



## Psychophysiological responses to eye contact with a humanoid robot: Impact of perceived intentionality

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### ABSTRACT

Eye contact with a social robot has been shown to elicit similar psychophysiological responses to eye contact with another human. However, it is becoming increasingly clear that the attention- and affect-related psychophysiological responses differentiate between direct (toward the observer) and averted gaze mainly when viewing embodied faces that are capable of social interaction, whereas pictorial or pre-recorded stimuli have no such capability. It has been suggested that genuine eye contact, as indicated by the differential psychophysiological responses to direct and averted gaze, requires a feeling of being watched by another mind. Therefore, we measured event-related potentials (N170 and frontal P300) with EEG, facial electromyography, skin conductance, and heart rate deceleration responses to seeing a humanoid robot's direct versus averted gaze, while manipulating the impression of the robot's intentionality. The results showed that the N170 and the facial zygomatic responses were greater to direct than to averted gaze of the robot, and independent of the robot's intentionality, whereas the frontal P300 responses were more positive to direct than to averted gaze only when the robot appeared intentional. The study provides further evidence that the gaze behavior of a social robot elicits attentional and affective responses and adds that the robot's seemingly autonomous social behavior plays an important role in eliciting higher-level socio-cognitive processing.

### 1. Introduction

Whether it is an exhibition at a mall, collaboration in a work environment, or receiving assistance at home, a notable proportion of people have experienced encounters with so-called social robots, robots designed to interact with people in a natural and interpersonal manner. Social robots have been developed to aid in, for example, healthcare (Basteris et al., 2014; Prange et al., 2006), elderly care (Birks et al., 2016; Wada and Shibata, 2007), children's therapeutic interventions (Dautenhahn, 2003; Robins et al., 2005), and educational settings (Kory and Breazeal, 2014; Mubin et al., 2013). Even though social robots are merely machines with preprogrammed behavior, people tend to attribute human characteristics to them, an automatic process known as anthropomorphism (Fink, 2012; Hofree et al., 2014, 2015; Kiesler et al., 2008). Importantly, these characteristics include perceiving non-human entities as possessing a humanlike mind. People thus tend to attribute

mental capabilities such as intentionality, agency, and experience to robots and other non-human entities (de Graaf and Malle, 2019; Gray et al., 2007; Thellman et al., 2017; Ward et al., 2013). Perceived intentionality in humanoid robots may be induced by certain behavioral attributes (Wiese et al., 2017), such as verbal communication (Duffy, 2003) and humanlike movement with the lack of causal predictability (Caporael, 1986; Chouchourelou et al., 2012; Sciutti et al., 2015; Waytz et al., 2010b), or by observing harm being done to robots (Swiderska and Küster, 2018; Ward et al., 2013). However, robots are still generally perceived as having less of a mind than humans (Levin et al., 2008; Marchesi et al., 2019).

In addition to verbal communication, robot designers have focused on developing robots' nonverbal communication. Nonverbal communication has been programmed into robots as social hand gestures, nods of the head (Li and Chignell, 2011), and even facial expressions (Becker-Asano and Ishiguro, 2011; Zecca et al., 2008). It has been shown that

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human individuals can correctly differentiate between a robot's positive and negative mood based on its behavior (e.g., motion speed and motion amplitude) and, moreover, that participants' own affective states can be influenced by the mood of the social robot (Xu et al., 2015). In another study, participants perceived a robot as more likeable when it used social gestures as compared to when the gestures were absent (Salem et al., 2011). Furthermore, in an interactive task requiring cooperation between a human and a robot, the completion times were faster when the robot used nonverbal cues to aid the interaction (e.g., shrugging and confused facial expressions) as compared to performance without the cues (Breazeal et al., 2005). In addition to these findings, physiological studies that have shown that the mirror neuron system in the brain may respond similarly to perceived human and robotic movements (Gazzola et al., 2007; Oberman et al., 2007; see also Wykowska, 2020). Indeed, a growing body of research shows that, despite the artificial nature of social robots, humans tend to react to their nonverbal social cues in a relatively similar manner as they react to corresponding cues in social interaction with another human (Nass and Moon, 2000; Reeves and Nass, 1996).

Besides facial expressions and body gestures, humans use eye contact to aid everyday social interaction (for a review, see Kleinke, 1986). Eye contact is used to regulate communication (Kendon, 1967; Levine and Sutton-Smith, 1973), assert dominance (Dovidio and Ellyson, 1982; Exline, 1971), express the intensity of emotions (Kimble et al., 1981; Kimble and Olszewski, 1980; Laljee, 1978), enhance cooperation (Foddy, 1978; Jellison and Ickes, 1974), and it also modulates the way people evaluate others (Amalfitano and Kalt, 1977; Beebe, 1974; Wheeler et al., 1979). Importantly, eye contact has been shown to influence people's affective state, that is, eye contact is often found to evoke more positive affective reactions than looking toward someone with averted gaze (see J. K. Hietanen, 2018 for a review). Moreover, eyes gazing toward perceivers are shown to automatically capture our visuospatial attention (Senju and Hasegawa, 2005; von Grünau and Anston, 1995), as well as evoke mentalizing processes in the brain (Cavallo et al., 2015; Kampe et al., 2003; Schilbach et al., 2006).

The affective and attentive reactions to eye contact are reflected on psychophysiological responses as well (for reviews, see J. K. Hietanen, 2018; Senju and Johnson, 2009). Perceiving another individual's direct (toward the perceiver) versus averted gaze has been found to elicit greater skin conductance responses (SCRs; Helminen et al., 2011; J. K. Hietanen et al., 2008; Jarick and Bencic, 2019; Nichols and Champness, 1971; Pönkänen and Hietanen, 2012; Prinsen and Alaerts, 2019) reflecting affective arousal (Critchley, 2002; Dawson et al., 2000). Facial electromyographic (EMG) responses have also been shown to differentiate between seeing another's direct and averted gaze. Compared to a perceived averted gaze, direct gaze increases the activity of the *zygomatic major* muscle in the cheek region and decreases the activity of the *corrugator supercilii* muscle in the eyebrow region (J. K. Hietanen et al., 2018; J. K. Hietanen and Peltola, 2021; J. O. Hietanen et al., 2020). This pattern of muscular response is often associated with a positive affective reaction (Cacioppo et al., 1986; Dimberg, 1990; Larsen et al., 2003). In addition to affective reactions, psychophysiological studies have also shown attention orienting-related responses to seeing another's direct gaze. Attending to affectively or socially salient stimuli is associated with a brief deceleration of heart rate (HR), followed by acceleration toward baseline (Bradley, 2009; Graham and Clifton, 1966), and this response has been shown to be more pronounced to perceiving direct versus averted gaze (Akechi et al., 2013; Myllyneva and Hietanen, 2015; Syrjämäki et al., 2020).

The affective and attentive reactions to eye contact are reflected in the face- and gaze-sensitive brain responses as well, as suggested by electroencephalographic (EEG) studies measuring event-related potentials (ERPs). The N170 response is an occipitotemporal ERP that peaks approximately 140–170 ms after stimulus onset, and it is larger in the right than the left hemisphere (George et al., 1996; Rossion and Jacques, 2008). The response is associated with structural encoding of face

features (Bentin et al., 1996, 2002; Eimer, 2000). The P300 response is another ERP that occurs at approximately 300–400 ms after stimulus onset and is associated with attention orienting toward affectively or motivationally arousing stimuli (Cuthbert et al., 2000; Keil et al., 2002; Polich and Kok, 1995). Conty et al. (2007) studied N170 and frontal P300 responses to apparent gaze motions in pictorial face stimuli and found that both ERPs were larger (meaning more negative N170s and more positive frontal P300s) in response to eye movements toward the perceiver (direct) than to eye movements away (averted) from the perceiver. Pönkänen et al. (2011a) similarly demonstrated that the N170 responses were greater to direct versus averted gaze of motionless live face stimuli as well.

It is important to note that most of the previous findings regarding the effects of gaze direction on psychophysiological responses have been observed in studies using a live person as a stimulus. Several studies have reported that when using pictorial stimuli (e.g., pictures or videos of a face), gaze direction of a neutral face does not influence observers' SCRs (J. K. Hietanen et al., 2008; Joseph et al., 2008; Syrjämäki et al., 2020; Wieser et al., 2009), facial EMG (Rychlowska et al., 2012; Schrammel et al., 2009; Soussignan et al., 2013), HR deceleration responses (Lyyra et al., 2018), or N170 amplitudes (Pönkänen et al., 2011a; Taylor et al., 2001). It has been proposed that for eye contact to evoke distinguishable psychophysiological reactions, the observer needs to have the experience of being perceived by another mind, in addition to the visual eye stimulus (J. K. Hietanen et al., 2008; Myllyneva and Hietanen, 2016; Pönkänen et al., 2011b). Myllyneva and Hietanen (2015) investigated this possibility directly by using a one-way window deception (the alleged "one-way window" was a fully transparent panel) to manipulate the participants' beliefs of whether the stimulus person can see them or not. They measured SCRs, HR deceleration responses, and frontal P300 responses to perceived direct versus averted gaze and found that all the responses were greater to direct than averted gaze, but only when the participant believed they were seen by the stimulus person.

Interestingly, recent research has demonstrated that also the gaze behavior of a social robot may elicit affective and attentive responses in the observer. For example, eye contact with a social robot sets up joint attention with the robot as well as increases impressions of the robot's humanlikeness and experienced engagement with the robot, as compared to seeing the same robot with averted gaze (Kompatsiari et al., 2021b; Kompatsiari et al., 2018). Moreover, eye contact versus no eye contact with a social robot has been shown to elicit greater EEG alpha-band desynchronization in the left fronto-central areas, possibly reflecting joint attention and engagement in social interaction (Kompatsiari et al., 2021a). In studies by Kiilavuori and colleagues (2021, 2022), a social robot's (NAO) as well as human partner's direct versus averted gaze evoked discriminative SCRs, facial EMG, and HR deceleration responses, similar to those described above in human-human studies. Also, by using the one-way window deception, Kiilavuori et al. (2022) found that when the participants believed not to be seen by the robot, the psychophysiological responses to the robot were attenuated, as compared to when the participants viewed the robot while presuming that the robot could also see them. These results suggest that humans may anthropomorphize social robots to the extent that they respond to the direct gaze of the robot as if they were perceived by another mind.

