The Perception of Emotion in Artificial Agents

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***Abstract*—Given recent technological developments in robotics, artificial intelligence, and virtual reality, it is perhaps unsurprising that the arrival of emotionally expressive and reactive artificial agents is imminent. However, if such agents are to become integrated into our social milieu, it is imperative to establish an understanding of whether and how humans perceive emotion in artificial agents. In this review, we incorporate recent findings from social robotics, virtual reality, psychology, and neuroscience to examine how people recognize and respond to emotions displayed by artificial agents. First, we review how people perceive emotions expressed by an artificial agent, such as facial and bodily expressions. Second, we evaluate the similarities and differences in the consequences of perceived emotions in artificial compared to human agents. Besides accurately recognizing the emotional state of an artificial agent, it is critical to understand how humans respond to those emotions. Does interacting with an angry robot induce the same responses in people as interacting with an angry person? Similarly, does watching a robot rejoice when it wins a game elicit similar feelings of elation in the human observer? Here, we provide an overview of the current state of emotion expression and perception during interactions with artificial agents, as well as a clear articulation of the challenges and guiding principles to be addressed as we move ever closer to truly emotional artificial agents.**

***Index Terms*—Artificial agent, emotion, human–robot interaction (HRI).**

I. Introduction

WE SPEND our entire lives navigating a vast and complex social environment. From our homes to our schools, from work to online life, our lives revolve around interactions with other people. Emotions serve as clues for these interactions. Powerful drivers of human behavior [1], emotions expressed by an agent communicate social information to an observer. Whether subtle facial expressions of sadness or angry bodily gestures to signal dominance, we are experts in recognizing emotion expression across a broad range of situations. The importance of emotion recognition for these interactions is well established [2]–[5]. For instance, accurate recognition of emotional facial expressions is related to higher perceived quality of daily interaction between people [4]. However, technology is continuing to change the social interactions we have. In the last years, and in the decades to come, artificial agents are increasingly entering our social environment, with growing numbers of these agents appearing in hospitality, care, and education contexts [6]. From conversing with a humanoid robot to check into a hotel room, to collaborating with a virtual agent in a medical rehabilitation context, social interactions with artificial agents are predicted to play an ever great role in our daily lives. This prospect raises important questions regarding how these agents will be accepted and incorporated into our social milieu.

To maximize the quality of social interactions between humans and artificial agents, it is important that the artificial agent is not only responsive to emotions expressed by the human agent but is also able to express emotions itself. As interest and investment in social robotics continues to grow, developing artificial agents with this kind of emotional capacity is a core requirement for truly social robotic agents [7], [8]. While the emotional component of artificial agents has been long neglected, a recent surge in technological development and empirical investigations is starting to shift the focus. Emerging research documents how expressive robots are rated as more likeable and humanlike, lead to higher engagement and more pleasurable interactions [9]–[11]. Importantly, acceptance of and cooperation with a robot is dependent on the match between the situation and the emotional behavior of the robot [12].

In this review, we aim to provide an integrative overview of the perception of emotions in artificial agents by human observers by discussing insights and perspectives from the field of social robotics, virtual reality, psychology, and neuroscience. We discuss how people recognize emotions expressed by artificial agents via different modalities such as the face and body, and consider two distinct types of emotional artificial agents: robotic and virtual agents. The first category includes physically instantiated or embodied robots, such as humanoid or pet-like robots. The second category includes visually presented digital agents or avatars, such as those used in virtual reality environments [13], therapeutic interventions [14], and educational contexts [15]. The embodied and virtual artificial agents discussed in this review are described in detail in Table I and several examples are presented in Fig. 1. In the second part of this review, we describe the behavioral consequences of an emotional artificial agent by separately considering positive reactions, such as empathy for robots, as well as negative reactions, such aggression toward robots. We conclude by examining some of the challenges that remain in studying emotion perception during human–robot interaction

