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Making eye contact with a robot: Psychophysiological responses to eye contact with a human and with a humanoid robot

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ABSTRACT

Previous research has shown that eye contact, in human-human interaction, elicits increased affective and attention related psychophysiological responses. In the present study, we investigated whether eye contact with a humanoid robot would elicit these responses. Participants were facing a humanoid robot (NAO) or a human partner, both physically present and looking at or away from the participant. The results showed that both in human-robot and human-human condition, eye contact versus averted gaze elicited greater skin conductance responses indexing autonomic arousal, greater facial zygomatic muscle responses (and smaller corrugator responses) associated with positive affect, and greater heart deceleration responses indexing attention allocation. With regard to the skin conductance and zygomatic responses, the human model's gaze direction had a greater effect on the responses as compared to the robot's gaze direction. In conclusion, eye contact elicits automatic affective and attentional reactions both when shared with a humanoid robot and with another human.

1. Introduction

With the rapid progress in robotics over the past decade, so-called social robots are becoming a part of people's lives. These robots are increasingly being designed to interact with people and to assist in various humane environments, such as schools, hospitals, and even homes (Breazeal, Dautenhahn, & Kanda, 2016; Matarić & Scassellati, 2016). To ensure robots' smooth integration to human society, we need to understand how people react to robots and interact with them (Breazeal et al., 2016). Studies investigating human-robot interaction (HRI) could also be used to advance the design of social robots.

Despite robots' artificiality, people seem to socially react to and ascribe humane attributes to robots, a phenomenon known as anthropomorphism (Hofree, Ruvolo, Bartlett, & Winkielman, 2014; Hofree, Urgen, Winkielman, & Saygin, 2015; Kiesler, Powers, Fussel, & Torrey, 2008). For instance, there are studies demonstrating that people may perceive different qualities, such as knowledgeability, sociability, and likability, in humanoid robots based on their appearance and/or behavior (Powers & Kiesler, 2006; Willemse & Wykowska, 2019). Interestingly, some studies suggest that people even tend to perceive robots as if they had a mind (Gazzola, Rizzolatti, Wicker, & Keysers, 2007; Oberman, McCleery, Ramachandran, & Pineda, 2007; Thellman, Silvervarg, & Ziemke, 2017) – a capability for internal states, intentions and experiences (Gray, Gray, & Wegner, 2007). For example, when participants were asked to judge the behavior of a human and a humanoid robot presented in a series of images and verbal descriptions, the results showed that the behavior of these two agents were rated as similarly intentional (Thellman et al., 2017). In line with this finding, two studies provided evidence that observing a robotic hand performing goal directed motor actions evoked similar putative mirror neuron system activity as was evoked by observing the same actions performed by other humans (Gazzola et al., 2007; Oberman et al., 2007). It should be noted, however, that although these findings provide evidence that people tend to perceive mind in robots, there are also studies that have resulted in different conclusions (Chaminade et al., 2012; Rauchbauer et al., 2019). For instance, when participants were playing rock-paper-scissors while believing their opponent was another human, a humanoid robot equipped with artificial intelligence, or a computer playing randomly, brain areas associated with mentalizing (medial prefrontal cortex and right temporoparietal junction) responded only to playing the game with another human, but not the robot (Chaminade et al., 2012). According to some studies, human-like appearance of an artificial agent may enhance ascribing mental attributes to it (Abubshait & Wiese, 2017; Kiesler et al., 2008; Krach et al., 2008, Martini,

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Gonzalez, & Wiese, 2016).

Although previous studies on human-robot interaction have provided significant knowledge on how people perceive robots and their behavior, few studies have investigated people's psychophysiological responses to robots' nonverbal cues. Among humans, various non-verbal cues play a significant role in regulation of social interaction. Along with facial expressions and bodily gestures, another person's gaze is one of the most crucial cues in social communication. Another person's gaze reveals the direction of their attention and possible target for their intentions: an averted gaze signals attention being directed to something in the surrounding environment, whereas a direct gaze indicates another person's attention being directed towards oneself (George & Conty, 2008; Itier & Batty, 2009). Eye contact can be considered as a foundation for social interaction, since it signals initiative for communication (George & Conty, 2008; Itier & Batty, 2009; Kleinke, 1986) and motivates to approach the other individual (Hietanen, 2018).

An extensive line of research has demonstrated that the direction of another person's gaze has effects on an observer's own attention. Observing another person's gaze directed away from oneself triggers attention orienting towards the gazed-at direction (for a review, see Frischen, Bayliss, & Tipper, 2007), a phenomenon known as gaze-cueing. Observing a direct gaze, in turn, captures attention resulting in automatic attention orienting toward faces (Conty, Tijus, Hugueville, Coelho, & George, 2006; Doi, Ueda, & Shinohara, 2009; von Grünau & Anston, 1995). Along with behavioral measures, attention orienting toward faces with direct gaze is also reflected in physiological measures. Compared to averted gaze, direct gaze has been found to induce more pronounced heart rate deceleration response (Akechi et al., 2013; Myllyneva & Hietanen, 2015), a psychophysiological response associated with attentional orienting toward external stimuli (Bradley, 2009).

Interestingly, in addition to influencing perceivers' attention, another individual's direct gaze has also affective-motivational effects (for a review, see Hietanen, 2018). Seeing another person's gaze directed towards oneself has been reported to evoke increased self-evaluated affective arousal (Hietanen et al., 2018; Hietanen, Leppänen, Peltola, Linna-aho, & Ruuhiala, 2008; Marschner, Pannasch, Schulz, & Graupner, 2015). Measurements of physiological arousal have indicated compatible results: seeing another's direct gaze has been shown to elicit greater autonomic nervous system (skin conductance) responses as compared to averted gaze (Helminen, Kaasinen, & Hietanen, 2011; Hietanen et al., 2018; Hietanen et al., 2008; Nichols & Champness, 1971; Prinsen & Alaerts, 2019). These results indicate that another person's direct gaze is an affectively arousing signal. Regarding affective valence, explicit self-evaluations have resulted in mixed findings. Some studies have reported more positive feelings to another's direct than averted gaze, whereas others have reported an opposite effect or no difference between the gaze directions at all (Hietanen et al., 2008, 2018; Pönkänen, Alhoniemi, Leppänen, & Hietanen, 2011; Uono & Hietanen, 2015; Wirth, Sacco, Hugenberg, & Williams, 2010). However, studies relying on implicit psychophysiological measurements have resulted in more coherent findings. Direct gaze, as compared to averted gaze, has been shown to increase the activity of the zygomatic facial muscle associated with positive affective reactions (Hietanen et al., 2018; Hietanen, Peltola, & Hietanen, 2020) and induce greater left than right frontal electroencephalographic activity (frontal EEG asymmetry) associated with positively valenced affect and approach motivation (Hietanen et al., 2008; Pönkänen, Peltola, & Hietanen, 2011). In sum, there is considerable evidence that another person's direct gaze is perceived as an emotionally salient stimulus that captures a perceiver's attention and induces affectively positive reactions.

An important question is whether eye contact has similar attentional and affective effects when it is "shared" with a robot. Does a direct gaze by an agent known to be inanimate, yet possibly interpreted as having a mind, trigger similar attention and affect related responses as seeing another person's direct gaze? Among humans, enhanced psychophysiological responses to direct versus averted gaze may be dependent on having an experience of being a target of another person's attention. Previous studies have shown that a direct gaze elicits greater autonomic and brain responses compared to an averted gaze when facing a real, physically present human, but not when perceiving animated faces (Wieser, Pauli, Alpers, & Mühlberger, 2009) or human faces presented in still images (Donovan & Leavitt, 1980; Hietanen et al., 2008; Pönkänen, Alhoniemi et al., 2011; Pönkänen, Peltola et al., 2011) or videos (Hietanen et al., 2020; Lyyra, Myllyneva, & Hietanen, 2018; Prinsen & Alaerts, 2019). To explain these findings, it has been suggested that the differential reactions to a live person versus a still image are due to the fact that a still image does not induce an experience of being looked at (Hietanen et al., 2008; Pönkänen, Peltola et al., 2011). More direct support for this suggestion was gained from a study which showed that when the participants were led to believe that a one-way window was placed between them and a live stimulus person in such a way that the model was not able to see them, the model's gaze direction had no effects on the participants' psychophysiological responses (Myllyneva & Hietanen, 2015).

