaze type conditions (eye contact or no eye contact). The aim of the study reported in **Publication II** was to examine whether eye contact modulates the GCE depending on cue validity and SOA. Results showed that the GCE occurred as an interaction of a bottom-up reflexive orienting of attention, with top-down modulatory mechanisms related to social engagement exerted by eye contact, and "strategic" control combined. Importantly, the "strategic" top-down mechanism was activated when social engagement occurred (i.e., eye contact), but not when the context was less socially evocative (i.e., no eye contact). The study presented in **Publication III** aimed to examine how the gaze of a humanoid robot (i.e., establishing eye contact or not) was evaluated by participants based on subjective reports. Results demonstrated that when the robot established eye contact with the participants, it was rated as more human-like and engaging in comparison to when it did not establish eye contact. Similarly, the aim of the study presented in **Publication IV** was to investigate how eye contact established by a humanoid robot could affect implicit and explicit measures of engagement. Results showed a dissociation between objective and subjective measures. Objective measures showed a higher degree of "attentional engagement" when the robot established eye contact (i.e., longer fixations to iCub's face during eye contact compared to no eye contact, engagement to joint attention), while subjective feelings of engagements were not modulated by eye contact.

3.1.1 Implications for social cognition research

In the majority of the experiments reported here, participants rated online eye contact as more engaging compared to the no eye contact condition (studies reported in Publication II and Publication III but not Publication IV). The engaging and/or rewarding effect of eye contact is supported by previous neuroimaging studies. Indeed, it has been shown that eye contact positively modulates reward-related neural circuitry, as indicated by activation of dopaminergic systems when pleasing faces with a direct compared to averted gaze are presented (Kampe, Frith, Dolan, & Frith, 2001). Similarly, Schilbach et al. (Schilbach, Wilms, & Eickhoff, 2010) showed that other contingent behaviors, such as initiating a contingent gaze sharing, can also activate reward-related brain regions. Moreover, in our last study, we showed that eye contact 'attentionally' engaged participants (Publication IV). That is, participants, engaged in longer fixations at iCub's face during the eye contact compared to the no eye contact condition, thereby resulting in a difficulty to "disengage" from the task-irrelevant information (i.e., the head/eyes direction). The fact that eye contact can serve as an "attractor" of attention is demonstrated in earlier studies (Senju & Hasegawa, 2005; Palanica & Itier, 2012). For example, it has been shown that faces with direct gaze were looked at for longer durations compared to faces with averted gaze (Palanica & Itier, 2012). Additionally, Bristow et al. showed that a face with direct gaze attracted covert attention and facilitated joint attention (compared to a face with averted gaze) by facilitating the discrimination of the subsequent gaze shift (Bristow, Rees, & Frith, 2007). These results might indicate that the longer fixations at iCub during eye contact assisted participants in engagement to joint attention since it enhanced the detection of the subsequent gaze shifts. In the present project, it can be argued that the eye contact – acting as an engaging/rewarding signal – engages attention towards the directional gaze and subsequently modulates joint attention.

In the first two studies, the effect of eye contact on gaze-mediated orienting of attention was systematically investigated. In the first study, non-predictive gaze cues were used together with a relatively short SOA (500 ms).[9] Results showed that GCE was evoked

[9] A relatively long SOA for classical screen-based paradigms (500 ms) appears much shorter when the entire head movement is displayed, given that the SOA is counted from the onset of the movement to its final position.