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TABLE I
LIST OF EXPRESSIVE ROBOTS REVIEWED IN THIS PAPER

Name	**Type of Robot**	**Manufacturer**	**Main expressive capabilities**
AIBO	Pet-like	Sony Corp.	Facial and bodily expressions
ASIMO	Humanoid	Honda Motor Co.	Bodily expressions
BERT(2)	Humanoid	Elumotion/Bristol Robotics Lab	Facial, bodily and vocal expressions
DustCart	Mechanoid	DustBot Project	Facial expressions
Einstein	Humanoid	Hanson Robotics	Facial and vocal expressions
F.A.C.E.	Android	Hanson Robotics	Facial expressions
Feelix	Mechanoid	[22]	Facial expressions
Geminoid HI-2	Android	Advanced Telecommunication Research Institute International	Facial and bodily expressions
Haptic Creature	Pet-like	Haptic Creature Project	Bodily and vocal expressions
iCat	Pet-like	Philips Research	Facial and vocal expressions
iCub	Humanoid	Instituto Italiano di Tecnologia/RobotCub Consortium	Facial, bodily and vocal expressions
KaMERo	Mechanoid	Korea Advanced Institute of Science and Technology	Bodily expressions
Keepon	Mechanoid	National Institute of Information and Communications Technology	Bodily and vocal expressions
Mung	Mechanoid	Yonsei University/ Korea Advanced Institute of Science and Technology	Bodily expressions
NAO	Humanoid	Aldebaran Robotics	Bodily and vocal expressions
Piero	Mechanoid	Telerobotic and Interactive Systems lab, University of Málaga	Vocal expressions
Peoplebot	Mechanoid	Adept Mobile Robots	Facial expressions
Pepper	Humanoid	Aldebaran Robotics	Bodily and vocal expressions
Robovie(X)	Humanoid	Advanced Telecommunications Research / Vstone Co.	Bodily and vocal expressions
Sophia	Android	Hanson Robotics	Facial and vocal expressions
Sparky	Mechanoid	Interval Research Corp.	Facial expressions
Unnamed lego robot	Mechanoid	[117]	Facial and vocal expressions
Unnamed lego robot	Mechanoid	[67]	Bodily expressions
WE-4R(II)	Humanoid	Waseda University	Facial and bodily expressions

(HRI) and articulate guiding principles for future research and development of emotional artificial agents. This review is not meant to be all-encompassing. Instead, we focus on highlighting research on how the human observer perceives and reacts to emotional artificial agents. While the technical aspects of emotion recognition within artificial agents are beyond the scope of the present review, the literature covered here certainly has the potential to inform future technical developments of social artificial agents as well.