Despite the various affective and attentional effects of eye contact in human-human interaction, few studies have investigated these effects in an interaction with robots. The majority of studies investigating the role of eye contact in human-robot interaction, to date, has mainly focused on whether eye contact established by a robot has an influence on various subjective impressions of the robot. These studies have provided evidence that eye contact established by a robot enhances favorable attitudes towards the robot (Shiomi, Nakagawa, & Hagita, 2013; Yonezawa, Yamazoe, Utsumi, & Abe, 2007). For instance, one study reported that a humanoid robot who looked at the participant after making a small mistake (failing to put an object into a box) was perceived as more friendly than a robot who looked down or avoided eye contact with the participant after the mistake (Shiomi et al., 2013). Kühnlenz et al. showed that eye contact with a humanoid robot during a task execution enhanced participants' perception of the robot's animacy and anthropomorphism (Kühnlenz, Wang, & Kühnlenz, 2017). Furthermore, there is evidence showing that eye contact established by a robot enhances self-reported feelings of engagement in social interaction with the robot (Kompatsiari, Ciardo, Tikhanoff et al., 2019). In line with this finding, a recent study employing implicit behavioral measures showed that participants fixated longer to a humanoid robot's (iCub) face in an eye contact than in no eye contact condition (Kompatsiari, Ciardo, De Tommaso, & Wykowska, 2019). The same study showed also that participants engaged in joint attention with the robot only when the robot established an eye contact before the gaze shift (Kompatsiari, Ciardo, De Tommaso et al., 2019). The authors concluded that eye contact holds attention to the robot's face and, thus, may facilitate people's engagement in social interaction with robots (Kompatsiari, Ciardo, De Tommaso et al., 2019). In sum, there is evidence that humanoid robots' gaze direction has an influence on human partners' evaluations and social reactions towards the robots. However, as mentioned above, the majority of these studies were based on self-reports. Although self-reports are an important method for measuring people's subjective experiences, they reflect controlled information processing and are vulnerable to different kinds of higher order inferences (Evans, 2008; Hofmann, Gawronski, Gshwendner, Le, & Schmitt, 2005). Furthermore, it may not always be easy to recognize and report one's own affective reactions towards a presented stimulus when asked explicitly (Hofmann et al., 2005). Implicit measurements, instead, can enable detecting participants' automatic reactions that are resistant to explicit information processing, and therefore, may provide information that is not accessible by explicit measurements (Evans, 2008).

The aim of the current study was to investigate participants' responses to being looked at or not by a robot by measuring psychophysiological skin conductance responses (SCR), facial electromyography (EMG) responses, and heart rate (HR) deceleration responses as well as subjective self-ratings (affective feelings). Measurements of SCRs have commonly been used as a method to investigate emotion-related sympathetic arousal (Critchley, 2002). Rapid HR deceleration, followed by acceleration towards baseline, indexes attention orienting to external stimuli and is known to be amplified by affectively salient stimuli (Bradley, 2009; Graham & Clifton, 1966). Measurements of EMG responses from the facial muscles involved in producing facial emotional expressions are considered to indicate the valence of the affective responses (Cacioppo, Petty, Losch, & Kim, 1986; Dimberg, Thunberg, & Elmehed, 2000). Given that the EMG responses have been shown to occur rapidly, only 300−400 ms after exposure to the stimulus, they are considered to reflect relatively automatic affective reactions (Dimberg & Thunberg, 1998). Affectively positive stimuli increase the activity of *Zygomaticus major* (smile) and decrease the activity of *Corrugator supercilii* (furrows between the eyebrows) muscles while negative affective stimuli lead to increased activation of *Corrugator supercilii* (Cacioppo et al., 1986; Schumacher et al., 2015). To the best of the authors' knowledge, no previous studies have measured these types of psychophysiological responses to a humanoid robot's different gaze directions. In order to investigate whether these responses to a robot's gaze directions resemble those observed in response to another human's gaze directions, we also measured them, in identical conditions, while the participants were facing another person. Importantly, in the present study, we investigated the psychophysiological responses when the participants were facing a real robot and another person physically present in the laboratory. In recent years, researchers investigating social cognition have become increasingly aware that studies conducted in a laboratory by showing images of other people may not succeed in capturing all the critical aspects of natural social interaction (Kingstone, Smilek, & Eastwood, 2008; Risko, Richardson, Kingstone, & 2016). There is evidence showing that, similarly to when studying human-human interaction, it may be important to study human-robot interaction with physically present robots instead of pictures of them. A study measuring facial EMG to investigate spontaneous mimicry of an android's facial expressions showed that the participants spontaneously matched the android's facial expressions more strongly when the android was physically present as compared to when they were viewing a video of the android (Hofree et al., 2014). In the same study, the participants rated the physically present android more humanlike than its video counterpart.

In sum, in the present study, we measured participants' autonomic arousal (SCR), facial EMG activity from the zygomatic (cheek) and corrugator (brow) muscle regions, and heart rate (HR) deceleration responses when they were presented with a humanoid robot (NAO) and a live model person through an electronic shutter. On half of the trials, the model person and NAO robot looked directly at the participant, whereas on the other half of the trials their gaze was directed sideways (at a predetermined fixation spot). Based on the previous findings suggesting that people tend to ascribe humane characteristics, sometimes even minds, to robots (Gazzola et al., 2007; Kiesler et al., 2008; Powers & Kiesler, 2006; Thellman et al., 2017), we expected that seeing the robot's as well as the model person's direct gaze would elicit greater responses compared to seeing their averted gaze. In addition to physiological measurements, we measured participants' explicit affective feelings (affective valence and arousal) in response to different gaze conditions. In order to investigate whether the physiological responses to NAO's gaze directions would be modulated by participants' general perceptions of NAO, we also measured participants' evaluation of NAO on four different dimensions (anthropomorphism, animacy, likeability, and perceived intelligence).

2. Methods

2.1. Participants

We gathered data from 48 participants mainly recruited among undergraduate students of Tampere University and Tampere University of Applied sciences. This exceeds the required sample size for finding a moderate effect ($d = 0.50$) at 0.80 power and α level of 0.05 (Cohen, 1992). Neither students majoring in psychology, students with reported neurological or psychiatric diagnoses, nor students who had previously taken part in a similar type of studies in our laboratory were allowed to participate in this study. Despite these pre-determined criteria, four participants participated who did not fulfill the inclusion criteria. This was discovered only after the experiment, during debriefing and the final check-up of the exclusion criteria. These participants were excluded from the final analyses. Furthermore, two participants were excluded from the final analyses due to technical problems (see Footnote[1]). Thus, altogether 42 participants (29 females and 13 males) were included in the final analyses (age range = 19–45 years; mean age = 25.381, SD = 6.293), which still exceeds the required sample size for finding a moderate effect. The data were not analyzed before the data collection was completed. All participants gave a written, informed consent, and received either course credits or a movie ticket for their participation. Ethical statement for the experiment was obtained from the Ethics Committee of the Tampere Region.

2.2. Stimuli

One male and one female, previously unknown to the participants, served as stimulus persons (models) in the human-human conditions. The model's and the participant's gender were matched. The models bore a neutral expression and kept their face as motionless as possible throughout the experiment. However, when necessary, eye blinks were allowed to occur. The models were instructed to maintain a slight muscle tonus in the lower part of the face in order not to look sullen or fatigued. Depending on the trial, the models had their head and gaze either straight ahead or averted 65° to the left or right (see Fig. 1). When averting their head and gaze side-ways (gaze always pointing to the direction of the nose), the models were instructed to turn their heads but not their shoulders. The stimulus in the human-robot condition was a humanoid NAO robot developed by SoftBank Robotics (formerly: Aldebaran). The behavior of the robot was programmed with Choregraphe software SoftBank Robotics (formerly: Aldebaran). As in the human-human condition, the robot had its head and gaze either straight ahead or averted to the left or right. When the robot's head and gaze was rotated 65° to the left or right, the participant could only see a part of the "pupil" of the robot's eye on his/her side (see Fig. 1). Thus, the difference between the robot's direct and averted gaze was aimed to be as clear as possible. The robot's eye LEDs were programmed to blink every third second in order to make an impression of eye blinking and to make the gaze look more natural. As the stimuli were always presented for 3000 ms, the blink occurred once, at the most, during each stimulus-presentation period. During the stimulus presentation, the models and the robot were static except for occasional blinks.