independent of the gaze type condition (eye contact or no eye contact). Due to the non-predictive design of the task and the relatively short SOA (given the natural interaction), the observed gaze-cueing effects is probably due to the reflexive orienting of attention. In subsequent study (Experiment 1 of Publication I), the gaze direction was non-predictive and the SOA was longer (1000 ms). In this case, GCE occurred only in the eye contact condition[10]. Results from the first two experiments showed that when there was no need for top-down 'strategic' control over orienting of attention (50% validity), the top-down social component of the eye contact up-regulated the baseline GCE only when long SOA's were used. Thus, the enhanced reflexive component of attentional orienting allowed the attention-related activity to be larger and/or last longer than the default reflexive component, in line with the idea that the top-down mechanisms of attentional orienting have a longer-lasting effect than the transient, reflexive component (Müller & Rabbitt, 1989). In the no eye contact condition, no GCE was observed for long SOA's (1000 ms). Although it cannot be conclusively supported by the present data, the absence of a social/engaging context might have allowed the reflexive gaze-cueing effect observed in the first study to fade-away within the longer SOA, which is also in line with literature showing that the bottom-up mechanisms of attention orienting are transient and short-lived (Müller & Rabbitt, 1989). Finally, in the follow-up study (Experiment 2 of Publication II), the SOA was the same as the first study (500 ms) but the influence of the top-down strategic component was attenuated by decreasing the gaze validity to 25%. Given the counter-predictive design of the task and the relatively short SOA, it was hypothesized that if a GCE emerges, it would be due to a reflexive component of attentional orienting, while the lack of GCE would reflect a top-down suppression of the reflexive mechanism. In this experiment, a GCE was observed only in the no eye contact condition, reflecting the reflexive default mechanism of attentional orienting. Results from this study demonstrated that when there is a need for top-down strategic control due to a misleading cue (25 % validity), the eye contact actively down-regulated the reflexive component of orienting of attention even with a short SOA. Taken together, results of these three experiments showed that GCEs emerged because of an

[10] This result was replicated in the study reported in Publication IV, in which participants engaged to joint attention only in the eye contact condition (using the same parameters for the gaze cueing procedure)

interaction between the social (eye contact) and strategic (gaze validity) top-down components on the reflexive gaze-induced orienting of attention.

Based on these findings, we postulate the following cognitive mechanisms elicited in the condition of social engagement exerted by eye contact (cf. Figure GD1). The proposed neural correlates are speculative, based on previous literature. The idea is that eye contact – due to its larger degree of social engagement– activates the social areas of the cortex, such as the medial pre-frontal cortex (mPFC) and superior temporal sulcus (STS; Senju & Johnson, 2009). Interestingly, the activated parts of the "social brain" are more likely to activate the "strategic" top-down control regions of the prefrontal cortex (Figure GD1, black box, second from bottom) – (most probably in the dorsolateral portion (dlPFC) (Miller & Cohen, 2001; Senju & Johnson, 2009). Subsequently, dependent on the cue predictivity and the SOA, the strategic component either does not regulate (default attentional orienting mechanism) the activation of the attentional network (intraparietal sulcus, IPS and the inferior frontal cortex, IFC) (Corbetta & Schulman, 2002), up-regulates (enhances) or down-regulates (suppresses) it. The STS is also included in the areas involved in this attentional network as this area is responsible for gaze direction detection (Hoffman and Haxby, 2000). When following gaze direction is low in costs (50% cue validity), the top-down active enhancement of reflexive attentional orienting needs some time to develop (in the case of our experiments, it was 1000 ms). Hence it has been observed in Experiment 1 of Publication II (Figure GD1, middle.) but not in the first study (Publication I) with 500 ms SOA (Figure GD1, left.). In Experiment 2 of Publication II, given that following the gaze was high in cost (25% validity), the engaging condition of eye contact presumably induced active suppression of the reflexive component of attentional orienting, and therefore, the GCE was not observed for the eye contact condition (Figure GD1, right).