In order to socially engage with others, agents need to appear intentional (Perez-Osorio and Wykowska, 2020; Wiese et al., 2017; Wykowska et al., 2016). When we adopt the intentional stance toward others, we predict and explain their behavior with reference to mental states, such as beliefs, desires, and intentions (Dennett, 1971, 1987). By contrast, when the behavior is explained and predicted using the knowledge or assumptions of the system's functional design, the design stance is adopted (Dennett, 1971). Several studies have shown that people indeed ascribe intentionality to social robots' actions instead of adopting the design stance (Duffy, 2003; Krach et al., 2008; Waytz et al.,

### 2010c).

In the present study, we wanted to test whether the affect- and attention-related psychophysiological responses to eye contact with a social robot, as observed in our previous studies (Kiilavuori et al., 2021, 2022), require adopting the intentional stance toward the robot. Therefore, we manipulated the participants' stance toward a humanoid robot (NAO), that is, intentional versus human-controlled stance, and measured participants' face- and gaze-sensitive N170 and attention-sensitive frontal P300 ERPs, facial muscle activity from the areas of zygomaticus major and corrugator supercilii, affective arousal (SCR), and heart rate deceleration responses to eye contact with the robot. We investigated whether these responses to a humanoid robot's direct versus averted gaze are modulated by the degree of intentionality ascribed to the robot. We randomly assigned participants to two groups. For the autonomous robot group (A), we introduced NAO as an autonomous and intentional robot that can use humanlike social behaviors (both verbal and nonverbal) to interact with the participant. For the controlled robot group (C), we introduced NAO as a remote-controlled robot not capable of any voluntary social interaction or autonomous movement. During the experimental trials, the participants in both groups viewed NAO gazing either toward them or to its side. Based on previous research, we expected that i) perceiving the robot's direct gaze would evoke greater ERPs, facial EMG (zygomatic contraction and corrugator relaxation), SCR, and HR deceleration responses than perceiving the robot's averted gaze, and ii) that the effect of gaze direction on these responses is seen in group A but not in group C. In addition to the psychophysiological responses, we measured participants' subjective feelings of affective valence and arousal. The participants also filled in questionnaires about perceptions of robots and attributing intentionality to robots as well as about their personal characteristics.

## 2. Methods

### 2.1. Participants

Sixty-eight volunteers (19–60 years old,  $M_{\text{age}} = 28.6$ ,  $SD_{\text{age}} = 11.0$ ; 47 females, 21 males) that were randomly assigned either to group A (autonomous robot group,  $N = 33$ ;  $M_{\text{age}} = 28.2$ ,  $SD_{\text{age}} = 10.3$ ; 22 females, 11 males) or group C (controlled robot group,  $N = 35$ ;  $M_{\text{age}} = 28.9$ ,  $SD_{\text{age}} = 11.7$ ; 25 females, 10 males). The two groups did not differ by age ( $p = .786$ ) or by gender distribution ( $p = .671$ ). A sensitivity analysis ( $1 - \beta = 0.8$ ,  $\alpha = 0.05$ ,  $df_n = 1$ ,  $df_{in} = 66$ ,  $\epsilon = 1$ ) with G\*Power (Faul et al., 2007) indicated that our sample size is sufficient to reliably detect medium-sized ( $\eta_p^2 \geq .109$ )  $2 \times 2$  interactions. The participants were recruited from Tampere University's email lists and news feed. None of the participants reported any history of psychiatric or neurological disorders. All participants gave their written informed consent, and they were rewarded either with a movie ticket or course credit. The Ethics Committee of the Tampere region reviewed the experimental protocol and gave a favorable statement about it.

Three participants were excluded from the ERP analyses, eight participants from the SCR analyses, and one participant from the HR analyses due to poor data quality. Additionally, due to incomplete answers to questionnaires (see 2.3.3 Questionnaires), one participant was excluded from the analyses of NARS and IDAQ questionnaires and two participants were excluded from the analyses of S5 and SPS questionnaires. Therefore, the final data sample consisted of 65 participants (32 in group A, 33 in group C) for the EEG data, 68 participants for the EMG and questionnaire data (excluding NARS, IDAQ, S5, & SPS), 60 participants (32 in group A, 28 in group C) for the SCR data, and 67 participants (33 in group A, 34 in group C) for the HR data.

### 2.2. Stimuli

The stimulus for both groups A and C was a humanoid robot NAO

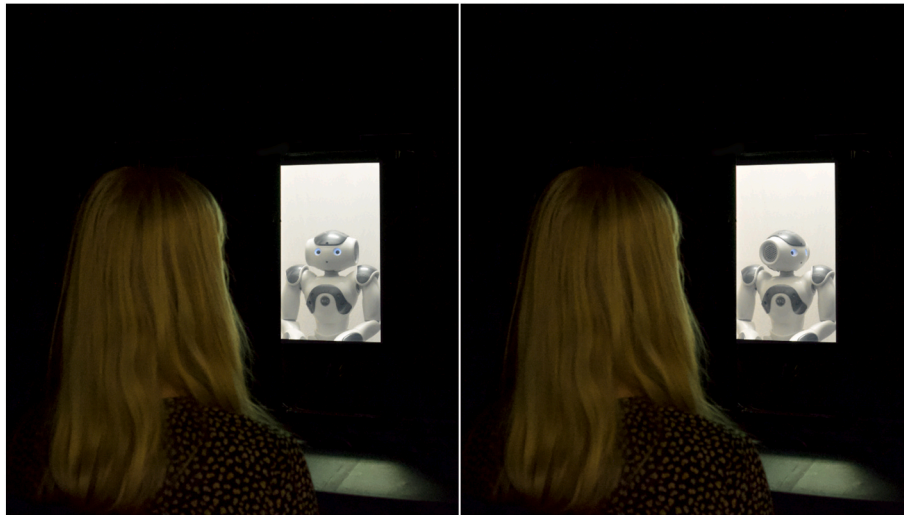
(Softbank Robotics Group Corp.) which was physically present in the laboratory. Its behavior was programmed using the Choregraphe software and Python API for Aldebaran robots (Softbank Robotics Group Corp.). During the direct/averted gaze trials (see 2.3.2 Gaze direction trials), the robot was presented through a  $21.5 \times 37.5$  cm voltage-sensitive liquid crystal (LC) window (NSG Umu Products Co., Ltd.) attached to a black frame (see Fig. 1). The experimenter could turn the LC window transparent or opaque by using E-Prime 2.0 software (Psychology Software Tools, Inc.) running on a desktop computer. The LC window turned from opaque to transparent in 3 ms. This setup allowed the experimenter to precisely control the visibility of the stimulus robot to the participant, which was crucial for the measurement of the ERPs. During the stimulus presentation, the robot's head and gaze were oriented either toward the participant (direct gaze) or  $65^\circ$  to the right or left (averted gaze). The head of the robot was always static during the stimulus presentation, and it was rotated remotely between trials by using a laptop (not visible to the participant). The rotation speed of the robot's head was programmed to be slow to avoid any noise audible to the participant. Contrary to our previous studies (Kiilavuori et al., 2021, 2022), the robot's eye LEDs did not occasionally turn off for a short period to mimic eye blinking. Instead, the eye LEDs were kept constantly on for the whole experiment. We expected that the eye blinking would have increased the robot's perceived intentionality in group C, thus counteracting the manipulation. The participant sat at approximately 60 cm from the LC window, and the robot was placed at the other side, approximately 40 cm from the window. The participant's seat was adjusted so that the participant's eyes were vertically at the same level with the robot's eyes. The participants were able to see the robot's head and upper body. The participants were instructed to keep their gaze toward the LC window throughout the experiment, and gaze toward the robot, whenever the window was transparent.

### 2.3. Procedure

The experiment was conducted by two experimenters, one leading the experiment and instructing the participant, and the other assisting in placing the measurement electrodes and controlling the robot. The procedure was mostly the same for both groups A and C, but with some key differences in how the robot was introduced to the participants in these two groups before the gaze direction trials. Throughout the experiment, the experimenters referred to the robot differently between the groups to highlight either its autonomy and intentionality (group A) or its mechanicalness and non-autonomous nature (group C). With the participants in group A, the experimenters referred to the robot using its name (NAO) or with a third-person singular pronoun (in Finnish language, this pronoun is gender neutral), whereas, with the participants in group C, the experimenters referred to the robot using the word "robot" or the pronoun "it". The experimenters also attributed the robot's movement (i.e., head turning) as either self-initiated (group A) or controlled via a computer (group C).

In the beginning of the experiment, the participant was informed that the purpose of the study is to measure physiological reactions in simple interaction situations. The participant was shown the opaque LC window and informed either that NAO, a social robot would be sitting on the other side of the LC window (group A) or that a robot would be placed on the other side of the LC window (group C). The experimenters said that the LC window between the participant and the robot would occasionally turn transparent, revealing the robot to the participant, and back to opaque. Participants in group A were informed that when the LC window turns transparent, NAO would either be gazing at the participant or away from them, while the participants in group C were informed that the robot is remote-controlled via a computer and when the LC window turns transparent, the robot's head is oriented either toward the participant or away from them. Regardless of which group they belonged to, every participant was instructed that their task is to gaze at the robot and to keep their gaze on the LC window when it is opaque. To





**Fig. 1.** An illustration of the stimulus presentation setup. A humanoid robot's direct and averted gaze directions were presented to the participant through a voltage-sensitive LC window.

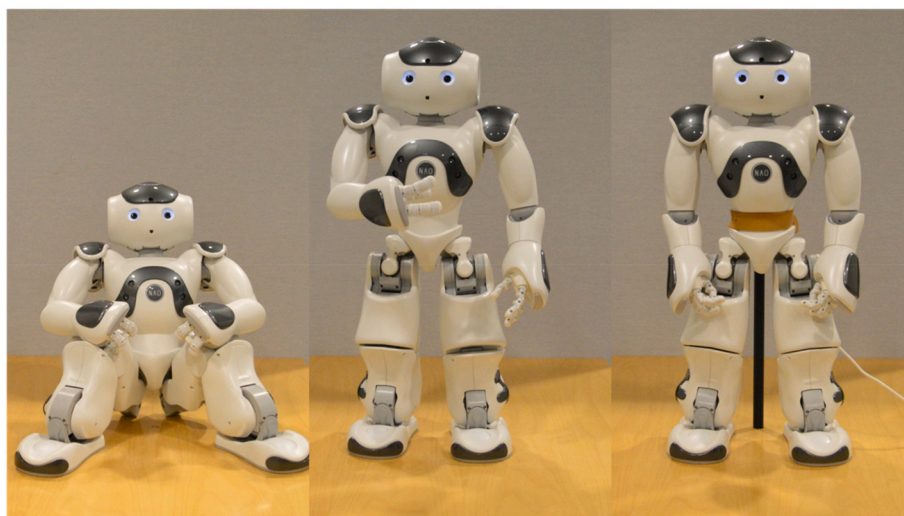
demonstrate the transparent and opaque states of the LC window, the leading experimenter switched the LC window to transparent and then back to opaque two times. During this demonstration, the assisting experimenter sat on the other side of the LC window where the robot would later be placed, allowing the participant to see the assisting experimenter through the transparent LC window.