The model and the robot were presented to the participants through a voltage sensitive LC window (NSG UMU Products Co., Ltd.) attached to a black frame between the model and the participant (see Fig. 2). The participant was seated at a distance of approximately 60 cm from the LC

[1] One participant was excluded from the final analyses because NAO remained unresponsive and did not perform the pre-programmed interactive behavior during the interaction session before the experimental trials. The decision to exclude this participant was based on the possibility that the lack of the entire interaction session could have affected the responses. However, as we can not know for sure whether the lack of the interaction session affected the participant's responses, we analyzed the results of the physiological measurements also having included the data from this participant. These analyses resulted in only slightly different mean values in each condition and a similar pattern of statistically significant differences between conditions as compared to those reported in the results section.

Fig. 1. An illustration of the different gaze direction conditions for a human model and the NAO robot.

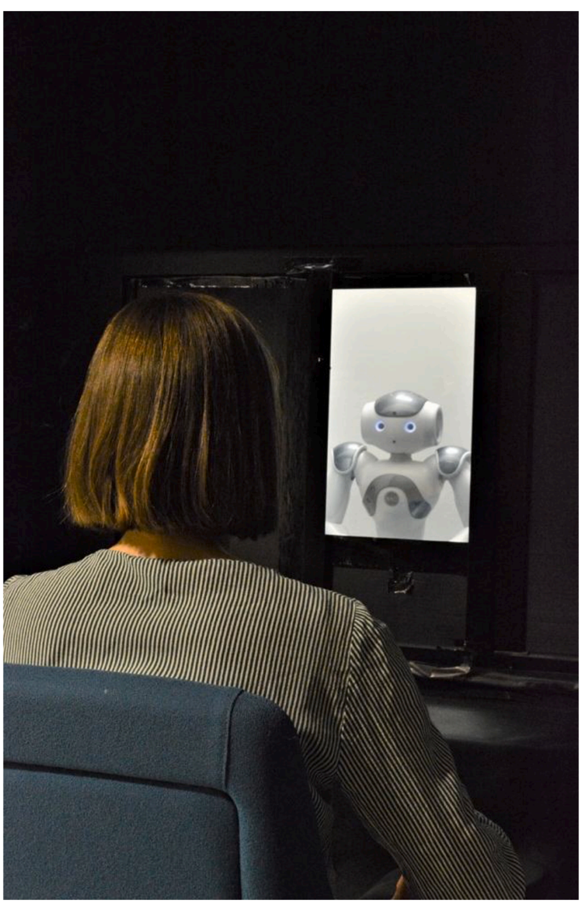

Fig. 2. The robot (and the human model) was presented to the participants through a voltage sensitive LC window.

window. The model was sitting at a distance of approximately 60 cm and the robot at a distance of approximately 40 cm from the other side of the shutter. The participant's seat was adjusted in such a way that vertically their eyes were at the same level with the model's/robot's eyes. For both the human model and the robot, the participants were able to see their upper body and head. The participants were instructed to sit straight and keep their gaze directed to the LC window throughout the experiment. The state of the LC window (transparent or opaque) was operated by E-Prime 2.0 software (Psychology Software Tools, Pittsburgh, PA) running on a desktop computer.

2.3. Experimental procedure

The experiment was conducted in two separate blocks: one with the human model and another with the robot as a stimulus. The order of the blocks was counterbalanced (half of the participants started with the human-human condition and the other half with the human-robot condition). For the SCR measurements, the participants were asked to wash their hands without soap before entering the laboratory. Each experiment was conducted by two experimenters. The leading experimenter informed the participants about the experiment, gave the instructions to the participant, and controlled initiating the trials during the experiment. The other experimenter assisted with placing the electrodes onto the participant's skin and controlled NAO's behavior before the experimental trials. In the beginning of the experiment, the experimenters introduced themselves and informed the participant that the purpose of the study was to measure physiological responses during a simple interaction situation. To disguise the purpose of the facial EMG electrodes, the participants were told that the facial sensors were attached for measuring skin temperature.

The same instructions regarding the experimental procedure were given in the beginning of both blocks. The participants were informed that the experiment would consist of two separate parts, which they would carry out with two different partners (the first block with one partner and the second block with another one). The participants were told that the partner would be seated/placed on the other side of the LC window opposite to the participant. They were told that during the experimental trials, the LC window would alternate between transparent and opaque states, and, during the transparent periods, they and the partner would be able to see each other. The participants were instructed that their task was simply to look at the partner (human model/robot) while the shutter was transparent ("opened"). To demonstrate the functioning of the LC window, the experimenter opened and closed the window three times before proceeding to the actual trials. The demonstration was operated by E-prime. The partner of each block was not revealed to the participant until the beginning of the particular block.

After the demonstration, the human model/robot was introduced to the participant. In the human-human block, the human model entered the laboratory and they were introduced by name to the participant by the experimenter. No further interaction took part between them before the experimental trials to ensure that the relationship between the participant and the human model would be as neutral and as similar as possible to all participants. After the greeting, the human model got seated behind the other side of the panel and the LC window. When the human model had seated themselves, the leading experimenter opened the window and asked whether the participant and the human model felt that their eyes were vertically at the same level. If necessary, the participant's seat was adjusted to obtain the level of the human model's eyes. When NAO was introduced, the experimenter opened the curtains behind which NAO was sitting, and the robot stood up autonomously and introduced itself to the participant by saying "hi, my name is NAO". Then the robot performed some human-like gestures, such as nodding and hand movements. The participant, who was already sitting on the chair with the electrodes attached onto their skin, was asked to move their body from left to right to notice that NAO was able to follow the participant's movements by turning its head. The aim of this short interaction session with the robot was to familiarize the participant with NAO and enhance the participant's impression of the robot as a socially intentional agent, capable of communicating, "seeing", and reacting to its surroundings. After this, the assistant experimenter placed NAO on the other side of the LC window. When NAO had been placed on the other side, the leading experimenter opened the window and asked whether the participant felt their eyes were at the same level with NAO's eyes. Then the experimenter "asked" NAO to adjust its gaze/head towards the participant. Immediately after making this request, the assistant experimenter, who was standing behind the curtains, pressed a key on the laptop on which the program controlling NAO was running, and the robot started to perform some head movements (similar to all participants) as if it was searching for the right head position. After completing the movements, the robot's gaze ended up being on a little higher level as compared to the starting position (in the starting position, the robot had its head slightly bowed, yet its eyes visible to the participant). If NAO's eyes were still too high or low, the participant's seat was adjusted to obtain the level of NAO's eyes.

On each trial, the window became transparent for 3000 ms, during which the human model/robot looked either directly at or away (right or left) from the participant. The human model/robot maintained the gaze direction until the window became opaque again. To know where to look at, on each trial, the human models read instructions from a monitor located on the model's side of the panel (hidden from the participants' view). The instructions were delivered by E-prime. The robot's gaze direction was controlled by the experimenter via a laptop. The instructions regarding the robot's gaze direction on each trial were delivered by E-prime and appeared on a monitor next to the experimenter. The experimenter monitored the participant's skin conductance level on-line and initiated the next trial when the skin conductance level had returned to the baseline level, however, not before at least 15 s had passed from the LC window turning opaque. In both blocks, 10 trials were collected for both gaze conditions (direct gaze: 10; averted gaze: 5 left/5 right). The order of the trials was randomized. Both experimenters sat behind curtains during the experimental trials, and the participants could not see them.