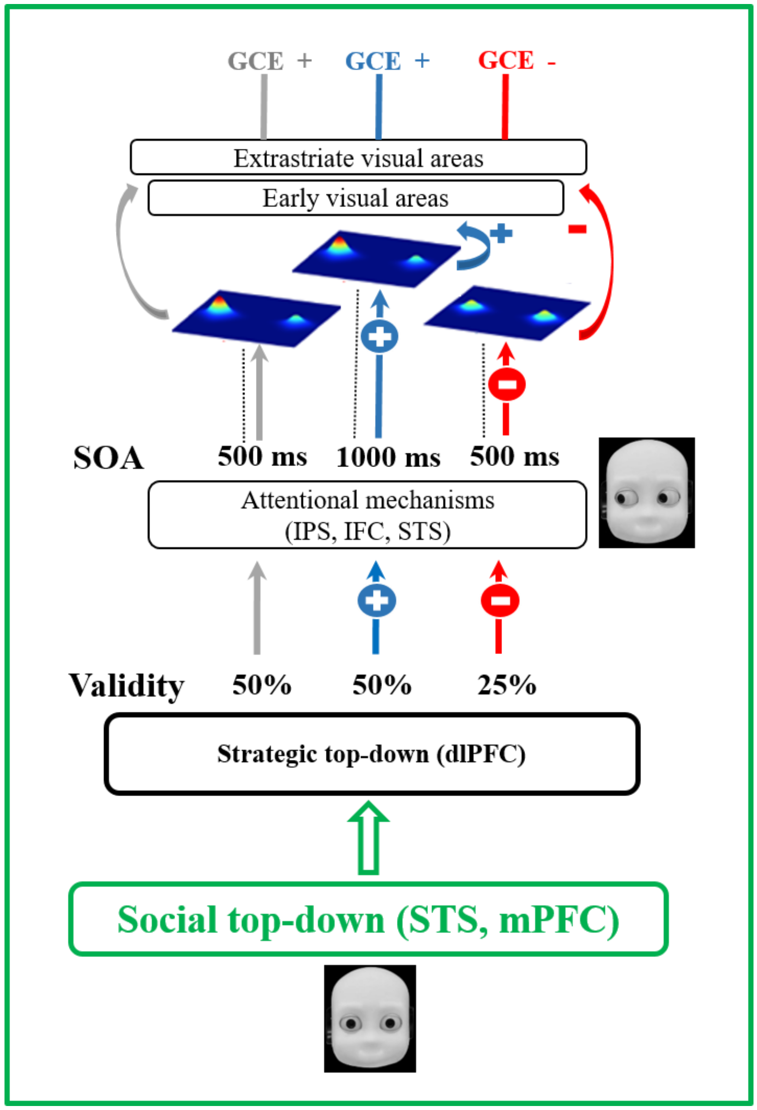

Figure GD1. **Eye contact condition**. Left: Cue validity, 50%, SOA, 500 ms. Middle: Cue validity, 50%, SOA, 1000 ms. Right: Cue validity, 25%, SOA: 500 ms. Eye contact (bottom) activates the "social brain" areas (green box at the bottom). Once activated, they activate the more "strategic" top-down control, which can either not regulate (left, grey arrows), up-regulate (middle, blue arrows) or down-regulate (right, red arrows) the default attentional orienting mechanism (black box, third from bottom) depending on the gaze validity and the SOA. This mechanism prioritizes gazed-at locations. Subsequently, when a cued target is presented, it is processed with priority by the default attentional mechanism (left), it is top-down enhanced (middle) or suppressed (right). The modulation from the attentional network (IPS, IFC, STS) over processing of the target letter occurs at the extrastriate areas, as this is related to the sensory gain control mechanism (Hillyard, Vogel & Luck, 1998).

In Figure GD2, the mechanisms involved in the no eye contact condition are presented. In the case of no eye contact, since there was no rewarding/engaging signal the areas of the "social brain" were *not* activated (two bottom grey dotted boxes). Therefore, only the default reflexive attentional orienting mechanism related to gaze direction (Driver et al., 1999; Friesen & Kingstone, 1998) was presumably at stake. This mechanism enhanced the processing of the target at the cued, relative to uncued, location, but the enhancement – being bottom-up – was likely transient (e.g., Müller & Rabbitt, 1989). Therefore, the GCE was observed with the short SOAs, (500 ms SOA), presumably reflecting a reflexive default mechanism of attention, which likely faded away when the SOA was longer.