### 2.3.1. Introducing the robot

After demonstrating the LC window, the leading experimenter informed the participant that they would now meet the robot. The participant was moved from the LC window to face a curtain that blocked the view to one side of the laboratory room. The experimenter told the participant that the robot is on the other side of the curtain and then moved the curtain so that the participant could see the robot. The robot had been placed on a table (56 cm from the floor level) for the introduction. For group A, the robot was revealed to the participant in a sitting position, from which it autonomously stood up (see Fig. 2) and oriented its gaze toward the participant's face (NAO is equipped with an integrated face detection function). The robot introduced itself by saying [in Finnish] "Hi, I'm NAO!" and made some humanlike hand gestures

and nods. The experimenter then informed the participant that the robot can follow the participant with its gaze. As social interaction with a robot is found to enhance anthropomorphism (Spatola et al., 2020), the experimenter encouraged the participant to interact with the robot and test its ability to follow the participant with its gaze. The purpose of this introduction was to show the robot's humanlike movement and verbal communication to enhance the participant's perception of the robot as being intentional and capable of social interaction.

For group C, the robot was revealed to the participant in a static standing position, mounted to a stand with a supporting metal rod (see Fig. 2). Contrary to the presentation for group A, the charging cable of the robot was left connected to the robot and visible to the participant. Upon revealing the robot to the participant, the experimenter told the participant that although the robot is rather simple, the experimenter could turn its head in horizontal plane remotely by using arrow keys on a keyboard. The experimenter then proceeded to demonstrate this with a wireless keyboard. After pressing the arrow keys a few times, the experimenter asked the participant to press the keys themselves and experiment with the robot's turning head. The purpose of this introduction was to create an impression of the robot being unintentional,



**Fig. 2.** Introduction of the humanoid robot to the participants. For the autonomous robot group (group A), the robot was first presented in a sitting position (left), from which it stood up and then started interacting with the participant (middle). For the controlled robot group (group C), the robot was presented motionless (right). For more detailed description of the introduction procedure, see main text.

fully controlled by the experimenter, and not capable of any social interaction.

After introducing the robot to the participant, the participant was asked to sit in front of the LC window, and the robot was placed on the other side of it. The LC window was then once more turned transparent, this time to ensure that the participant's eyes were vertically at the same level with the robot's eyes. For group A, the robot's gaze was initially oriented slightly downward. The leading experimenter addressed the robot and asked it to adjust its gaze, while the assisting experimenter, nonvisible to the participant, activated a preprogrammed sequence of head gestures, making it appear as if the robot autonomously tried to match its eyes with those of the participant. The purpose of this head adjustment maneuver was to give the participant the impression that the robot could perceive the participant through the LC window and intentionally adjust its head orientation toward the participant. For group C, when placing the robot behind the opaque LC window, the assisting researcher purposely rotated the robot's head to the left. When the LC window was turned transparent, the leading experimenter reacted as if the robot's head had been left in its side-position by mistake and proceeded to rotate it forward using the keyboard in the participant's field of view. The purpose of this sequence was to give the participant the impression that the robot could not actually perceive them and instead, to make it appear as if the robot was gazing at the participant, its head needed to be rotated by the experimenter. Finally, for both groups A and C, the participant's seat was adjusted if needed until the participant felt that their eyes were vertically on the same level with the robot's eyes. The experimenters then attached the measuring electrodes onto the participant and said that everything is ready to start the gaze direction trials.

### 2.3.2. Gaze direction trials

The direct gaze and averted gaze trials (see Fig. 1) were presented in four blocks separated by short breaks. Blocks one and three were identical and they both consisted of 12 trials, of which six were with the robot's direct gaze and six with averted gaze (3 left and 3 right). In these trials, the LC window became transparent for 3000 ms before turning back opaque. The purpose of these trials was to measure participants' facial EMG, SCRs, and HR deceleration responses to the gaze directions. Between the trials, the next gaze direction was shown to the experimenters on a computer monitor delivered by E-Prime, and the leading experimenter rotated the robot's head using a laptop. The leading experimenter monitored the participant's skin conductance level and initiated the next trial when the skin conductance seemed to have recovered from the previous response, however, not before at least 6 s had passed since the LC window turning back opaque.

Blocks two and four were identical and they both consisted of 80 trials, in which the LC window became transparent for 500 ms before turning back opaque. During these trials, the ERPs were measured. Of the 80 trials in each block, 40 were with the robot's direct gaze and 40 with averted gaze (20 left and 20 right). To compensate for time-consuming rotation of the robot's head, the trials were grouped into sequences of five. During each 5-trial sequence, the LC window turned transparent five times (for 500 ms each), revealing the same gaze direction five times in a row, with 1500–2500-ms inter-stimulus intervals, randomized with 200-ms grading. The intervals between the 5-trial sequences were approximately 10 s. As in blocks one and three, the experimenter rotated the robot's head between the trial sequences according to the instructions delivered by E-Prime. The order of the trials in blocks one and three and the order of the 5-trial sequences in blocks two and four was pseudo-randomized in a way that no more than four consecutive trials or trial sequences of similar type (direct/averted) were possible. In all blocks, during the experimental trials, the experimenters and all the monitors were behind a curtain, invisible to the participant.

After the experimental blocks, the three gaze directions (direct, left, and right) were once more presented to the participant (for 3000 ms each) in a random order. Immediately after each stimulus presentation,

the participant was asked to fill in Self-Assessment Manikins (Bradley and Lang, 1994) to evaluate their affective valence and arousal (scale range: 1–9; 1 = unpleasant/calm, 9 = pleasant/arousing), as well as to evaluate the statement “NAO-robot was gazing toward me” on a 9-point scale (–4 = strongly disagree, 4 = strongly agree). The purpose of the affective valence and arousal ratings was to measure the participants' subjective affective responses to the robot's gaze directions, whereas the purpose of the gazing direction evaluation was to confirm that the participants actually felt that the robot was gazing toward them in the direct gaze condition. Finally, at the end of the experiment, the participants were asked to fill in several brief questionnaires.

### 2.3.3. Questionnaires

The first questionnaire was a mind attribution (MA) questionnaire (Ward et al., 2013), slightly modified to fit the present study. The questionnaire served as a manipulation check, that is, we presumed that the participants in group A would attribute more mind to NAO than the participants in group C. The questionnaire contained four scales: pain, experience, agency, and consciousness. The pain scale consisted of a single item (“In some way, NAO-robot can experience pain”), whereas other scales consisted of multiple items. The other scales included statements regarding NAO's ability to experience feelings (experience scale, 6 items), ability to control its actions (agency scale, 7 items), and NAO's awareness of itself and its surroundings (consciousness scale, 2 items). One item (“In some way, NAO-robot can experience feelings”) in the experience scale of the original questionnaire (Ward et al., 2013) was omitted from the Finnish translation to avoid a possible confusion with another item (“In some way, NAO-robot is able to experience emotions”). The participants evaluated the statements on a 9-point scale (–4 = strongly disagree, 4 = strongly agree).

Next, to consider individual characteristics that could modify the physiological responses to eye contact with a robot, the participants filled in questionnaires measuring negative attitudes toward robots (NARS; Nomura et al., 2004) and individual differences in anthropomorphism (IDAQ; Waytz et al., 2010a). NARS and IDAQ both consist of three subscales (NARS: negative attitude toward HRI situations, social influence of robots, or emotions in HRI; IDAQ: anthropomorphism of technology, nature, or animals). The reliability scores for each subscale are presented in Supplementary material. Finally, the participants were asked to fill in two online questionnaires at home in the subsequent days. The first online questionnaire was the Short Five (S5; Konstantel et al., 2012); it measured the participants' big five personality traits. The second questionnaire was the Social Phobia Scale (Mattick and Clarke, 1998). The online questionnaire data were collected by using LimeSurvey (LimeSurvey GmbH).

## 2.4. Acquisition and analysis of the physiological data

The physiological signals were amplified with QuickAmp amplifier (Brain Products GmbH) and recorded with BrainVision Recorder software (Brain Products GmbH). The sampling rate for the digitized signals was 1000 Hz.

### 2.4.1. Electroencephalography

Continuous EEG was recorded using an ActiCap 64-channel active electrode system (Brain Products GmbH). The EEG-signal was low-pass filtered at 200 Hz and referenced to the common average. Vertical eye movements and eye blinks were monitored with electrodes placed above and below the right eye (VEOG). Horizontal eye movements were monitored using the EEG electrodes (FT9 & FT10) closest to the outer canthi of the eyes (HEOG). Electrode impedances were reduced to under 30 k $\Omega$ . Using BrainVision Analyzer 2.1 software (Brain Products GmbH, Munich, Germany), the continuous EEG data were filtered with a 0.5–30 Hz band-pass filter and corrected for ocular artifacts (vertical/horizontal eye movements and eye blinks) with semi-automatic independent component analysis. Individual channels that received either a flat

signal or excessive noise for the majority of the trials were interpolated using spherical spline interpolation, as long as the number of poor-quality channels was not greater than six (i.e., 10% of the channels). Next, the continuous signal was segmented to 600-ms epochs starting 100 ms prior to stimulus presentation during the ERP blocks, and baseline-corrected against the average activity during the pre-stimulus period. Residual artifacts were removed from all EEG channels using an automated artifact detection algorithm, which rejected all epochs containing a voltage step greater than 50  $\mu\text{V}/\text{ms}$ , absolute amplitude exceeding  $\pm 75 \mu\text{V}$ , or a voltage change smaller than 0.5  $\mu\text{V}$  during an interval of 100 ms. As a result, 8.36% of the epochs (from 65 participants) were rejected. Finally, the data from accepted epochs ( $M_{\text{direct gaze}} = 73.29$ ,  $SD = 7.28$ ;  $M_{\text{averted gaze}} = 73.34$ ,  $SD = 7.26$ ) were averaged in each gaze direction for each participant. Groups A and C did not differ by the number of accepted epochs ( $p > .1$ ).