Immediately after each experimental block, the participants were asked to complete brief questionnaires to evaluate their explicit affective feelings in response to different gaze conditions. In order to help the participants recall their feelings in each condition, the window was opened three times for 3000 ms to show the different gaze conditions. Each of the three gaze directions was presented to the participant once. After each stimulus presentation, the participants evaluated their own feelings of affective valence and arousal on a 9-point Self-Assessment Manikin (SAM, see Bradley & Lang, 1994) scales (1 = unpleasant/calm, 9 = pleasant/arousing). After completing the Self-Assessment Manikin questionnaire, the participants were asked to evaluate the gaze directions again; this time they were asked to rate their experience regarding whether they felt the human model/robot was looking at them or not. The purpose of this task was to confirm that they felt that the robot and the human model were looking at them when their gaze/head was direct. The participants were asked to answer to a single statement on a 9-point scale: "The model/robot looked directly at me" (1 = totally disagree, 9 = totally agree). As for the SAM evaluations, the window was opened three times for 3000 ms to show the different gaze conditions, and each of the three gaze directions was presented to the participant once. In the end of the experiment, the electrodes were removed and the participants were asked to complete two more brief questionnaires. The first questionnaire was for measuring participant's perception of NAO on four dimensions (animacy, anthropomorphism, likeability and perceived intelligence). Each dimension consisted of three 5-point items. The questionnaire was based on the GODSPEED questionnaire, which is one of the most used questionnaires in studies investigating people's perceptions of robots (Bartneck, Kulić, Croft, & Zoghbi, 2009; Weiss & Bartneck, 2015). In the present study, we slightly modified the questionnaire. To shorten the questionnaire, we included only four of the five dimensions: anthropomorphism, animacy, likeability, and perceived intelligence. The excluded dimension was perceived safety. To further shorten the questionnaire, we included only three items of each selected dimensions. Thus, the questionnaire contained altogether 12 items. The other questionnaire was for measuring the participants' previous experiences with robots. It consisted of closed questions such as "Have you seen or heard any material related to robotics or artificial intelligence during the past 12 months?", "Have you seen a NAO-robot (similar to the one in the experiment) before?", "Have you seen a live robot before?", and "Have you used robots at home or at work?". If the participant answered "yes" to a question, he/she was asked to specify the answer on separate lines. In the latter questionnaire, the participants were also asked to respond to a single question associated with their general impression of robotics and artificial intelligence on a 4-point scale: "What is your general impression of robotics and artificial intelligence?" (1 = very negative, 4 = very positive).

2.4. Acquisition of the physiological data

The acquisition and the analyses of the physiological data are described in reference to previous studies from our laboratory, because the measurements and the data handling strategies were similar to the ones used in our previous studies (e.g. Hietanen et al., 2018; Myllyneva & Hietanen, 2015).

For the SCR measurements, two electrodes (Ag/AgCl) were filled with isotonic paste and attached to the palmar surface of the distal phalanxes of the index and middle fingers of the participant's left hand. EMG was used to measure facial muscle activity over *Zygomaticus major* and *Corrugator supercilii* muscle regions. The skin over the recording sites was rubbed with alcohol. Electrode paste (Signa gel) was injected to bipolar 4-mm Ag/AgCl electrodes (BioMed Electrodes) which were then attached over the recorded muscle sites according to the placement guidelines by Fridlund and Cacioppo (1986). A ground electrode was attached in the middle forehead, directly below the hairline. HR was measured with two electrodes (Ag/AgCl) that were applied with electroconductive paste and placed below both collarbones. The signals were amplified by a QuickAmp amplifier and continuously recorded with BrainVision Recorder software (Brain Products GmbH, Munich, Germany). The sampling rate for the digitized signals was 1000 Hz.

2.5. Analysis of the physiological data

2.5.1. Skin conductance

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 frame of 900–6000 ms after stimulus onset. To calculate the maximum change, the lowest skin conductance was detected within 900–3500 ms after stimulus onset and subtracted from the largest skin conductance value detected within 900–6000 ms after stimulus onset (Sjouwerman & Lonsdorf, 2019). In a case of two peaks within one response, only the first one was taken into account. The trial was coded as a zero response if the maximum amplitude change was less than 0.01 μS. Also trials with no amplitude rise (of at least 0.01 μS) until the first 3500 milliseconds after stimulus onset were coded as zero responses. However, if there was an amplitude rise of 0.01 μS or more during the first 900 milliseconds after stimulus onset, the trial was rejected. 9.0 % of all trials (from the 42 participants) were eliminated due to this criterion. The data from accepted trials (mean number of accepted trials/condition; Human Direct (HD): M = 9.0; Human Averted (HA): M = 9.0; Robot Direct (RD): M = 9.2; Robot Averted (RA): M = 9.1) were averaged in each condition for each participant, including trials with zero responses. This calculation results in the magnitude of the skin conductance responses referring to a measure that combines response size and response frequency (Dawson, Schell, & Filion, 2000). Because the SCRs were not normally distributed, a two-step transformation procedure was performed to normalize the SCR data (Templeton, 2011). The procedure involves first transforming the values into percentile ranks and then performing an inverse-normal transformation on these percentile ranks. After this transformation procedure, the SCRs followed a normal distribution in each condition.

2.5.2. Facial muscle activity

EMG activity was quantified for multiple (6) time intervals, each lasting 500 ms. This was done because EMG responses can vary from momentary spikes to longer lasting "mounds" depending on the underlying emotional process (Cacioppo, Martzke, Petty, & Tassinary, 1988). The signal was filtered offline with a 28–249 Hz bandpass filter and a 50-Hz notch filter using BrainVision Analyzer 2.1 software. The EMG signal around each experimental trial was visually inspected for artifacts due to excessive muscle movements and blinks. The inspection of the signal was performed individually for each muscle region, independently from each other. As a result, 7.8 % of the trials (from 42 participants) were excluded. From five participants, the data of the corrugator region activity was excluded completely due to thoroughly poor signal quality. For the analyses, the signal was rectified, smoothed, and segmented into 500-ms epochs from 500 ms prior to stimulus onset to 3000 ms post-stimulus. Within each participant, condition, and time epoch, the signal was averaged across all accepted trials (mean number of accepted trials/condition for *Zygomaticus major*; HD: M = 9.6; HA: M = 9.7; RD: M = 9.8; RA: M = 9.8; and for *Corrugator supercilii*; HD: M = 8.5; HA: M = 8.6; RD: M = 8.7; RA: M = 8.7). These values were then standardized within participant and within muscle region to reduce the influence of extreme values. The muscle response was calculated as change scores by subtracting the baseline muscle activity from each 500-ms average value within each experimental condition. Baseline was defined as the average of the activity during the 500-ms pre-stimulus period.

2.5.3. Heart rate

As mentioned in the introduction, the attention orienting response is known to include a rapid deceleration of HR followed by an acceleration towards baseline. To enable detecting progressive changes in HR (instead of momentary ones), HR was calculated for multiple (12) short time-intervals (500 ms).

The ECG (electrocardiogram) 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-waves (inter-beat interval, IBI). After the computer-based detection of the R-peaks, the data were manually inspected trial by trial to correct the falsely detected and missing peaks. Trials with excessive distortion in the signal were excluded from the analysis (0.4 % of the trials). For a period between 500 ms pre-stimulus (baseline) and 6000 ms post-stimulus within each trial, the IBIs were quantified and assigned to 500-ms intervals. Lastly, IBIs were converted to beats per minute (bpm) and averaged across accepted trials (mean number of accepted trials/condition; HD: M = 9.9; HA: M = 9.9; RD: M = 10.0; RA: M = 9.9) within each condition. 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.

2.6. Statistical analyses

The main statistical analyses were conducted using repeated measures ANOVAs with model (human model vs. robot) and gaze direction (direct vs. averted) as within-subjects factors. For the EMG and HR analyses, time was included as a third within-subjects factor (EMG: 6 epochs, each lasting 500 ms; HR: 12 epochs, each lasting 500 ms). When interactions between the factors were observed, planned pairwise comparisons were performed for the analysis of simple main effects. A Greenhouse-Geisser correction procedure was applied when the assumption of sphericity was violated. For the analyses of the physiological measurements, secondary analyses including the human model's gender/identity as a between factor were performed. According to the analyses, this factor had no main effects nor was it interacting with any other effects. Thus, only the analyses without the between factor are reported in the results section.