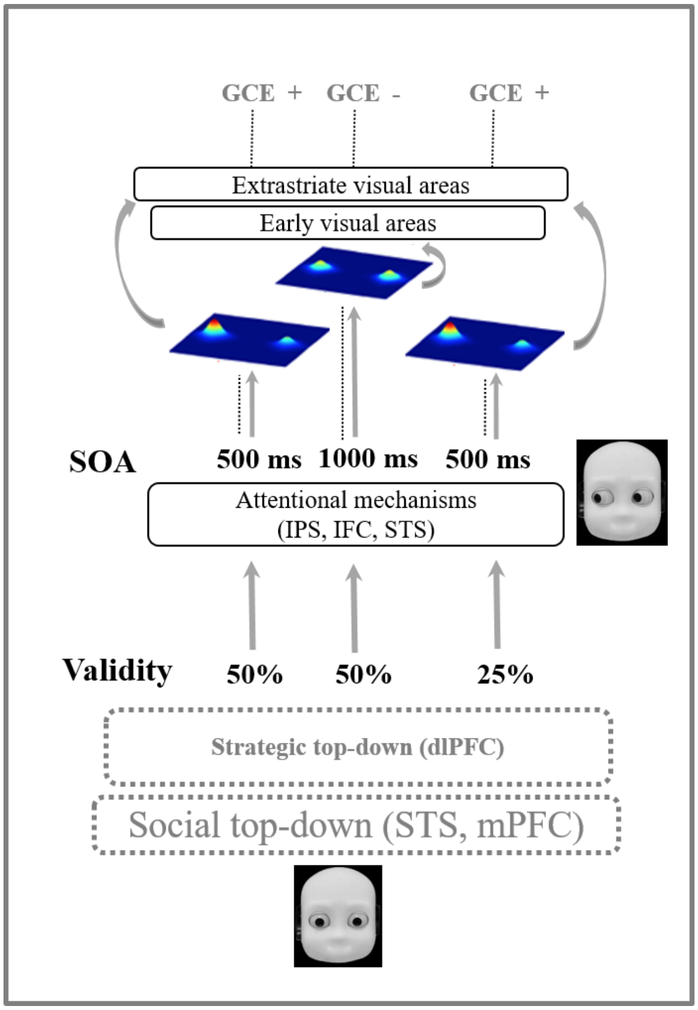

Figure GD2. **No eye contact** condition. Left: Cue validity, 50%, SOA, 500 ms. Middle: Cue validity, 50%, SOA, 1000 ms. Right: Cue validity, 25%, SOA: 500 ms. With no eye contact, "social brain" areas are not activated (grey dashed box at the bottom), and processing of the target is modulated only through a default attentional orienting mechanism (black box, third from bottom). This mechanism prioritizes gazed-at locations in a reflexive manner. However, when the target is presented after a long SOA (middle), it is no longer processed with priority, as the transient enhancement related to reflexive attentional orienting fades away. However, when the target is presented after a short SOA (left, right), the transient enhancement is still present independent of cue validity. The modulation from the attentional network (IPS, IFC, STS) over target processing occurs at the extrastriate areas, as this is related to the sensory gain control mechanism (Hillyard, Vogel & Luck, 1998).

3.1.2 Implications for HRI research

Cognitive neuroscience methods in HRI research

The gaze-cueing experiment with iCub humanoid robot combined with the EEG methodology (Publication I) consists an important work in implementing a well-studied paradigm of cognitive science (i.e., gaze-cueing paradigm) in a HRI setup using objective neuroscientific methods. Importantly, well-documented results were replicated both at behavioral and neural levels. First, faster reaction times were found for discrimination of cued, relative to uncued targets. Second, N1 ERP component of the EEG signal was larger and peaked earlier in valid compared to invalid trials, thereby demonstrating that the attentional focus was enhanced for validly- compared to invalidly-cued targets. These findings provide supportive evidence for the feasibility and the scientific value of adding neuroscientific methods in human-robot experimental protocols.