For statistical analyses, N170 amplitude was calculated for each participant by subtracting the peak value of N170 from that of the preceding positive peak P1 (see Gao et al., 2019). For this purpose, peak values for P1 and N170 were extracted as the maximum amplitude within 70–130 ms and the minimum amplitude within 140–200 ms, respectively. On visual inspection, occipitotemporal electrode sites P7 and P8 showed pronounced P1 and N170 responses and were therefore chosen for these analyses. N170 latency was determined simply as the latency of the N170 peak extracted within 140–200 ms. For the frontal P300, response peaks were less pronounced, and therefore the P300 amplitude was determined by the mean amplitude within 300–400 ms. Frontal P300 was analyzed from electrode sites F3 and F4, as those sites have been used in previous frontal P300 studies (e.g., Conroy and Polich, 2007; Keil et al., 2002).

#### 2.4.2. Facial muscle activity

The facial muscle activity was recorded with EMG over the participant's zygomaticus major and corrugator supercilii muscle regions. Before attaching the electrodes, the skin over the recording sites was rubbed with alcohol. Electrode gel (Signa gel) was injected to bipolar 4-mm Ag/AgCl electrodes (BioMed electrodes), which were attached 1 cm apart with a tape over the recorded muscle sites according to the placement guidelines by Fridlund and Cacioppo (1986). Offline, the EMG signal was filtered with a 28–249 Hz bandpass filter and rectified using BrainVision Analyzer 2.1 software. The signal around each experimental trial was visually inspected for artifacts due to eye blinks or excessive muscle activity at baseline. As a result, an average of 1.13% of the trials (from 68 participants) were rejected. For the statistical analyses, the signal was segmented into 500-ms epochs from 500 ms pre-stimulus onset to 3000 ms after stimulus onset. Within each participant, condition, and time epoch, the signal was averaged across all accepted trials (zygomaticus:  $M_{\text{direct gaze}} = 11.82$ ,  $SD = 0.46$ ;  $M_{\text{averted gaze}} = 11.82$ ,  $SD = 0.60$ ; corrugator:  $M_{\text{direct gaze}} = 11.94$ ,  $SD = 0.29$ ;  $M_{\text{averted gaze}} = 11.87$ ,  $SD = 0.57$ ). Groups A and C did not differ by the number of accepted trials in either muscle region (all  $ps > .1$ ). The average values were standardized within participants and muscle regions to reduce the influence of extreme values. Finally, the muscle response was calculated as change scores by subtracting the baseline value (average activity during the 500-ms pre-stimulus period) from each 500-ms average value within each experimental condition.

#### 2.4.3. Skin conductance

For the skin conductance measurements, two electrodes (Ag/AgCl) containing isotonic paste were attached to the distal phalanges of the index and middle fingers of the participant's left hand. The SCR data were re-sampled offline to 100 Hz and filtered with a 10-Hz high-cutoff filter. A response was defined as the maximum skin conductance change within a time window of 900–6000 ms after stimulus onset. The maximum change was calculated by first detecting the lowest skin conductance (within 900–3500 ms after stimulus onset) preceding the highest skin conductance (within 900–6000 ms after stimulus onset) and

then by subtracting the former value from the latter value. In a case of two peaks within one response, only the first one was considered. Trials in which the maximum conductance change was less than 0.01  $\mu\text{S}$  were marked as zero responses. Trials containing a conductance rise ( $>0.01 \mu\text{S}$ ) during the first 900 ms were rejected. If more than half of the trials ( $>6$ ) in either gaze condition were rejected, the participant was excluded from final analyses. From the 60 participants included in the final analyses, 15.5% of trials were rejected. Within each participant and condition, the data were averaged across the accepted trials ( $M_{\text{direct gaze}} = 10.28$ ,  $SD = 1.72$ ;  $M_{\text{averted gaze}} = 10.08$ ,  $SD = 1.59$ ), including the trials with zero responses. This calculation results in the magnitude of the skin conductance responses; a measure that combines response size and frequency (Dawson et al., 2000). Groups A and C did not differ by the number of accepted trials ( $p > .1$ ). The mean SCR magnitudes were used in the statistical analyses.

#### 2.4.4. Heart rate

Electrocardiography (ECG) was measured with two electrodes (Ag/AgCl) containing electroconductive gel that were placed below both collarbones. The ECG data were analyzed offline with an in-house (Matlab-based) algorithm which first identifies QRS complexes (the combination of three successive deflections in typical ECG) and then measures the time intervals between two successive R-peaks (interbeat interval, IBI). After the automatic detection of R-peaks, each trial was manually inspected to correct the falsely detected and missing peaks. Trials with excessive distortion in the signal were rejected (0.37% of the trials of 67 participants). To detect progressive changes in the HR (in order to analyze a deceleration response), the IBIs within each trial were quantified and assigned to 500-ms intervals for a period between 500 ms pre-stimulus (baseline) and 6000 ms post-stimulus onset. Lastly, the IBIs were converted to bpm (beats per minute) and averaged across the accepted trials ( $M_{\text{direct gaze}} = 12.0$ ,  $SD = 0.00$ ;  $M_{\text{averted gaze}} = 11.91$ ,  $SD = 0.51$ ) within each condition. The two groups did not differ by the number of accepted trials ( $p > .1$ ). The analyses were performed with HR change scores that were calculated by subtracting the baseline bpm from the bpm of each post-stimulus 500-ms interval. Regarding one participant in group C, HR could not be measured, and the participant was therefore excluded from the statistical analyses.

#### 2.5. Statistical analyses

The main statistical analyses of the physiological responses (see Pyssysalo et al., 2022 for the data) were done using repeated measures analyses of variance (ANOVAs) with gaze direction (direct vs. averted) as a within-subject factor and group (A vs. C) as a between-subject factor. For the ERP analyses, hemisphere (left: P7/F3 vs. right: P8/F4) was added as a second within-subject factor. For the facial EMG and HR analyses, time (EMG: 6 epochs, each lasting 500 ms; HR: 12 epochs, each lasting 500 ms) was added as a second within-subject factor. Greenhouse-Geisser correction procedure was applied when the assumption of sphericity was violated. When a statistically significant interaction between gaze direction and group was observed, the responses to direct and averted gaze directions were compared within group with paired samples  $t$  tests. Statistically nonsignificant results from the  $t$  tests were further explored using a two one-sided test (TOST) procedure with equivalence bounds set at  $d = \pm 0.5$  (medium effect size).

### 3. Results

#### 3.1. Manipulation checks

To check whether the gaze manipulation was successful, the participants' ratings of gaze direction (scale range: 4–4, with 4 indicating full agreement with the statement that the robot was gazing at the participant) were analyzed with a 2(Gaze)  $\times$  2(Group) ANOVA. As expected,



the ANOVA showed a main effect of gaze ( $F_{(1,66)} = 482.06, p < .001, \eta_p^2 = .880$ ), indicating that participants showed greater agreement with the statement “the robot gazed at me” for NAO’s direct gaze ( $M = 3.39, SEM = 0.15$ ), compared to averted gaze ( $M = -2.76, SEM = 0.25$ ). None of the other effects were statistically significant.

To ensure that the different presentations of NAO to the two groups influenced the participants’ ascriptions of the robot’s intentionality, the data from MA questionnaire were subjected to a multivariate analysis of variance (MANOVA) with group (A vs. C) as a between-subject factor. The MANOVA indicated a main effect of group in agency ( $F_{(1, 66)} = 16.37, p < .001, \eta_p^2 = .199$ ) and consciousness ( $F_{(1, 66)} = 4.42, p = .039, \eta_p^2 = .063$ ) subscales of the MA (scale range: 4–4, with 4 indicating maximal ascription of given attribute to the robot), indicating that the agency and consciousness evaluations were higher in group A ( $M_{\text{agency}} = 1.39, SEM_{\text{agency}} = 2.14, M_{\text{consciousness}} = 0.73, SEM_{\text{consciousness}} = 0.76$ ) than in group C ( $M_{\text{agency}} = -10.66, SEM_{\text{agency}} = 2.08, M_{\text{consciousness}} = -3.03, SEM_{\text{consciousness}} = 0.76$ ). No other scales showed statistically significant effects of group.

Finally, to ensure that the groups A and C did not differ by some key individual characteristics that could influence the psychophysiological responses to gaze manipulation, the data from the NARS, IDAQ, S5, and SPS questionnaires were analyzed with MANOVAs, following the same design as described above. As expected, the two groups did not differ statistically significantly by any of these scales (all  $ps > .05$ ).

### 3.2. Event-related potentials

Fig. 3 shows the scalp potential maps for N170 and frontal P300 time windows. The ERP data were analyzed with a  $2(\text{Gaze}) \times 2(\text{Group}) \times 2(\text{Hemisphere})$  ANOVA. For the N170 amplitude, the ANOVA showed a main effect of gaze ( $F_{(1, 63)} = 12.64, p = .001, \eta_p^2 = .167$ ), indicating that responses were greater to direct ( $M = 10.43 \mu\text{V}, SEM = 0.59$ ) versus averted ( $M = 9.64 \mu\text{V}, SEM = 0.57$ ) gaze. There was also a main effect of hemisphere ( $F_{(1, 63)} = 19.8, p < .001, \eta_p^2 = .239$ ), indicating larger responses in the right ( $M = 11.35 \mu\text{V}, SEM = 0.70$ ) than in the left ( $M =$

$8.73 \mu\text{V}, SEM = 0.57$ ) hemisphere. The main effect of group was not statistically significant, and there were no statistically significant interactions between any of the main effects. Regarding the latency of N170, an ANOVA showed a main effect of gaze ( $F_{(1, 63)} = 82.04, p < .001, \eta_p^2 = .566$ ); the N170 latency was shorter to direct ( $M = 158.88 \text{ ms}, SEM = 1.14$ ) versus averted gaze ( $M = 164.81 \text{ ms}, SEM = 1.35$ ). The main effects of hemisphere and group were not statistically significant, and there were no statistically significant interactions between any of the main effects. We also tested whether the gaze direction or group had effects on the P1 responses by using a  $2(\text{Gaze}) \times 2(\text{Group}) \times 2(\text{Hemisphere})$  ANOVA. There was a main effect of hemisphere ( $F_{(1, 63)} = 15.39, p < .001, \eta_p^2 = .196$ ), indicating larger responses in the right ( $M = 5.39 \mu\text{V}, SEM = 0.33$ ) than in the left ( $M = 4.17 \mu\text{V}, SEM = 0.26$ ) hemisphere. The other main effects or interactions were not statistically significant. The ERP waveforms in P7 and P8 recording sites for groups A and C are shown in Fig. 4.