Based on the self-reports, all participants had heard or seen material related to robotics and artificial intelligence during the past 12 months. Eight participants reported having seen NAO live in a single occasion. Because none of the participants reported extensive previous experience with the NAO robot, all of the 42 participants were included in the final analyses.

3. Results

3.1. Skin conductance responses

The results of the skin conductance measurements are shown in

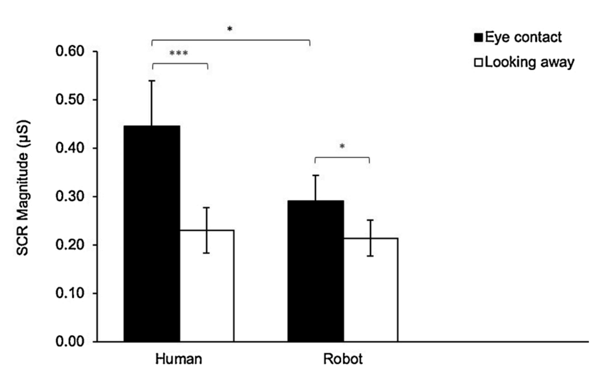

Fig. 3. Mean skin conductance responses (and standard error of means) to the human model's and robot's direct and averted gaze directions.

Fig. 3. These data were analyzed with a 2(Model) × 2(Gaze) ANOVA. The ANOVA showed a significant main effect for Gaze ($F_{(1,41)} = 15.007$, $p = <.001$, $\eta^2_p = 0.268$), indicating that SCRs were greater for direct ($M = 0.392$ μS, $SEM = 0.065$) than averted gaze ($M = 0.236$, $SEM = 0.035$). The interaction between Gaze and Model was also significant ($F_{(1,41)} = 6.317$, $p = .016$, $\eta^2_p = 0.133$). Importantly, however, the pairwise comparisons showed that the SCR was greater to direct than averted gaze both for the human model ($M_{direct} = 0.477$, $SEM = 0.090$ vs. $M_{averted} = 0.245$, $SEM = 0.045$; $t = 3.638$, $df = 41$, $p = .001$, $d = 0.561$), and for the robot ($M_{direct} = 0.308$, $SEM = 0.052$ vs. $M_{averted} = 0.227$, $SEM = 0.035$; $t = 2.582$, $df = 41$, $p = .013$, $d = 0.398$). When comparing the SCR to a gaze direction between the models, the results showed that the human model's direct gaze elicited greater responses than the robot's direct gaze ($t = 2.449$, $df = 41$, $p = .019$, $d = 0.378$), whereas the difference between the human model's and the robot's averted gaze was not statistically significant ($t = 0.430$, $df = 41$, $p = .669$, $d = 0.066$).

Because SCRs are known to habituate after repeated presentation of a stimulus (Boucsein, 2012), we also investigated whether the smaller overall SCR to the robot's vs. the human model's direct gaze could be explained by greater habituation to the robot's direct gaze. To analyze this, a generalized linear mixed model (GLMM) was used to explore the SCR data in a trial by trial manner. GLMM was chosen as a method because it allows utilizing incomplete data (participants with missing trials). In the model, SCR was set as a target variable, and Gaze, Model, and Trial number as independent variables. To specifically test the potential effect of Trial number on the gaze effect in robot vs. human condition, a Trial number*Gaze*Model interaction term was added to the model. Because of the skewness of the data, gamma distribution (with a log link function) was set as the assumption of the probability distribution.

The mean SCR as a function of Gaze, Model, and Trial number are presented in Fig. S1 in Supplementary materials. Parallel to the repeated measures ANOVA, the GLMM revealed a significant main effect of Gaze ($p = .001$), reflecting the fact that direct gaze elicited greater SCR than averted gaze. Also the main effect of Trial number was statistifically significant ($F_{(1,1515)} = 16.551$, $p < .001$), indicating decreasing SCRs along with the repetition of stimulus presentation. Most importantly, the effect of Trial number*Gaze*Model interaction term was also statistically significant ($F_{(3,1515)} = 3.276$, $p < .020$). As shown in Fig. S1, responses to the human model's direct gaze were greater than the responses to the robot's direct gaze throughout the trials, but especially on the first two trials. The significant interaction effect reflects the fact that, after the first and the second trial, the SCRs to the human's direct gaze habituated more strongly than the SCRs to the robot's direct gaze. Thus, importantly, the results of this analysis do not indicate that the greater overall SCRs to the human's direct gaze than the robot's direct gaze would be due to greater habituation to the robot's direct gaze.

3.2. Facial electromyography responses

The results of the facial electromyography measurement are shown in Fig. 4. Zygomatic region EMG responses were analyzed with a 2 (Model) × 2(Gaze) × 6(Time) ANOVA. The ANOVA indicated a main effect of Gaze ($F_{(1,41)} = 54.525$, $p < .001$, $\eta^2_p = 0.571$). The zygomatic activity increased more in response to direct ($M = 0.856$, $SEM = 0.096$) than to averted ($M = 0.175$, $SEM = 0.083$) gaze. The main effect of Time was also significant ($F_{(5,205)} = 19.663$, $p < .001$, $\eta^2_p = 0.324$), indicating increasing zygomatic activity as a function of time. The interaction between Model and Gaze was also statistically significant ($F_{(1,41)} = 4.374$, $p = .043$, $\eta^2_p = 0.096$). The pairwise comparisons showed that the zygomatic responses were greater to direct than averted gaze both for the human model ($M_{direct} = 0.938$, SEM = 0.125 vs. $M_{averted} = 0.082$, $SEM = 0.118$; $t = 6.624$, $df = 41$, $p < .001$, $d = 1.022$) and for the robot ($M_{direct} = 0.774$, $SEM = 0.128$ vs. $M_{averted} = 0.269$, $SEM = 0.095$; $t = 4.228$, $df = 41$, $p < .001$, $d = 0.652$). Although the pairwise comparisons of the responses to a gaze direction between the models showed that

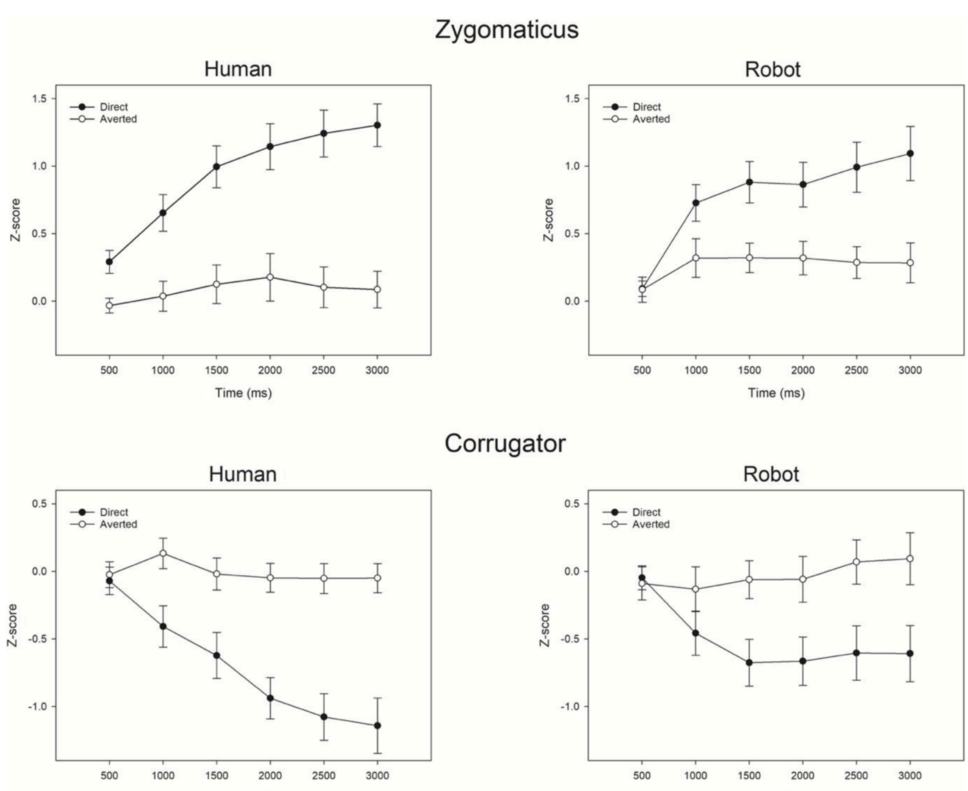

Fig. 4. Standardized mean zygomatic and corrugator electromyographic (EMG) responses (and SEM) to the human model's and the robot's direct and averted gaze directions.

there were no significant differences between the human model's and the robot's direct gaze ($t = 0.981$, $df = 41$, $p = .332$, $d = 0.151$) nor averted gaze ($t = 1.367$, $df = 41$, $p = .179$, $d = 0.211$), the significant interaction between Model and Gaze indicated that the magnitude of the gaze direction effect (direct gaze minus averted gaze) on zygomatic activity was greater for the human model ($M = 0.855$, $SEM = 0.129$) than for the robot ($M = 0.506$, $SEM = 0.120$). The interaction between Gaze and Time was significant ($F_{(5,205)} = 13.314$, $p < .001$, $\eta^2_p = 0.245$), indicating an increasing difference in the zygomatic activity in response to direct vs. averted gaze as a function of time.