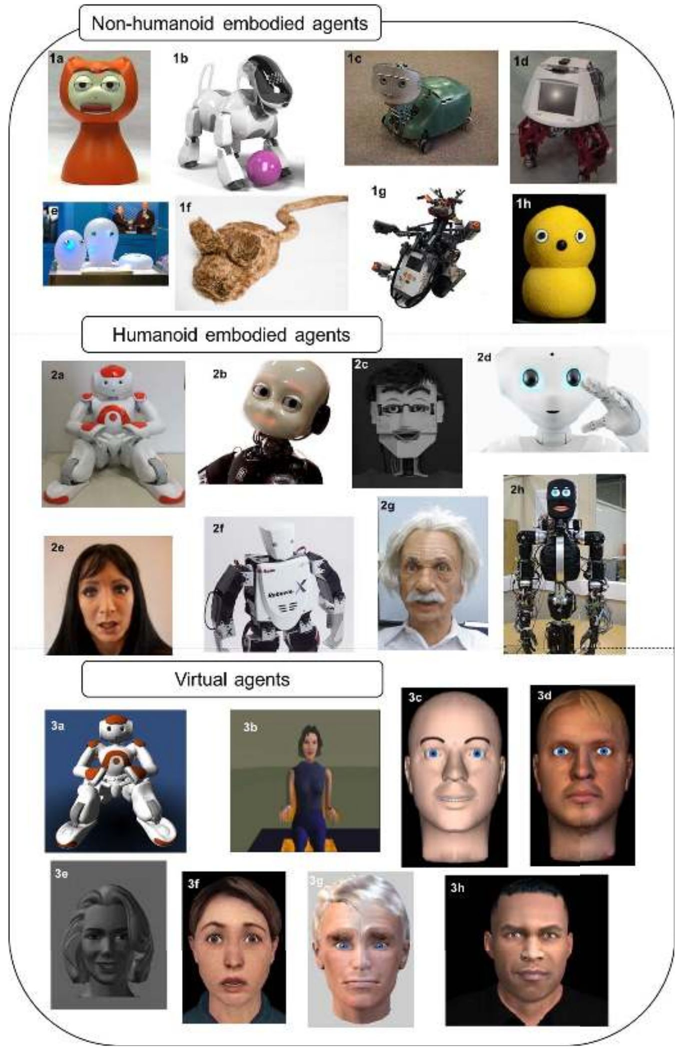

Fig. 1. Examples of emotional artificial agents. (1a) iCat (Philips Research). (1b) AIBO (Sony Corporation). (1c) Sparky (Interval Research Corporation). (1d) KaMERo (Korea Advanced Institute of Science and Technology). (1e) Mung (Yonsei University/Korea Advanced Institute of Science and Technology). (1f) Haptic Creature (Haptic Creature Project). (1g) Unnamed lego robot [67]. (1h) Keepon (National Institute of Information and Communications Technology). (2a) NAO (Aldebaran Robotics). (2b) iCub (Instituto Italiano di Tecnologia/RobotCub Consortium). (2c) WE-4RII (Waseda University). (2d) Pepper (Aldebaran Robotics). (2e) F.A.C.E. (Hanson Robotics). (2f) Robovie-*X* (Vstone Corporation). (2g) Einstein (Hanson Robotics). (2h) BERT2 (Elumotion/Bristol Robotics Laboratory). (3a) Virtual version of NAO [102]. (3b) Female virtual avatar [118]. (3c) and (3d) Male virtual avatar [75]. (3e) Female virtual avatar [47]. (3f) Female virtual avatar [41]. (3g) Male virtual avatar [55]. (3h) Male virtual avatar [40].

II. PERCEPTION OF EMOTION IN ARTIFICIAL AGENTS

Humans use a range of facial and bodily expressions, as well as vocal tone, to communicate their emotional state and salient events in the environment to other individuals. Artificial agents are becoming progressively better at reading and appropriately responding to emotions expressed by humans [7], with many artificial agents programmed to display emotional reactions, such as sadness or joy. From a design perspective, emotional reactions such as facial expressions often act as feedback to the human collaborating with the robot. For example, an artificial agent might react with an emotional facial expression in response to a mistake it made during a collaborative task [16], or in response to a human action such as touch for pet-like robots [17]. It has been reported that naïve users, for example children, can regard these responses as genuine emotions [18]. Psychology and neuroscience already provide a detailed picture of the processes underlying perception of human emotional expressions [3], [19], with the most studied emotional signals being facial and bodily expressions. Work from these fields provides a framework for understanding the mechanisms for perceiving artificial agents' emotional expressions, as detailed in the next section.

A. Facial Expressions

The crucial role played by faces in emotional communication during social interaction between humans has inspired creators of artificial agents to incorporate elements of dynamic facial expressions in both virtual and physically instantiated faces. For instance, people prefer a mechanical Peoplebot robot with an expressive humanlike face display and perceive it as more alive, humanlike, sociable and amiable compared to the same Peoplebot robot with a silver face or no face [20]. But can people accurately infer emotions from robotic facial expressions?

Two early studies provided the first evidence on the recognition of emotions expressed by a robot by human observers. In 2004, Miwa *et al.* [21] developed a widely used emotional humanoid robot, WE-4R. The authors showed that humans are able to recognize most of the prototypical emotions expressed by this robot in static photographs, including happiness, disgust, surprise, sadness, and anger, but not fear. Another study by Nadel *et al.* [22] investigated the recognition accuracy of adults and three-year old children. Participants were presented with static or dynamic facial expressions made by a nonhumanoid robot head or human agent. Again, these expressions covered almost all of the so-called basic or prototypical emotions—joy/happiness, sadness, fear, surprise, and anger. Results showed that, for adults and children alike, human expressions are better recognized than robotic expressions. Accuracy per emotion showed that joy/happiness and sadness, but not anger, fear and surprise, were recognized by children at above chance level for robots. While no information is provided for adult observers in the study of Nadel *et al.* [22], other studies show that joy/happiness, surprise, and sadness are well recognized, followed by recognition of anger, while disgust and fear have proven more difficult to recognize when expressed by a robot [23]–[28].