The analysis of the frontal P300 response showed a main effect of group ( $F_{(1, 63)} = 9.21, p = .004, \eta_p^2 = .127$ ), indicating more positive P300 responses in group A ( $M = -0.99 \mu\text{V}, SEM = 0.38$ ), as compared to group C ( $M = -2.61 \mu\text{V}, SEM = 0.38$ ). Importantly, the ANOVA also showed an interaction between gaze and group ( $F_{(1, 63)} = 8.63, p = .005, \eta_p^2 = .121$ ) as well as group and hemisphere ( $F_{(1, 63)} = 7.53, p = .008, \eta_p^2 = .107$ ). Regarding the Gaze  $\times$  Group interaction, pairwise comparisons showed that in group C, P300 responses were indifferent to gaze direction ( $t = -1.75, df = 32, p = .089, d = 0.31$ ), whereas in group A, P300 responses were more positive to direct versus averted gaze ( $t = 2.36, df = 31, p = .025, d = 0.42; M_{\text{direct}} = -0.79 \mu\text{V}, SEM = 0.44 \text{ vs. } M_{\text{averted}} = -1.18 \mu\text{V}, SEM = 0.42$ ). A TOST procedure indicated that, within the participants in group C, the observed effect size was statistically significantly within the upper bound of  $d = 0.5$  ( $t = -4.63, df = 32, p < .001$ ) but not within the lower bound of  $d = -0.5$  ( $t = 1.12, df = 32, p = .136$ ). We can therefore conclude that, in group C, the frontal P300 responses were not meaningfully greater to the robot’s direct than averted gaze, but it is possible that the responses were smaller to direct versus averted gaze. For the Group  $\times$  Hemisphere interaction, pairwise

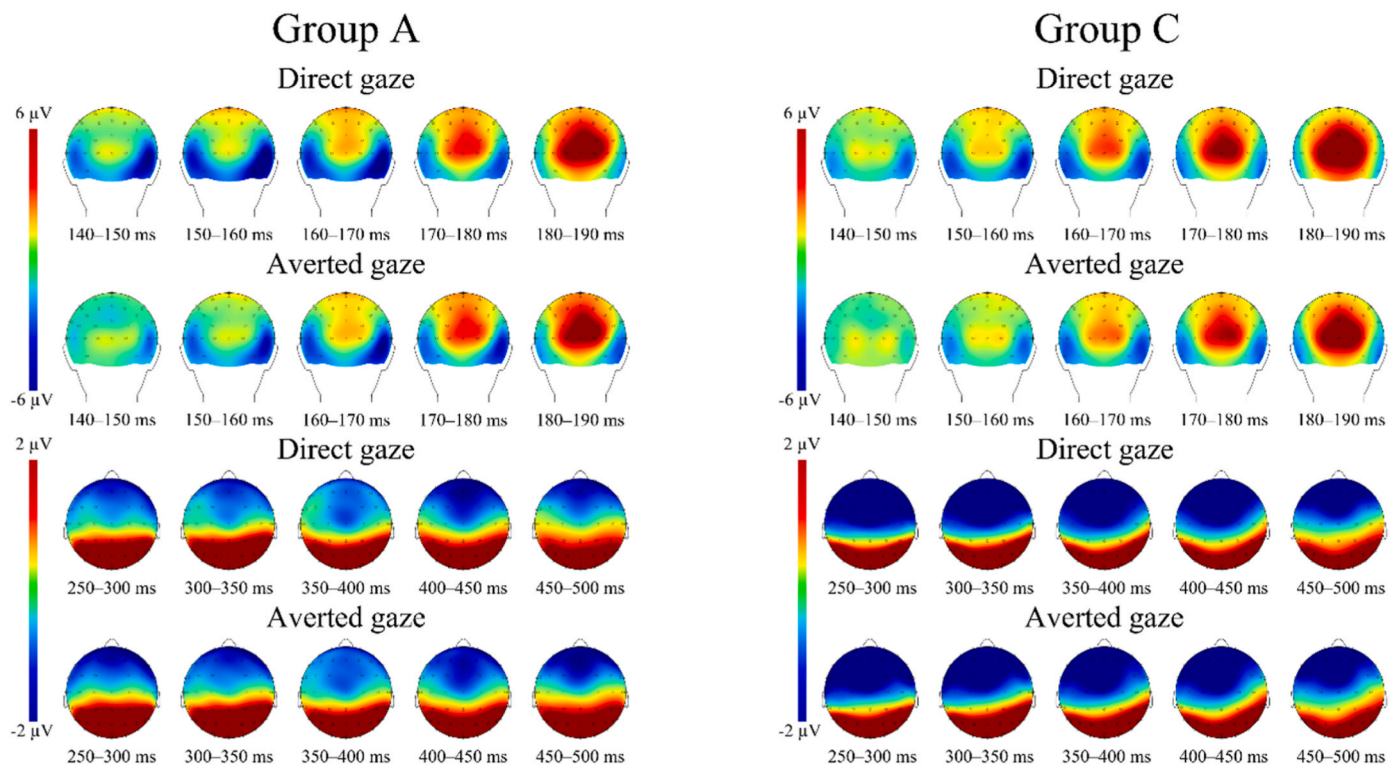
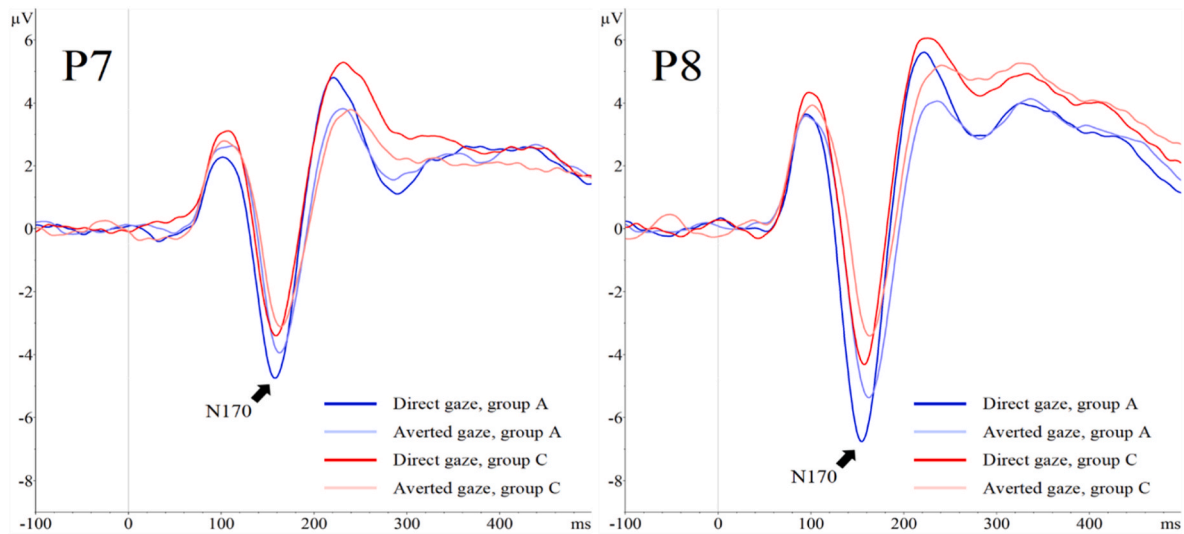


Fig. 3. Scalp distribution of average amplitude during the time windows of N170 (back view) and frontal P300 (top view), presented separately for both direct gaze and averted gaze conditions and for both group A (autonomous robot) and group C (controlled robot).



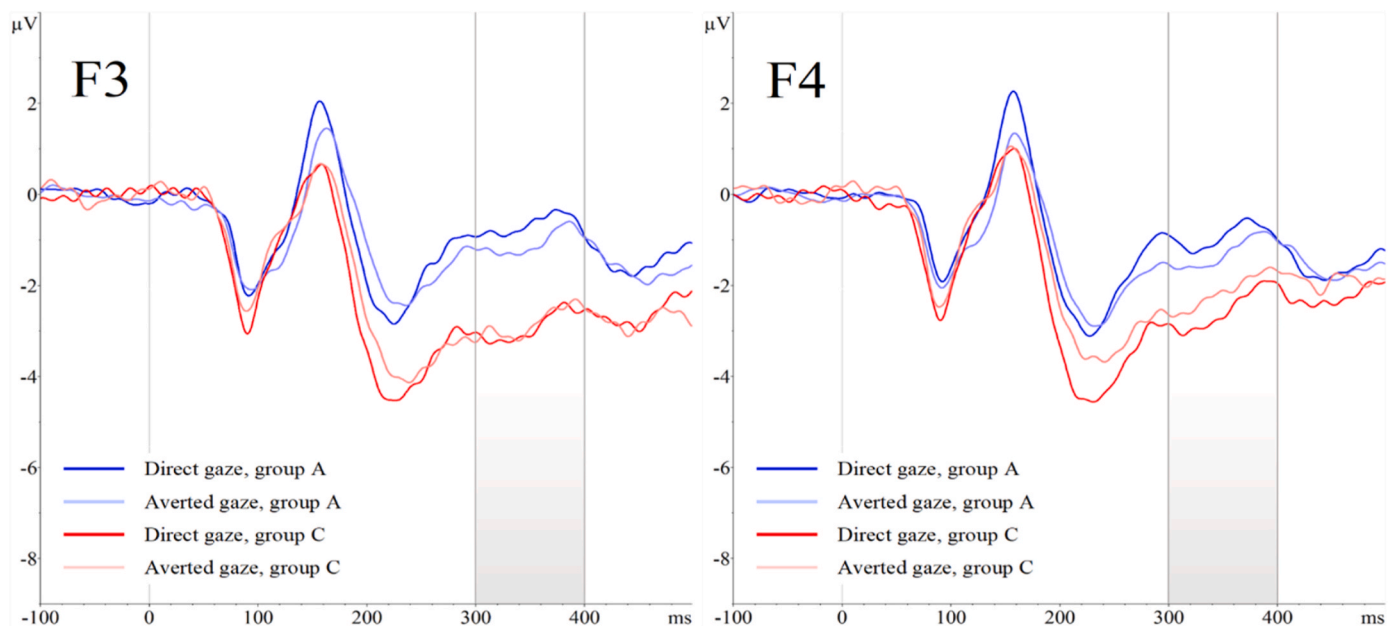
**Fig. 4.** Mean N170 responses to the robot's direct and averted gaze directions. The mean responses are presented separately over the P7 and P8 electrodes and for both group A (autonomous robot) and group C (controlled robot).