The necessity for adding objective methods to HRI is further supported by the results of studies, in which we found a dissociation between explicit (self-reports) and implicit measures of engagement (i.e., joint attention and patterns of fixations). More specifically, we showed that eye contact condition enhanced the feeling of engagement towards the robot compared to no eye contact condition, independently of the cue predictivity (Publication II). However, eye contact modulated the joint attention mechanism in a dissimilar way across the different gaze validity ratios, i.e., it enhanced the GCE with respect to a non-predictive gaze while it suppressed the GCE with respect to a counter-predictive gaze. Moreover, in the last study, we found that eye contact did not affect the subjective feelings of engagement compared to no eye contact (Publication IV). However, it modulated implicit measures of engagement. First, eye contact engaged participants' attention to iCub's face by enabling longer fixations to the face compared to no eye contact. Second, eye contact engaged participants to joint attention, as indicated by the GCE, while no-eye-contact did not. Dissociation between implicit and explicit measures is supported by previous studies (Martini, Buzzell, & Wiese, 2015). Thus, current findings suggest that designing HRI experimental protocols grounded in neuroscience methods can assist in targeting specific cognitive mechanisms that are at stake during HRI and cannot be fully addressed with explicit measures, e.g. subjective evaluations and questionnaires.

Effects of eye contact in human-robot interaction

Results reported in Publication III show that an artificial agent that needs to convey a social communicative cue to a human interaction partner (e.g. to orient its attention) appears more human-like when it establishes eye contact with the human compared to when it avoids human's gaze contact. These findings have implications for the design of robots, since it has been shown that human-like behavior is one of the most critical aspects (the other is human-like appearance) for artificial agents to appear social (Wiese, Metta, Wykowska, 2017), and it can thus facilitate smooth HRI. For example, it could be argued that for social robots that need to guide people's attention in public spaces, establishing eye contact would assist their attentional orienting towards the relevant location (e.g., an emergency exit during a fire).

Results from subjective reports of our studies show that an artificial agent establishing eye contact engages humans more in a task they are performing with the agent. Furthermore, as shown by the eye tracking results presented in Publication IV, eye contact 'freezes' attention at the robot's face. Such results could have important implications for the design of robots' behavior. On the one hand, when a robot has to sustain our attention (e.g. a teaching assistant robot or a robot giving instructions), the establishment of eye contact might facilitate the HRI by increasing our engagement to the robot and learning as a consequence. Furthermore, in a clinical context, where robots are used to train social capabilities in clinical populations, (e.g., children with the autism spectrum disorder, ASD), online eye contact may facilitate the engagement of ASD children and thus enhance social training outcomes, especially for those protocols that aim at training social communicative signals (e.g., joint attention). That said, it remains to be tested whether eye contact can engage ASD patients as it does with typically developed adults. On the other hand, it remains to be noted, that when the robot has to perform a difficult action with another person (e.g. cooking a meal or moving a heavy object together), the eye contact might hinder the HRI by delaying the shifting of attention to crucial locations in space (e.g. one's own actions while preparing the food or an obstacle in the environment).

3.2. Future directions

The present findings argue in favor of the idea that eye contact can modulate joint attention depending on the validity of the cue and the duration of the SOA. However, there are certain limitations that need to be taken into account for future studies. First, current studies do not include a neutral condition. Although selecting a neutral condition in a gaze-cueing procedure is challenging due to a potential communicative content associated by almost any gaze - one could potentially involve a condition where the robot remains with eyes closed after creating an eye contact or not. A neutral condition would assist in disentangling whether indeed following the gaze cue in a non-predictive gaze-cueing procedure does not impact task performance (low-cost of gaze following in a 50% gaze-cueing study, as suggested in 3.1.1) while following the gaze cue in a counter-predictive gaze-cueing procedure would impose a cost in task performance (high-cost of gaze following in a 25% gaze-cueing study, as suggested in 3.1.1). Second, the duration of eye contact was not held constant across experiments. More specifically, in Experiment 2 of Publication II, the gaze contact duration was reduced by half relative to Experiment 1 (Experiment 1: 2000 ms, Experiment 2: 1000 ms) so that the ratio of the duration between eye contact and SOA (Exp 1: 1000 ms, Experiment 2: 500 ms) would remain similar. To exclude any effect of the gaze duration on the pattern of results, it would be important to perform the same experiments keeping the duration of eye contact/no eye contact phase constant. Furthermore, one more experiment should be conducted to have a clearer view of how eye contact modulates the GCE depending on the cue validity and the SOA, i.e., counter-predictive cue and long SOA (1000 ms). Based on current findings, it is expected that such a design would lead to no GCE for both eye contact and no eye contact conditions. This result is expected since eye contact condition suppressed the GCE even with a short SOA using a counter-predictive cueing procedure (Publication II, Experiment 2). Moreover, the reflexive GCE present in no eye contact condition (Publication II, Experiment 2) will presumably fade-out due to the longer SOA (similar to Experiment 1 in Publication II).