For the corrugator responses, a 2(Model) × 2(Gaze) × 6(Time) ANOVA showed a significant main effect for Gaze ($F_{(1,36)} = 19.992$, $p < .001$, $\eta^2_p = 0.357$). The corrugator responses decreased more in response to direct ($M = -0.610$, $SEM = 0.132$) than to averted gaze ($M = -0.020$, $SEM = 0.099$). The main effect of Time was significant ($F_{(5,180)} = 8.675$, $p < .001$, $\eta^2_p = 0.194$), indicating decreasing corrugator activity as a function of time. Neither the main effect of Model ($F_{(1,36)} = 0.583$, $p = .450$, $\eta^2_p = 0.016$) nor the interaction between Gaze and Model ($F_{(1,36)} = 2.186$, $p = .148$, $\eta^2_p = 0.057$) were statistically significant. The interaction between Model and Time was significant ($F_{(5,180)} = 7.997$, $p < .001$, $\eta^2_p = 0.182$), reflecting that the decrease of corrugator activity lasted longer in the human-human condition than in the human-robot condition (see Fig. 4). The interaction between Gaze and Time was also significant ($F_{(5,180)} = 20.467$, $p < .001$, $\eta^2_p = 0.362$). This reflected the decrease of corrugator activity to direct gaze as a function of time while the activity to averted gaze remained at the same level throughout the time window of analysis.

3.3. Heart rate deceleration response

The results of the heart rate measurement are shown in Fig. 5. The HR change scores were analyzed with a 2(Model) × 2(Gaze) × 12(Time) ANOVA. The results showed an HR deceleration response both in the human and in the robot condition. The ANOVA showed a main effect for Gaze ($F_{(1,141)} = 5.459$, $p = .024$, $\eta^2_p = 0.118$) indicating that the HR deceleration was more pronounced in response to direct gaze ($M = -1.538$, $SEM = 0.229$) than to averted gaze ($M = -1.026$, $SEM = 0.229$). Also the main effect of Time was statistically significant ($F_{(11,451)} = 10.915$, $p < .001$, $\eta^2_p = 0.210$), reflecting that the HR deceleration lasted until approximately 3.5 s after stimulus onset, after which it started to accelerate towards its baseline level. Neither the main effect of Model ($F_{(1,41)} = 0.595$, $p = .445$, $\eta^2_p = 0.014$) nor the interaction between Gaze and Model ($F_{(1,41)} = 0.322$, $p = .574$, $\eta^2_p = 0.008$) were significant. However, the interaction between Model and Time ($F_{(11,451)} = 4.506$, $p = .007$, $\eta^2_p = 0.099$) was significant reflecting the fact that, after deceleration, the HR returned earlier back to the baseline level in the human-robot condition than in the human-human condition.

3.4. Questionnaires

The results of the self-evaluations of affective arousal and valence are shown in Table 1. The arousal ratings (scale range: 1–9, with 9 indicating maximal arousal) were analyzed with a 2(Model) × 2(Gaze) ANOVA. The ANOVA showed no main effects, but a significant interaction between Model and Gaze ($F_{(1,41)} = 4.357$, $p = .043$, $\eta^2_p = 0.096$). When analyzing the model conditions separately, pairwise comparisons showed that the participants felt more aroused in response to direct gaze than to averted gaze in the human-human condition ($t = 2.175$, $df = 41$, $p = .035$, $d = 0.336$) but not in the human-robot condition ($t = 0.175$, $df = 41$, $p = .862$ $d = 0.027$). For the valence ratings (scale range: 1–9, with 9 indicating maximal pleasantness), a 2(Model) × 2(Gaze) ANOVA showed a main effect for Gaze ($F_{(1,41)} = 29.959$, $p < .001$, $\eta^2_p = 0.422$) indicating that the participants felt more positive when the robot and the human model looked directly at them ($M = 6.679$, $SEM = 0.199$) as compared to when they were looking away ($M = 5.661$, $SEM = 0.192$). The other effects were not statistically significant.

A Pearson correlation analysis was conducted to investigate possible relationships between participants' perception of NAO as measured with the self-ratings on four dimensions (anthropomorphism, animacy, likeability and perceived intelligence) and the effect of the robot's gaze direction on participants' physiological responses. In order to quantify the effect of the robot's gaze direction on the physiological responses, a difference between the averaged responses to the robot's direct and averted gaze were calculated for each physiological variable for each participant (gaze effect). These values were then correlated with the total scores on each dimension of the NAO perception scale. As a result, correlation analyses were conducted for 16 pairs of variables. The analyses showed no significant correlations between the variables ($p \geq .057$).

A Pearson correlation analysis was also conducted to investigate possible relationships between participants' general impression of robotics and/or artificial intelligence and the effect of robot's gaze on the physiological responses. The analyses were conducted for 4 pairs of variables. None of the correlations were statistically significant ($p \geq .526$).

As a manipulation check, the gaze direction ratings were analyzed

Table 1
The self-reported ratings (and the standard error of means) of affective valence and arousal (1 = unpleasant/calm, 9 = pleasant/arousing) in response to the robot's and the human model's direct and averted gaze.

Model	Arousal		Valence	
	Gaze			
	Direct M (SEM)	*Averted M (SEM)*	*Direct M (SEM)*	*Averted M (SEM)*
Robot	2.31 (0.20)	2.27 (0.16)	6.55 (0.27)	5.42 (0.21)
Human	2.79 (0.26)	2.29 (0.17)	6.81 (0.23)	5.90 (0.23)

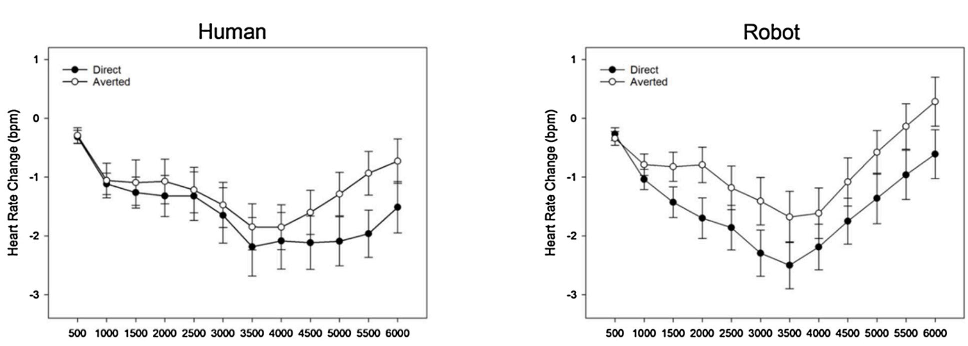

Fig. 5. Mean heart rate changes (and SEM) in response to the human's and the robot's direct and averted gaze directions.