comparisons showed that in group C, P300 responses were more positive in the right versus left hemisphere ( $t = -2.81, df = 32, p = .008, d = 0.49$ ;  $M_{\text{right}} = -2.35 \mu\text{V}, SEM = 0.33$ ;  $M_{\text{left}} = -2.87 \mu\text{V}, SEM = 0.36$ ), whereas in group A, P300 responses did not differ significantly between the hemispheres ( $t = 1.17, df = 31, p = .251, d = 0.21$ ). None of the other effects were statistically significant. Fig. 5 shows the ERP waveforms in F3 and F4 areas for both groups A and C.

### 3.3. Facial electromyography responses

The EMG data were analyzed with a  $2(\text{Gaze}) \times 2(\text{Group}) \times 6(\text{Time})$  ANOVA. Zygomatic and corrugator responses were analyzed separately. For zygomatic responses, an ANOVA showed a main effect of gaze ( $F_{(1, 66)} = 19.56, p < .001, \eta_p^2 = .229$ ), indicating that the zygomatic activity increased more in response to direct gaze ( $M = 0.65, SEM = 0.14$ ) versus averted gaze ( $M = 0.05, SEM = 0.12$ ). There was also a main effect of

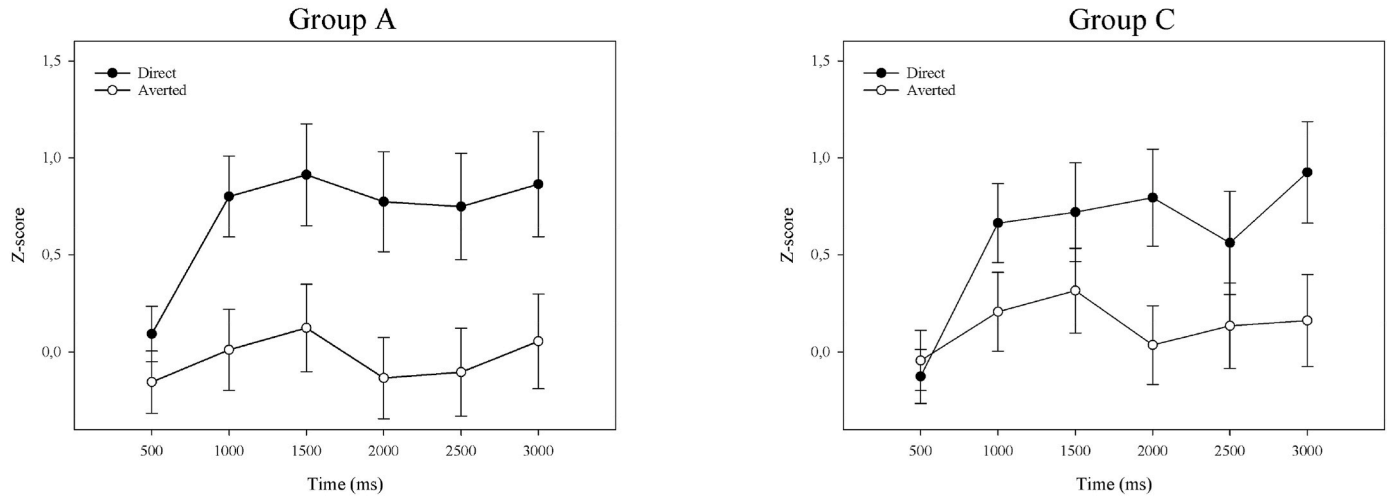
time ( $F_{(3.926, 259.119)} = 7.95, p < .001, \eta_p^2 = .107$ ) due to muscle activity increasing as a function of time. Additionally, there was a Gaze  $\times$  Time interaction ( $F_{(3.813, 251.645)} = 3.95, p = .005, \eta_p^2 = .057$ ), indicating that the increase in muscle activity as a function of time was greater in the direct gaze than in the averted gaze condition. For corrugator responses, an ANOVA showed a main effect of gaze ( $F_{(1, 66)} = 15.22, p < .001, \eta_p^2 = .187$ ), indicating that the corrugator activity decreased more in response to direct gaze ( $M = -0.46, SEM = 0.17$ ) than to averted gaze ( $M = 0.15, SEM = 0.15$ ). There was also a main effect of time ( $F_{(3.277, 216.304)} = 3.67, p = .011, \eta_p^2 = .053$ ); the corrugator activity decreased as a function of time. Gaze  $\times$  Time interaction was also statistically significant ( $F_{(4.185, 276.210)} = 4.80, p = .001, \eta_p^2 = .068$ ), indicating that the decrease in muscle activity as a function of time was greater in the direct gaze than the averted gaze condition. Any other main effects or interactions were not statistically significant. The zygomatic and corrugator responses are shown for groups A and C in Fig. 6.



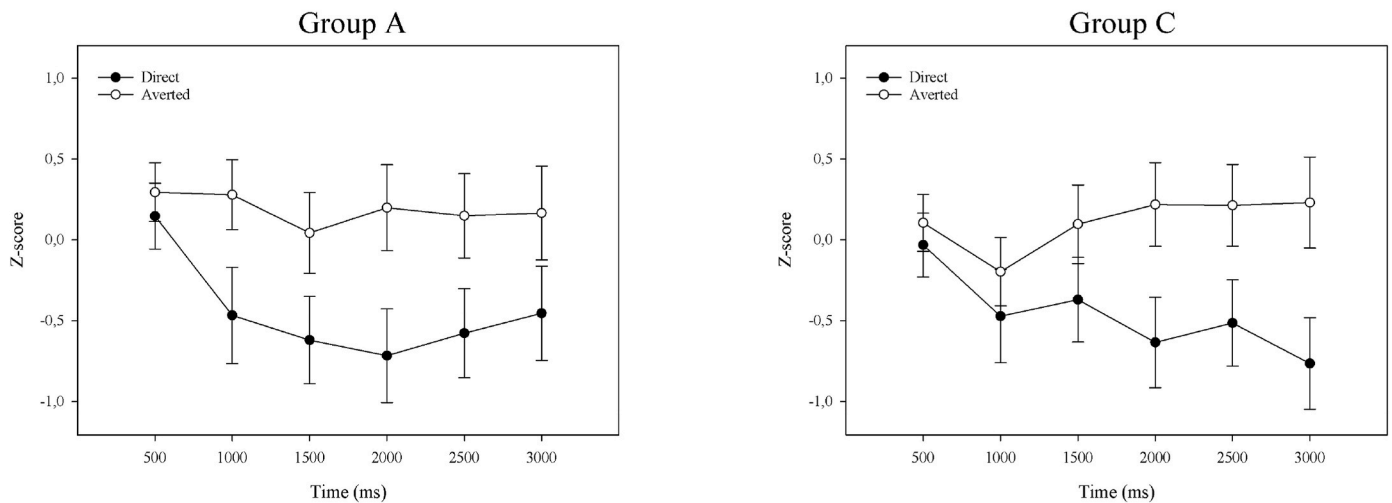
**Fig. 5.** Mean frontal P300 responses to the robot's direct and averted gaze directions, presented separately over the F3 and F4 electrodes and for both group A (autonomous robot) and group C (controlled robot). The time window of interest is highlighted.



## Zygomatiscus



## Corrugator



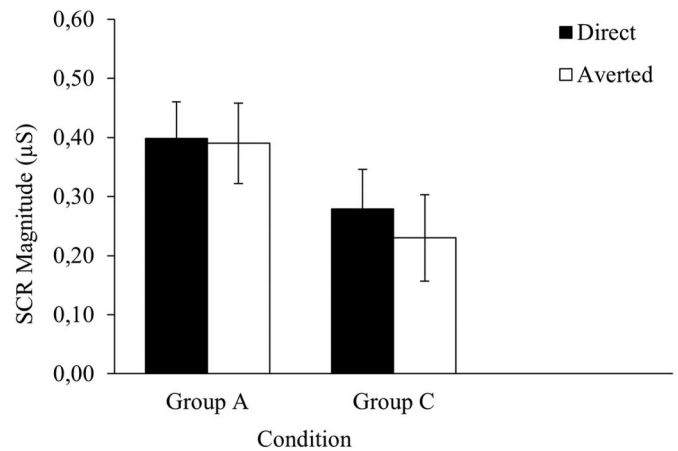
**Fig. 6.** Standardized mean EMG responses (and SEM) to the robot’s direct and averted gaze directions over the zygomatiscus major and corrugator supercilii muscle regions, presented separately for both group A (autonomous robot) and group C (controlled robot).