Our well-controlled interactive setup allows for developing future studies that would tackle specific theoretical questions in attentional orienting that are not fully yet understood. For example, it could be investigated how the various non-verbal cues such as eyes, head, body posture or pointing are integrated in order to direct attention (Langton, Watt, & Bruce, 2000). This question could be addressed with our gaze-cueing procedure, since the robot can act as a cue by using separate components (e.g. only eyes) or a selected combinations of them (e.g. only eyes and pointing) (Sciutti, Ansuini, Becchio, & Sandini, 2015), thus allowing for examining the effect of each combination on the subsequent attentional orienting. This topic is also relevant for clinical applications, in order to design appropriate training protocols for those individuals with deficits in attentional orienting. Indeed, preliminary studies showed that a robot needed to employ a richer combination of cues (face and arm) to engage children with ASD to joint attention compared to a human (only face) (Anzalone et al., 2014; Bekele et al., 2014; David et al., 2018). Second, another parameter that could potentially influence joint attention but is difficult to tackle with either naturalistic human-human setups or screen-based static pictures is the speed of the attentional cue movement. This topic has also implications for populations with impaired processing of visual motion, such as ASD patients (Simmons et al., 2009). For example, children diagnosed with ASD showed an improvement of verbal cognition performance (i.e., ability to understand questions/instructions and answer them verbally/nonverbally) and behavior (i.e., attention, verbal/nonverbal communication, social reciprocity) in slowed-down videos compared to real-time videos (Tardif, Latzko, Arciszewski, & Gepner, 2017).

3.3. Using humanoids robots for joint attention research: limitations and guidelines

The current project showed that embodied humanoid robots in interactive protocols could lead to new insights regarding joint attention mechanisms. However, it is important to note that using humanoid robots as sophisticated stimuli to study joint attention should be performed with particular attention. Importantly, researchers should be aware that robots obviously cannot replace a human interactive partner, or elicit exactly the same mechanisms as those involved in real-life human-human interactions. That being said, this limitation is not exclusively associated with the use of robots as social stimuli. Even human agents in the role of interaction partners in controlled experimental setups could impose the same constraint, e.g., by repeating the same monotonous movements over a relatively long time period. Furthermore, even the knowledge of participants that they are under examination might alter their behavior compared to spontaneous human-human interactions. However, robot stimuli might entail a particular limitation associated with their artificial nature. To begin with, their artificial nature might not be sufficient to elicit mechanisms of joint attention under certain conditions. For example, in term of appearance, Martini and colleagues' showed that only robotic agents with a moderate level of human-likeness (60 % human morph) elicited a reflexive GCE while robotic agents with 100 % robot-likeness or 100 % human-likeness effect suppressed the GCE (Martini, Buzzell, & Wiese, 2015). In terms of behavior, the present thesis showed that only a real-time eye contact sustained the GCE with non-predictive gaze cues when the SOA was long (1000 ms). Furthermore, eye contact initiated by a humanoid robot was shown to increase its perceived human-likeness and engagement with the robot. Thus, it would also be beneficial if robots are endowed with algorithms that allow them to establish eye contact with users in real-time. Another limitation of robots' artificial nature is the potential negative attitudes that they could evoke in some people, e.g., anxiety towards robots and artificial intelligence. To address this limitation, individual bias should be always measured and the effects of inter-individual differences should be controlled. Another possible limitation of using robots as social stimuli is the generalizability of the results and the comparison between studies since robotic platforms can differ largely across laboratories. This constraint could be addressed by comparing the same robotic platforms or using robots that have similar mechanical characteristics of the eyes, thereby evoking similar gaze cues. Finally, to ensure the reproducibility of the results in gaze-cueing studies, authors should report the controller used for producing robot's movements, as well as the desired and actual measured kinematic parameters (e.g. eyes/head velocity) and follow open research practices.