with a 2(Model) x 2(Gaze) ANOVA to test whether the participants discriminated between the robot's and the human model's direct and averted gaze/head direction. The results from the gaze direction ratings are shown in Table 2. The ANOVA indicated significant main effects of Gaze ($F_{(1,41)} = 747.240$, $p < .001$, $\eta^2_p = 0.948$) and Model ($F_{(1,41)} = 11.613$, $p = .001$, $\eta^2_p = 0.221$). The main effect of Gaze indicated that participants agreed more to the statement ("The model/robot looked directly at me") when the gaze was directed at them ($M = 8.631$, $SEM = 0.111$) than when the gaze was directed away from them ($M = 2.137$, $SEM = 0.201$). The main effect of Model indicated that overall the values of these ratings were greater in the robot condition ($M = 5.768$, $SEM = 0.215$) than in the human condition ($M = 5.000$, $SEM = 0.061$). The interaction between Gaze and Model was also significant ($F_{(1,41)} = 24.013$, $p < .001$, $\eta^2_p = 0.369$). The pairwise comparisons showed that the agreement ratings were significantly greater both when the human model ($t = 51.724$, $df = 41$, $p < .001$, $d = 7.981$) and the robot was looking at them ($t = 13.278$, $df = 41$, $p < .001$, $d = 2.049$) than when they were looking away. The agreement ratings did not differ between the robot's and the human model's direct gaze ($t = 1.460$, $df = 41$, $p = .152$, $d = 0.225$), but differed significantly between the robot's and the human model's averted gaze ($t = 4.370$, $df = 41$, $p < .001$, $d = 0.674$) reflecting the fact that the participants disagreed more to the statement in response to the human model's than to the robot's averted gaze. Thus, the results indicate that the human model's averted gaze induced a stronger feeling of not being looked at as compared to the robot's averted gaze. However, as described above, despite this difference in the self-evaluations, there was no difference in the physiological responses to the human model's vs. the robot's averted gaze.

4. Discussion

In the present study, our goal was to examine whether eye contact with a humanoid robot (NAO) would have similar effects as eye contact with another human on affective and attention related psychophysiological responses. We measured skin conductance responses indexing autonomic arousal, facial electromyography from zygomatic and corrugator muscle regions reflecting the valence of affective reactions, and heart rate deceleration responses indexing attentional orienting to direct and averted gaze of a human model and humanoid robot stimuli. Based on previous research showing the effects of eye contact with another human on these responses (for a review, see Hietanen, 2018) and studies suggesting that people have a tendency to ascribe humane attributes and react socially to robots (Gazzola et al., 2007; Hofree et al., 2014; Kiesler et al., 2008; Thellman et al., 2017), we expected that seeing a robot's as well as another human's direct gaze would elicit greater psychophysiological reactions as compared to seeing their averted gaze. In addition to physiological measurements, we measured self-evaluations of the affective valence and arousal in response to seeing direct and averted gaze, and participants' perception of NAO on four different dimensions (anthropomorphism, animacy, likeability and perceived intelligence). The results provided evidence that eye contact with a robot elicits similar types of automatic affective and attentional responses as compared to eye contact with another human. All the measured psychophysiological responses discriminated between direct and averted gaze both in the human-human and human-robot condition. However,

Table 2
The self-reported ratings (mean and the standard error of means) of the robot's and the human model's direct and averted gaze.

Model	Gaze			
	Direct		Averted	
	M	*SEM*	*M*	*SEM*
Robot	8.52	0.16	3.01	0.39
Human	8.74	0.10	1.26	0.09

with regard to the SCR and zygomatic responses, the human model's gaze direction had a greater effect on the responses as compared to the robot's gaze direction.

The present results are unique for two major reasons. First, to the best of our knowledge, no previous studies have investigated these kinds of psychophysiological responses to eye contact with a humanoid robot. Second, this is the first study to investigate participants' reactions to a humanoid robot's and another human's gaze in the same experiment, thus enabling a direct comparison of reactions to eye contact elicited by a human and a non-human agent. Furthermore, an important feature of the study is that the psychophysiological responses were measured while the participants were facing a real, physically present, humanoid robot and a human model as stimuli. In recent years, researchers in the field of social cognition have become aware that studies conducted with images or video tapes of other humans may not provide reliable knowledge on the socio-cognitive processes occurring in normal, daily interactions (Hietanen, 2018; Kingstone et al., 2008; Risko et al., 2016).

With regard to the psychophysiological responses to another person's (human model) gaze directions, the results of the present study are in line with the previous findings. First, this study replicates several earlier findings demonstrating that observing another person's direct gaze versus averted gaze results in greater skin conductance and heart rate deceleration responses indexing physiological arousal and attention orienting (e.g., Akechi et al., 2013; Helminen et al., 2011; Hietanen et al., 2008; Myllyneva & Hietanen, 2015; Nichols & Champness, 1971; Prinsen & Alaerts, 2019). Furthermore, this study replicates the results of two recent studies showing greater zygomatic responses and smaller corrugator responses to seeing another person's direct gaze than seeing another's averted gaze (Hietanen et al., 2018, 2020). Thus, the results of the present study further accentuate the view that eye contact with another person is perceived as a powerful social signal that evokes positive affect and captures an observer's attention.

The most important and novel finding of the present study was that eye contact with a humanoid robot resulted in similar psychophysiological responses as eye contact with a human model. The SCRs were greater to the robot's direct than averted gaze suggesting that eye contact with a robot is perceived as an affectively arousing signal. This finding is considerably interesting, since previous studies have suggested that eye contact with another person increases affective arousal only when it induces an experience of being a target of another individual's "mind" (Hietanen et al., 2008; Myllyneva & Hietanen, 2015; Pönkänen, Peltola et al., 2011). Thus, the present results suggest that, although human perceivers know that the robot does not have a mind and does not really see them, they may implicitly ascribe mental attributes to it, and consequently react to the robot's direct gaze as if the robot was "looking" at them. This speculation is supported by several previous studies demonstrating that people tend to anthropomorphize and socially react to social robots, and more strikingly, sometimes even perceive them as having a capability for mental states, such as intentionality (Gazzola et al., 2007; Hofree et al., 2015; Kiesler et al., 2008; Oberman et al., 2007; Thellman et al., 2017). If people perceive robots' behavior as intentional, it is possible that observing a robot's direct gaze induces a feeling of being a target to the robot's "intentions" and, therefore, the robot's direct gaze enhances the observer's self-awareness. This could explain the enhanced affective arousal responses to the direct gaze of a social robot (cf. Conty, George, & Hietanen, 2016; Hietanen, 2018).

Compatible with the results of the SCR measurements, the HR deceleration was greater in response to the robot's direct than averted gaze. Given that the HR deceleration is associated with attention orienting to external stimuli, this result is in line with a previous study showing that participants fixated longer to a humanoid robot's (iCub) face during an eye contact than in no eye contact condition (Kompatsiari, Ciardo, De Tommaso et al., 2019). Furthermore, another study showed that the more a humanoid robot (NAO) looked at the participant's face during a joint-attention task the more the participants looked back at the robot's face (Xu, Zhang, & Yu, 2016). As seeing another person's direct gaze has been shown to result in enhanced heart rate deceleration only if the observer believes to be seen by the other person (Myllyneva & Hietanen, 2015), this result also brings further support for the speculation that eye contact with a humanoid robot induces an experience of being a target of another mind's attention.

The results from the measurements of facial electromyography responses indicated that zygomatic responses were greater in response to a robot's direct than averted gaze. Compatible with the zygomatic responses, the corrugator activity decreased more in response to robot's direct vs averted gaze. As previous studies have reported a decrease of corrugator activity in response to stimuli with positive valence (Dimberg & Lundquist, 1990; Dimberg & Thunberg, 1998; Dimberg et al., 2000), this result suggests that observing a robot's direct gaze triggers more positive reactions as compared to seeing the robot's averted gaze. Some previous studies employing self-reports have shown that eye contact established by a robot has a positive influence on how robots are perceived. Eye contact has been shown, for example, to induce favorable evaluations of a robot (Shiomi et al., 2013; Yonezawa et al., 2007) and enhance perceived socialness of a robot (Kompatsiari, Ciardo, Tikhanoff et al., 2019). The results of the present study extend these findings by providing evidence that, in addition to promoting positive attitudes towards robots, eye contact with a robot may also evoke a positive emotion in the observer. However, when interpreting the results of the facial EMG measurements, cautiousness is warranted. Although facial EMG has been used to measure automatic affective reactions (Cacioppo et al., 1986; Dimberg et al., 2000), there has been debate regarding whether facial reactions during social interactions reflect automatic emotional reactions or whether they serve as tools for communicating one's social motives and intentions to others (Fridlund, 1991; Hietanen, Kylliäinen, & Peltola, 2019; Parkinson, 2005). Thus, we cannot know for sure to what extent the greater zygomatic responses to seeing a direct gaze of a humanoid robot or another human being reflect automatic, positive affects or whether they actually reflect automatized social responses signaling affiliative intentions (Niedenthal, Mermillod, Maringer, & Hess, 2010).