### 3.4. Skin conductance responses

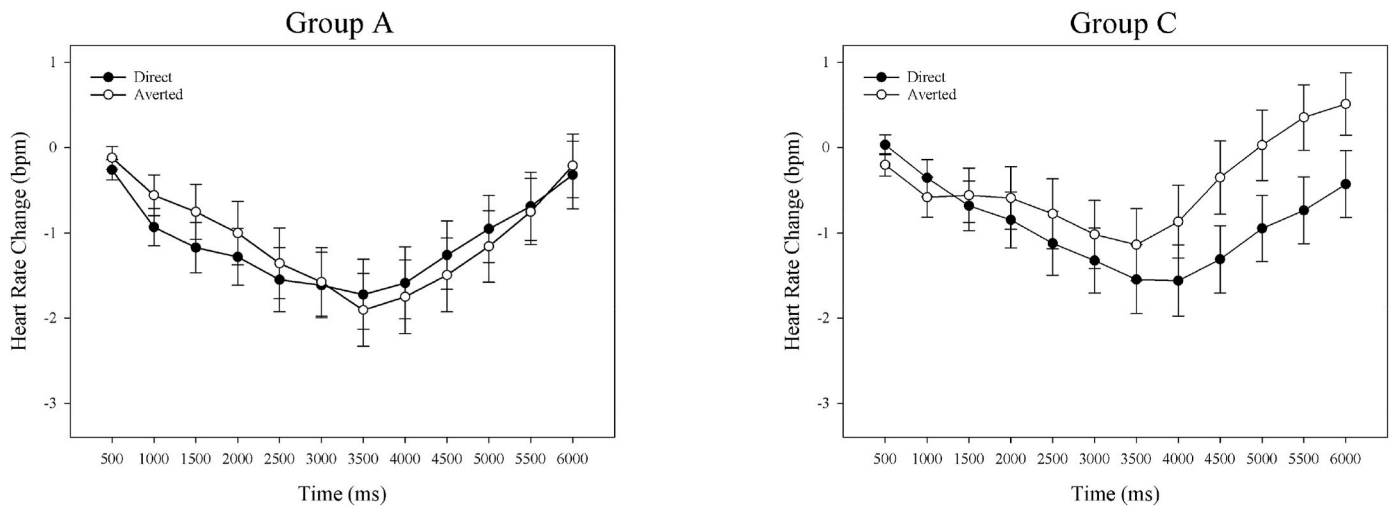
A 2(Gaze) × 2(Group) ANOVA indicated no statistically significant main effects (all  $p$ s > .1). Also the Gaze × Group interaction was not statistically significant ( $F_{(1, 58)} = 0.41, p = .523, \eta_p^2 = .007$ ). The average skin conductance responses per condition are shown for groups A and C in Fig. 7.

### 3.5. Heart rate deceleration responses

The HR data were analyzed with a 2(Gaze) × 2(Group) × 12(Time) ANOVA. The results showed a main effect of time ( $F_{(2,873, 186.743)} = 19.05, p < .001, \eta_p^2 = .227$ ), indicating a heart rate deceleration in response to seeing the robot. The ANOVA also showed a Gaze × Group × Time interaction ( $F_{(3,216, 209.052)} = 4.43, p = .004, \eta_p^2 = .064$ ); in group C, there was a Gaze × Time interaction ( $F_{(2,920, 96.374)} = 5.04, p = .003, \eta_p^2 = .133$ ), indicating that the heart rate deceleration response had longer duration in the direct than averted gaze condition, whereas such interaction was not found for group A ( $p > .1$ ). Any other main effects or interactions were not statistically significant. The HR results are shown in Fig. 8.



**Fig. 7.** Mean SCR magnitudes (and SEM) in response to the robot’s direct and averted gaze directions, presented separately for both group A (autonomous robot) and group C (controlled robot).



**Fig. 8.** Mean heart rate changes (and SEM) in response to the robot’s direct and averted gaze directions, presented separately for both group A (autonomous robot) and group C (controlled robot).

3.6. Questionnaire data

The affective valence and arousal were self-evaluated on a scale of 1–9, with 9 indicating maximal pleasantness/arousal. The valence and arousal ratings were analyzed separately using a 2(Gaze) × 2(Group) ANOVA. The results are shown in Table 1. For the valence ratings, the ANOVA showed a main effect of gaze ( $F_{(1, 66)} = 21.02, p < .001, \eta_p^2 = .174$ ), suggesting that participants felt more positive when perceiving NAO’s direct gaze ( $M = 6.18, SEM = 0.19$ ) compared to averted gaze ( $M = 5.40, SEM = 0.18$ ). The main effect of group ( $p = .565$ ) as well as Gaze × Group interaction ( $p = .253$ ) were not statistically significant. For the subjective arousal, the ANOVA showed no main effects of gaze ( $p = .553$ ) or group ( $p = .716$ ) nor a statistically significant Gaze × Group interaction ( $p = .955$ ).

We also explored possible relationships between the MA, NARS, IDAQ, S5, and SPS questionnaire ratings and the physiological responses to eye contact by using Pearson correlation analysis. For this purpose, we quantified the direct gaze effect by calculating the difference between response magnitudes during the direct and averted gaze conditions (i.e.,  $\Delta$  direct gaze – averted gaze). This variable was calculated for those physiological measures that significantly differentiated between perceived direct and averted gaze, either over the two groups (N170 and facial EMG) or in group A only (frontal P300). For N170, no statistically significant correlations were found. For the facial EMG, the direct gaze effect for zygomatic responses correlated positively with one of the subscales of NARS (Negative attitude toward situations of interaction with robots;  $r = 0.251, t_{(65)} = 2.09, p = .041, N = 67$ ) and negatively with S5 consciousness trait ( $r = -0.249, t_{(64)} = 2.06, p = .044, N = 66$ ), suggesting that higher negative attitudes toward interacting with robots and lower consciousness were associated with greater direct gaze effect in zygomatic responses. We also found that the direct gaze effect for frontal P300 responses correlated positively with two of the subscales of IDAQ (Anthropomorphism of technology;  $r = 0.432, t_{(30)} = 2.62, p =$

**Table 1**

Mean self-reported ratings (and SEM, displayed in brackets) of affective valence and arousal (1 = unpleasant/calm, 9 = pleasant/arousing) in response to the robot’s direct and averted gaze. The mean ratings are presented separately for both groups A (autonomous robot) and C (controlled robot).

	Valence		Arousal	
	Direct gaze	Averted gaze	Direct gaze	Averted gaze
Group A	6.39 (0.28)	5.36 (0.26)	3.03 (0.27)	2.91 (0.28)
Group C	5.97 (0.27)	5.43 (0.25)	3.14 (0.27)	3.04 (0.27)

.013,  $N = 32$ , and Anthropomorphism of nature;  $r = 0.378, t_{(30)} = 2.24, p = .033, N = 32$ ), but only within group A, whereas no statistically significant correlations were found within group C. This suggests that when the robot appeared intentional, a higher individual tendency to anthropomorphize technology and nature was associated with a greater direct gaze effect in the frontal P300 responses. No other statistically significant correlations were found. Finally, it is important to note that when the  $p$  values of the correlation analyses ( $N = 12$ ) were corrected for multiple testing with Holm-Bonferroni method (Holm, 1979), none of the previously mentioned correlation results remained statistically significant.

4. Discussion

In the present study, our goal was to investigate whether affect- and attention-related psychophysiological responses to perceived direct and averted gaze of a humanoid robot (NAO) are modulated by perceived intentionality of the robot. We measured N170 and frontal P300 event-related brain potentials (ERPs) associated with visual face processing and attention orientation, respectively. In addition to ERPs, we measured skin conductance responses (SCRs) reflecting autonomic arousal, facial electromyography (EMG) from zygomaticus major and corrugator supercilii muscle regions reflecting the valence of affective reactions, and heart rate (HR) deceleration response, another index of attention orienting to external stimuli. To manipulate the degree of ascribed intentionality to the robot, the robot was introduced either as an autonomous social robot (group A) or as a non-autonomous control-dependent robot (group C). Our hypothesis was that the psychophysiological reactions would be greater to perceived direct versus averted gaze of the robot, but this effect would be observed only in group A, where the robot was seen as intentional. The participants also filled in questionnaires to evaluate their own affective arousal and valence in response to the robot’s gaze directions, their mind attributions to the robot (MA), as well as their more general negative attitudes toward robots (NARS), individual degree of anthropomorphism (IDAQ), Big Five personality traits (S5), and their degree of social phobia (SPS).

The ERP results showed that, in line with our hypothesis, perceiving the robot’s direct gaze elicited greater (more negative) N170 responses than averted gaze. The N170 response is considered to reflect visual processing of a face (Bentin et al., 1996; Itier and Taylor, 2004; Tanaka, 2018). The present results are compatible with the results from previous studies (Conty et al., 2007; Pönkänen et al., 2011a) and suggest that the face processing is intensified when the face is gazing toward the perceiver, as opposed to displaying averted gaze. To our best knowledge,

this is the first study to show greater N170 responses to direct versus averted gaze of a robot face. In their recent literature review, Tautvydaitė et al. (2022) found that the sensitivity of N170 to gaze direction has been most prominent when either live faces or pictures of faces with dynamic gaze shifts were used as stimuli, as opposed to still images. It has been suggested that a direct gaze seen in a picture is not perceived as a cue of preparedness for communication and, therefore, it may not enhance face processing. However, a direct gaze of a face that is seen live may enhance the visual processing because of the live person's capability of social interaction and the need for more elaborated processing (Pönkänen et al., 2011a). Perhaps, in the present study, viewing an embodied humanoid robot primed a possibility of interaction and thus modified the N170 responses to eye contact with the robot. Contrary to our hypothesis, however, this gaze effect occurred in both groups A and C, suggesting that the robot does not necessarily need to be seen as an intentional agent for its direct gaze to elicit enhanced visual processing of the face. It is possible that the N170 response reflects such early encoding of faces that it is not influenced by perceived intentionality of the agent. There is a noteworthy study by Caruana and McArthur (2019), in which the participants' ERPs were measured while they viewed a virtual character's gaze shifts. Importantly, the participants' beliefs of the avatar's intentionality were manipulated (either human-controlled or robot-controlled). The results showed, compatibly with the present ones, that the belief of the character's intentionality did not affect the N170 responses, but instead its effect was seen in the later (>200 ms) ERPs that reflect more evaluative stages of neural processing.

We also found that the latency of the N170 response was reduced to perceived direct versus averted gaze of the robot regardless of the group. Previous literature has demonstrated that the latency of N170 is delayed when face perception requires more effort, for example, when perceiving inverted versus upright faces (Itier and Taylor, 2004; Rossion et al., 2000), and, compatibly, attained experience in a face discrimination task may lead to faster processing of facial stimuli and reduced N170 latency (Su et al., 2012). In the present study, we manipulated the robot's gaze direction by rotating its whole head. Therefore, it is possible that the reduced latency to the robot's direct versus averted gaze was due to the front-view of the robot's face being easier to perceive as a face, as humans are perhaps not as familiarized with the side-view of the robot's face (see Fig. 1). To explore this hypothesis further, future studies on gaze direction effects could be conducted with a humanoid robot that can rotate its eyes instead of needing to rotate its whole head.