3.4. Conclusions

In the present thesis, it is argued that embodied humanoid robots embedded in interactive experimental protocols that are grounded in well-established social cognitive paradigms can be extremely informative both for social cognition and HRI research. First, serving as social stimuli of higher ecological validity (e.g., compared to screen-based experiments) and excellent experimental control (e.g., compared to human-human interaction protocols), robots can assist in advancing the theoretical knowledge of social cognitive mechanisms in embodied interactions. Second, being embedded in experimental paradigms that target specific mechanisms of social cognition, embodied humanoid robots can inform the HRI community about the design of robot behaviors that would elicit specific mechanisms dependent on the context. In the near future, this would boost and facilitate smooth and effective interactions with artificial agents.

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Curriculum Vitae

Education

4/2016-now — **PhD** in Systemic Neurosciences, GSN, LMU Munich, Istituto Italiano di tecnologia, Genova.

- Research on the influence of eye contact on joint attention using humanoid-based protocols
- Supervised by prof. Agnieszka Wykowska, prof. Hermann Mueller, dr. Francesca Ciardo

9/2010-9/2012 — **Professional Doctorate in Engineering** in Information and Communication Technology, Technical University of Eindhoven (TU/e), Philips Healthcare.

- Thesis: Quantitative Angiogenesis Imaging in Prostate Cancer by DCE-MR Dispersion Imaging

9/2002-7/2009 — **Diploma (M.Sc.)** in Electrical and Computer Engineering, AUTh, Thessaloniki.

- Specialization: Computer Vision, Artificial Intelligence, Software applications.
- Thesis: Hierarchical Classifier Development using Operators of Fuzzy Decision Fusion

Professional Experience

9/2015-4/2016 — **Research Assistant** in Department of Experimental Psychology, LMU, Munich.

- Project: Cognitive Neuroscience and Social Robotics

5/2013-5/2016 — **Researcher** in Brain and Trauma Foundation, Chur, Switzerland.

- Project: Electrophysiological Biomarkers in ADHD, Mild traumatic brain injury, Heart Attack

12/2009-7/2010 **Research Assistant** in Artificial Intelligence & Information Analysis Laboratory, AUTh, Thessaloniki

- Project: An Integrated Intelligent Home Environment for the Provision of Health, Nutrition and Mobility Services to the Elderly (EU FP7 MOBISERV)

Additional Training

- **Beyond p < .05: Modern statistical approaches in psychological science**, Padova, Italy, 18/2-22/2 2019.
- **International Winter School on Humanoid Robot Programming**, Santa Marguerita, Italy, 30/1-8/2 2017.
- **IMPRS NeuroCom Summer school, "What makes us human"**, MPI, Leipzig, Germany, 4-6/7 2016.
- **Functional Biomarkers in Neurology and Psychiatry**, EEG info courses, HBImed, Berg , Germany, 14-18/5 2013.
- **Regularization Methods for High Dimensional Learning**, University of Genova, REGML 2013, 3-7/6 2013.
- **CIMST Summer School on Biomedical Imaging** ,ETH, Zurich, 3-18/9 2012.
- **Visiting student**, School of Informatics UPC – Barcelona Tech, Spain, 2/2008-6/2008

Computer Skills

- Software packages: Matlab, SPSS, EEGLAB, WINEEG, BRVA, Eprime, JASP.
- Programming languages: C/C++, R, Python.

Language Skills

English (Proficiency level), Spanish (B2), Italian (B1), German (B1), Greek (native speaker)

Publications

Chevalier, P., Kompatsiari, K., Ciardo, F., & Wykowska, A. (accepted). Examining joint attention with the use of humanoid robots - a new approach to study fundamental mechanisms of social cognition. *Psychonomic Bulletin & Review*.