Although all the measured physiological responses discriminated between eye contact and averted gaze both in the human-robot and human-human condition, the effect of the human's gaze direction on participants' SCRs and zygomatic responses was significantly greater than the effect of the robot's gaze direction. With regard to the SCRs, the greater effect of the human's vs. the robot's gaze direction resulted from that the SCRs were significantly greater in response to the human model's direct gaze than the robot's direct gaze. For the zygomatic responses, in turn, the greater effect of the human model's vs. the robot's gaze direction was not caused by significantly different responses to direct or averted gaze between the human and the robot, but rather reflected a greater difference between direct and averted gaze in the human-human than in the human-robot condition. It is possible that the greater effect of another human's vs a robot's gaze on SCRs and zygomatic responses is explained by the fact that people automatically ascribe higher degree of social relevance to other humans' than to robots' social cues and, consequently, react to other humans' gaze with greater affective reactions. Supporting this view, there are previous studies demonstrating that people ascribe lower degree of mental attributes to robots as compared to other humans (Gray et al., 2007; Krach et al., 2008; Martini et al., 2016).

The results of the subjective evaluations of affective arousal showed that the participants felt more aroused when the human model was looking at them as compared to when the model was looking away, whereas the robot's gaze direction did not affect the ratings. Thus, the results of the subjective evaluations of affective arousal match the results of the physiological measurements (SCRs) in the human-human condition but not in the human-robot condition. However, as mentioned earlier, since explicit (top-down influences) and implicit (bottom-up processing) responses reflect different types of information processing, it is not unusual that there is not a perfect match between these responses (Evans, 2008; Hofmann, Gawronski, Gschwendner, Le, & Schmitt, 2005). Regarding the present study, it is possible that, when the participants were asked to evaluate their feelings (arousal) to different gaze directions of the robot, the awareness of the robot's artificiality became prominent and attenuated, at least partly, the subjective feelings to the gaze directions. With regard to the ratings of affective valence, participants felt more positive when both the robot and the human model were looking at them as compared to when they were looking away. Thus, the subjective evaluations of affective valence match with the results of the physiological measurements within each block. It should be noted that some of the previous studies conducted with a live human model have reported less positive feelings to another's direct than averted gaze (or no difference between the gaze directions) (Hietanen et al., 2008, 2018; Pönkänen, Alhoniemi et al., 2011). This pattern of results has been suggested to be associated with the feelings of uneasiness evoked by being a target of someone's attention (Pönkänen, Alhoniemi et al., 2011). A possible explanation for the contradictory findings between the present and these previous studies could be associated with differences in the averted gaze stimuli. In the present study, the human models were presented with their whole heads rotated to the left or right, in the averted gaze condition, whereas in the previous studies, the model person's head/face was straight ahead (towards the participant) and only the eyes were laterally averted. Therefore, it is possible that observing the human model's head and gaze turned away from oneself induced a particularly strong feeling of ignorance and, consequently, resulted in less positive feelings than the human model's direct gaze. In previous studies, in turn, observing only the eyes averted away may not have resulted in similar feelings of ignorance and, thus, was not experienced as negative as the possible uneasiness evoked by the model person's direct gaze.

The results showed that none of the participants' evaluations regarding NAO's anthropomorphism, animacy, likeability and perceived intelligence correlated with the magnitude of any of the physiological gaze effects. This result reflects the possibility that people's implicit reactions to social cues displayed by a robot may be independent of how they perceive the robot explicitly. Thus, for example, a person rating a robot with a low level of anthropomorphism may still implicitly react to it in a similar way as he or she would react to another human. It should be noted that the participants' perception of NAO was measured with the GODSPEED questionnaire. Although this questionnaire is widely used in HRI, it has also attracted criticism. Carpinella and colleagues (Carpinella, Wyman, Perez, & Stroessner, 2017) argued that there are several problematic aspects of the original GODSPEED questionnaire, such as high correlations between the dimensions and weak loadings of the items onto the dimensions, which might attenuate the reliability of the questionnaire. In this study, we do not intend to take a strong stance on the psychometric properties of the questionnaire, but these potential psychometric problems should be taken into account when interpreting the results described above. We also examined whether the participants' general impression of robotics and artificial intelligence was related to the effect of the robot's gaze direction on physiological responses, and the analyses showed no significant correlations between these variables.

It is notable that the effects of the robotic gaze direction were found in response to NAO robot. After all, it is a rather simple looking humanoid robot, only 58 cm in height and, apart from the typical configuration of the facial features (eyes and mouth), its face bears relatively little resemblance to a human face. Thus, it seems that even a robot with a rather low level of human-likeness is sufficient to evoke reactions reminiscent of those evoked by other human beings. This finding is in line with previous findings showing implicit social reactions to mechanical-looking humanoid robots (e.g. Gazzola et al., 2007; Hofree et al., 2015; Oberman et al., 2007). It is possible, however, that the short interaction period between the robot and the participant prior to the experimental trials affected the participants' perception of NAO and, therefore, influenced the physiological responses. During the interaction, NAO was performing some human-like gestures, such as head nodding and hand gestures, and said "hi" to the participant. Furthermore, the robot was programmed to blink every third second in order to make its gaze more human-like. There is previous evidence suggesting that various non-verbal communicative behaviors displayed by a social robot, such as arm and head gestures, increase anthropomorphism toward the robot (Carter, Mistry, Carr, Kelly, & Hodgins, 2014; Salem, Eyssel, Rohlfing, Kopp, & Joublin, 2013). Thus, the present study suggests that relatively simple and short-lived interaction with a robot is enough to promote participants' anthropomorphic perceptions of NAO enough to such an extent that NAOs social signals (i.e., gaze direction) elicited psychophysiological responses in the observers similar to those elicited by corresponding social signals by another human being. It is also possible that the robot's gaze direction could have resulted in similar effects even without any prior interaction with the robot. An interesting topic for future studies would be to investigate how the nature of prior interaction with a robot influences people's physiological responses to the robot's social signals.

A limitation of the present study was that, during the experimental trials, the model stimuli (both NAO and the human model) varied their gaze direction by changing their head direction instead of moving only their eyes. As a consequence, the participants were able to see full faces only in the eye contact condition. It is possible that this influenced the participants' affective and attentional reactions to different gaze conditions. However, there are certain matters that speak against this possibility. When it comes to human models, the results of the present study (with regard to the physiological measurements) are similar to those of previous studies where the human models varied just their gaze direction, not head orientation (Akechi et al., 2013; Hietanen et al., 2008, 2018; Myllyneva & Hietanen, 2015; Pönkänen, Peltola et al., 2011).

Taken together, the present study provides evidence that eye contact with a robot can elicit similar type of automatic affective and attentional reactions as eye contact with another human being. The results were interpreted to support the view that, despite of robots' artificiality, people may automatically ascribe mental attributes to them, and consequently, react to their direct gaze as a socially relevant signal. It should be noted that the aim of the present study was to examine whether eye contact with a robot would elicit similar responses as an eye contact with another human. Importantly, however, the present study can not answer *why* these responses occurred. Thus, it is impossible to know, for sure, to what extent eye contact with the robot actually reflects the participants' experience of being a target of the robot's "mind". For future studies, it will be interesting to investigate whether the psychophysiological effects of eye contact with a robot are dependent on participants' attributions of robots' mental states.

In sum, the results of the present study provide novel evidence of an impact of eye contact in human-robot interaction. This finding argues for designing robots that have an ability to establish eye contact with humans. This ability might enhance pleasant experiences in social interaction between humans and robots, which, in turn, might smoothen robots' integration to human societies.

Declaration of Competing Interest

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

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.biopsycho.2020.107989.

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