In contrast to N170, frontal P300 responses were enhanced (more positive) to the robot's direct versus averted gaze only when the robot was presented as autonomous and intentional. These results are compatible with a previous EEG study by Kompatsiari et al. (2021a), in which eye contact with a social robot was associated with greater alpha-band desynchronization in the left fronto-central areas, possibly reflecting joint attention and engagement in social interaction. Moreover, our results are in line with those of Myllyneva and Hietanen (2015) showing that the frontal P300 responses were greater to perceived direct versus averted gaze of a live human only when the perceiver believed that they were seen by the other. This was interpreted to suggest that for eye contact to enhance attention orienting toward the face, the perceiver needs to feel that they are seen by another intentional mind. The frontal P300 response is suggested to reflect the activation of the medial prefrontal cortex (e.g., Mulert et al., 2004), which is associated with socio-cognitive functions such as mentalizing and adopting the intentional stance (Amodio and Frith, 2006; Gallagher et al., 2002; Kampe et al., 2003; Schilbach et al., 2006). There is also evidence that eye contact with a live partner activates the mentalizing-related anterior rostral prefrontal cortex and inferior frontal gyrus (Cavallo et al., 2015). It is possible that the present frontal P300 results reflect the functioning of socio-cognitive processes, as mentalizing was needed to decipher the meaning and intentions behind the direct gaze. Interestingly, the magnitude of the frontal P300 response to eye contact seemed to be associated with individual tendencies to anthropomorphize machines

and nature, but only for the participants to whom the robot was presented as intentional. However, as the correlation results did not hold statistical significance after correcting for multiple testing, these results are speculative. Still, the correlation results may further support the interpretation that the frontal P300 responses to eye contact reflect, at least to some extent, socio-cognitive processes that require ascribing intentionality to the other, and that also robots can elicit these processes. Finally, the frontal P300 responses were also overall greater in group A than group C, implying that regardless of gaze direction, the robot was a more engaging stimulus when it was presented as an autonomous agent.

Surprisingly, the robot's gaze direction did not affect the magnitude of the SCRs and HR deceleration responses in either group. Therefore, despite using a similar humanoid robot (NAO), we failed to replicate the results of our previous studies demonstrating that eye contact with a robot elicits affective arousal and attention-related heart rate deceleration responses (Kiilavuori et al., 2021, 2022). However, there was one important difference between the present and the previous experiments, which could explain these differential results. In the present study, the robot did not mimic eye blinking by briefly turning off its eye LEDs (see 2.2 Stimuli), whereas in the studies by Kiilavuori and colleagues (2021, 2022), the robot blinked once per stimulus presentation. Indeed, there is research showing that blinking behavior is a meaningful component of social interaction. For example, eye blinks may function as communicative signals capable of directly influencing the communicative behavior of others (Hömke et al., 2018). Moreover, there is evidence that eye blinks can modulate ERP responses related to social attention (Brefczynski-Lewis et al., 2011), suggesting that the brain registers blinks for their potential social salience. It is possible that, in the present study, the robot's lack of eye blinking attenuated the intentional appearance of the autonomous robot (the version presented to group A), thus also affecting the SCRs and HR deceleration responses. It is, of course, interesting then why we observed the effect of eye contact on the ERPs but not on SCRs and HR deceleration responses. In fact, the results may seem somewhat contradictory, as both frontal P300 and HR deceleration responses are considered to reflect attention orienting toward external stimuli. However, if the robot's lack of blinking attenuated the intentional appearance of the autonomous robot, it is plausible that this attenuation was more pronounced in the longer 3000-ms (i.e., SCR, EMG, & HR) than in the shorter 500-ms (i.e., ERP) gaze direction trials. Adult humans typically blink once every 3–4 s (Bentivoglio et al., 1997; Zametkin et al., 1979), and perhaps one would, therefore, expect to see a humanoid robot blink in the longer-lasting stimulus presentations but not necessarily in the brief presentations. Moreover, it is possible that the slower responses (i.e., SCR & HR) are more susceptible to the *degree* of intentionality ascribed to the robot, as compared to the faster responses (i.e., ERPs).

Regarding the facial EMG responses, the present study replicates our previous results showing that, compared to perceived averted gaze, eye contact with a humanoid robot increases activity in the muscle area of zygomaticus major and decreases activity in the area of corrugator supercilii (Kiilavuori et al., 2021). Similar EMG responses have also been observed to a live human's direct versus averted gaze (J. K. Hietanen et al., 2018; J. K. Hietanen and Peltola, 2021; J. O. Hietanen et al., 2020; Kiilavuori et al., 2021). Importantly, the EMG responses to the robot's direct versus averted gaze were similar in both groups A and C, suggesting that the robot did not need to be seen as an intentional agent for these enhanced responses to eye contact to occur. The contraction of the cheek muscle combined with the relaxation of the brow-region muscle is often associated with a positive affective reaction (Cacioppo et al., 1986; Dimberg, 1990; Larsen et al., 2003). Alternatively, it has been suggested that, in a social setting, this type of smiling response may also be a highly automatized affiliative signal that humans have learned to display when seeing someone gazing toward them (e.g., J. K. Hietanen et al., 2018; J. O. Hietanen et al., 2020). Our results seemed to further indicate that the direct gaze effect for zygomatic responses (i.e., greater muscle contraction to direct than averted gaze) correlated positively with



self-evaluated discomfort during hypothetical interaction with a robot, although this conclusion remains speculative, as the correlation results did not withstand correction for multiple testing. That being said, in the present study, smiling may have served to relieve the possible tension of a rather intimate interaction with the robot. This would support the role of a smile as an affiliative signal.

Regardless of the group, the participants' self-reported affect valence was more positive to direct versus averted gaze of the robot, whereas their affective arousal was indifferent to the robot's gaze direction. In this study, these self-evaluated affective responses were in line with the affect-related physiological responses. However, it is not uncommon that implicit and explicit measurements yield conflicting results (Evans, 2008; Hofmann et al., 2005), and one should, therefore, be careful when interpreting physiological and self-evaluation responses together. For example, many of our previous studies have shown a disparity between self-evaluated and physiological affect-related responses to facial stimuli (J. K. Hietanen et al., 2018; J. O. Hietanen et al., 2020; Kiilavuori et al., 2021). That being said, we found it intriguing that the present manipulation of the robot's intentionality influenced not only the implicit responses to viewing the robot but also the participants' explicit attributions of agency and consciousness to the robot. It has been argued that ascribing intentionality to social robots should be studied not only with implicit measures but also with self-evaluation ratings (see Kewenig et al., 2018), even though anthropomorphism is often considered as being a highly implicit process (see Fink, 2012). An interesting challenge for future research is to reveal to what extent the explicit and implicit ascriptions of the robot's intentionality reflect the same underlying socio-cognitive processes.

A possible limitation of the present study is that the impression of the robot's intentionality was manipulated by highlighting either its autonomy or dependence on human control. We wanted the participants to adopt either the intentional stance or design stance toward the robot. To stimulate the adoption of the design stance, we explicitly told the participants, in group C, that the robot would be controlled by the human experimenter during the gaze direction trials. Interestingly, there are comparable studies that have successfully manipulated participants' ascriptions of humanlikeness toward a virtual character by saying that the character was controlled either by a human or a computer (see Caruana et al., 2017; Caruana and McArthur, 2019). In these studies, joint attention with the character led to greater centroparietal P250 and P350 ERPs when the participants believed that the character was controlled by a human, as compared to the condition in which the character was allegedly controlled by a computer. Therefore, in the present study, we cannot rule out the possibility that the participants in group C may also have perceived a certain degree of "remote" intentionality in the human-controlled robot due to the human controller. This could have then led to amplified N170 and EMG responses to the robot's direct versus averted gaze. However, the responses to the mind attribution questionnaire seem to speak against this possibility, as the participants in group C strongly disagreed with attributing any mind characteristics to the robot. Nevertheless, this possibility could be explored in future research, for example, by telling the participants that the robot's behavior is either autonomous or *preprogrammed*.

In conclusion, the present study demonstrates that the way the robot is characterized to the viewers and the robot's verbal and nonverbal social cues seem to play a crucial role in determining whether the robot is seen as an intentional agent capable of social interaction, as well as in influencing human observers' brain responses to the robot's gaze behavior. In addition, we show that engaging in eye contact with a humanoid robot may also elicit psychophysiological responses that do not require that the robot is seen as intentional, possibly because the responses are highly automatized or reflect very early stage of cognitive processing. The present results should be useful to the developers of social robots, as the robots' social behavior and cues seem to be of great importance in aiding social interaction with humans. The current approach to studying psychophysiological responses to eye contact and

experimentally induced mental attributions may also be widely applicable for further studies of both human-robot as well as human-human interaction. Moreover, in future human-robot interaction research, more attention should be devoted to the developmental aspects of ascribing intentionality to social robots. Indeed, a growing body of research demonstrate that eye contact with a humanoid robot elicit attention- and affect-related responses in adult humans, but it would be interesting to know whether these responses are already seen in, for example, human infants as well. This could help us gain understanding of whether we react to social robots' social cues as we do because we have learned from, for example, the cinema, that social robots are highly sophisticated gadgets which are designed to imitate human behavior and supposed to elicit appropriate responses in us, or whether our reactions reflect more genuinely bottom-up regulated processes that can be triggered by a variety of humanlike stimuli. Finally, to ensure the ecological validity of human-robot interaction research, we stress using embodied social robots instead of pictures of robots' faces. This would help capture some of the small nuances in a natural social interaction, which clearly seem to play an important role in how we react to robots' social cues.

### Credit author statement

**Samuli Linnunsalo:** Conceptualization, Methodology, Software, Investigation, Validation, Data curation, Formal analysis, Writing – Original draft, Visualization; **Dennis Küster:** Conceptualization, Methodology, Writing – Review & Editing; **Santeri Yrttiaho:** Formal analysis, Writing – Review & Editing; **Mikko J. Peltola:** Software, Writing – Review & Editing; **Jari K. Hietanen:** Conceptualization, Methodology, Validation, Writing – Review & Editing, Supervision, Project administration, Funding acquisition.

### Data availability

Data have been published in Mendeley Data repository.

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### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.neuropsychologia.2023.108668>.

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