Kompatsiari, K., Ciardo F., De Tommaso, D., Wykowska, A (2019, November). Measuring engagement elicited by eye contact in Human-Robot Interaction. In *IROS* International Conference on Intelligent Robots and Systems, Macau.

Kompatsiari, K., Ciardo, F., Tikhanoff, V., Metta G. & Wykowska A (2018). It's in the eyes: The engaging role of eye contact in HRI, *International journal of Social Robotics*, pp. 1-11.
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Kompatsiari, K., Pérez-Osorio, J., De Tommaso, D., Metta, G., Wykowska, A (2018, October). Neuroscientifically-grounded research for improved human-robot interaction. In *IROS* International Conference on Intelligent Robots and Systems, Madrid, 3403-3408.

Candrian, G., Müller, A., Dall'Acqua, P., Kompatsiari, K., Baschera, G. M., Mica, L., ... & Meier, C. (2018). Longitudinal study of a NoGo-P3 event-related potential component following mild traumatic brain injury in adults. *Annals of physical and rehabilitation medicine*, *61*(1), 18-26.

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LIST OF PUBLICATIONS AND AUTHOR CONTRIBUTIONS

Publication I – Neuroscientifically-grounded research for improved human-robot interaction

Kompatsiari, K., Pérez-Osorio, J., De Tommaso, D., Metta, G., & Wykowska, A. (2018, October). Neuroscientifically-grounded research for improved human-robot interaction. *In 2018 IEEE/RSJ International Conference on Intelligent Robots and Systems* (IROS) (pp. 3403-3408). IEEE

Author contributions. KK, JPO contributed equally to the paper. KK, JPO, AW conceived and designed the experiment. JPO, KK, DT programmed the experiment. KK, JPO performed the experiment and analyzed the results. All authors discussed the results. KK, JPO wrote the paper. All authors revised the paper.

Publication II – On the role of eye contact in gaze cueing

Kompatsiari, K., Ciardo, F., Tikhanoff, V., Metta, G., & Wykowska, A. (2018). On the role of eye contact in gaze cueing. *Scientific reports*, 8(1), 17842.

Author Contributions. K.K. conceived, designed and performed the experiments, analyzed the data, discussed and interpreted the results, wrote the manuscript. F.C. conceived, designed and performed the experiments, analyzed the data, discussed and interpreted the results. V.T programmed the experiment, discussed and interpreted the results. G.M discussed and interpreted the results. A.W. conceived the experiments, discussed and interpreted the results, wrote the manuscript. All authors reviewed the manuscript.

Publication III – It’s in the eyes: The engaging role of eye contact in HRI

Kompatsiari, K., Ciardo, F., Tikhanoff, V., Metta, G., & Wykowska, A. (2019). It’s in the Eyes: The Engaging Role of Eye Contact in HRI. International Journal of Social Robotics, 1-11.

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Publication IV – Measuring engagement elicited by eye contact in Human-Robot Interaction

Kompatsiari, K., Ciardo, F., de Tommaso D., & Wykowska, A. (accepted, 2019). Measuring engagement elicited by eye contact in Human-Robot Interaction. *In 2019 IEEE/RSJ International Conference on Intelligent Robots and Systems* (IROS), Macau. IEEE.

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I hereby certify that the information above is true and accurate.

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EIDESSTATTLICHE VERSICHERUNG / AFFIDAVIT

Hiermit versichere ich an Eides statt, dass ich die vorliegende Dissertation **Humanoid-based protocols to study social cognition: On the role of eye contact in joint attention** selbstständig angefertigt habe, mich außer der angegebenen keiner weiteren Hilfsmittel bedient und alle Erkenntnisse, die aus dem Schrifttum ganz oder annähernd übernommen sind, als solche kenntlich gemacht und nach ihrer Herkunft unter Bezeichnung der Fundstelle einzeln nachgewiesen habe.

I hereby confirm that the dissertation **Humanoid-based protocols to study social cognition: On the role of eye contact in joint attention** is the result of my own work and that I have only used sources or materials listed and specified in the dissertation.

München, den 17.12.2019

Munich, date 17.12.2019 Unterschift/Signature

Kyveli Kompatsiari