One mediating factor that will likely influence recognition of robotic facial expressions is the physical presence or absence of the agent in the same room as the human observer. The impact of physical presence has been observed for other aspects of HRI. For instance, a recent review showed that physically present robots are perceived more positively and persuasively, and result in better user performance (as measured by attention paid to the robot or performance on a game), than visually presented counterparts [29]. While one of the first studies on robotic facial expression recognition already manipulated the presence of the robotic agent (without, however, reporting these results) [22], most studies use only visual presentation. Crucially, a recent study showed that emotions expressed by a physically encountered humanoid robot head called F.A.C.E. are recognized as well as human expressions, and sometimes even better (as in the case of anger, fear, and disgust) [30]. Recognition of expressions made by the physical robot was superior to 2-D or 3-D versions of the same robot presented on a screen. While another study found no effects of physical presence for iCat, a pet robot, on emotion recognition [31], other studies report robust effects of physically present artificial agents beyond mere emotion recognition. For example, Hofree *et al.* [32] examined spontaneous facial mimicry (defined as the automatic copying of observed facial expressions) when participants observed happy or angry expressions made by a humanoid robot designed to look like Albert Einstein that was either in the same room as participants or was visible on a screen. Spontaneous facial mimicry was highest when the robot was physically present, and participants rated this robot as more humanlike compared to the visually presented robot. Thus, physical presence seems crucial for optimal perception of emotional information conveyed by a robotic agent.

Does recognition of facial expressions by virtual agents follow similar patters as that of robotic agents? A first answer is provided by studies that selectively use computer-animated faces to investigate human face perception. Findings from these studies suggest that people are able to read social cues, including emotions, from virtual faces [33], [34]. Directly comparing recognition accuracy of virtual faces with that of human faces provides a more detailed answer. While some studies find that recognition accuracy is lower for virtual agents compared to human agents [35]–[38], others report similar recognition rates across these agents [39]–[43]. The difference between these studies is likely due to the construction quality of their virtual agents. This is not related to graphical details, but to the depiction of specific facial muscle movements (or action units). Indeed, emotions can be accurately recognized from simple computer-generated line drawings depicting specific muscle movements [36]. New techniques allow for high quality, expressive virtual agents, by synthesizing movements of distinct facial muscles [44]–[46]. Accordingly, a recent study by Joyal *et al.* [40] showed no differences on subjective and objective measures of perception between such virtual facial expressions and human facial expressions. In this paper, recognition accuracy, as well as facial muscle activation and gaze duration of the participant when looking at dynamic expressions of a wide range of emotions, were measured. No differences between virtual and human agents were found in recognition accuracy and facial muscle activation. Minor differences only were observed in gaze duration when looking at the mouth region of the face. Thus, emotions expressed by virtual agents are accurately recognized and can lead to rapid recognition by the human observer [47], [48].

To delve more deeply into questions concerning how people perceive emotions in artificial agents, we can examine and compare how portions of the human brain that have evolved for perceiving and interacting with other people are engaged when we observe artificial agents. For example, one question we can ask is whether facial expressions made by artificial agents are processed in the human brain to a similar extend as expressions made by conspecifics. Dubal *et al.* [49] recorded event-related potentials (ERPs) when participants watched happy and neutral expressions made by humans and by non-humanoid robots (similar to [22]). The dependent measure being explored in this paper, ERPs, are electrophysiological responses that can be observed using electroencephalography in response to specific stimuli. Itier and Taylor [50] looked at two ERP components, the $P1$ and the $N170$, that are related to the processing of faces. No differences were observed in the $P1$ component, while the $N170$ differed when observing robotic compared to human facial expressions. Another study by this group, using the same robotic heads, found that while the $P1$ and $N170$ are delayed during the observation of facial expressions made by a robot compared to a human, the amplitude of these components does not differ between agents [51]. The authors concluded that there is no systematic human bias in emotional face processing. Similarly, another study reported no clear differences in $N170$ amplitude when observing several prototypical emotions (e.g., disgust, surprise, and sadness) expressed by a physically present humanoid robot known as BERT2 [52]. Thus, so far, no clear picture emerges across these different studies regarding potential differences and similarities in neural processes underlying the perception of facial emotion expressed by robotic compared to human agents. One study directly contrasting virtual faces with real faces showed increased $P1$ and $N170$ amplitudes for virtual faces [53]. However, ERP studies on face perception should be interpreted with caution. One possible methodological confound is that ostensible face-selective ERP components serve as a function of within-category similarities [54]. Human faces are very similar to each other and the within-category similarity is very high, in contrast to robotic faces. Additional research is thus required to carefully assess this potential confound.

Besides ERPs, functional magnetic resonance neuroimaging studies have also been used to measure brain activity when individuals observed facial expressions made by a human or artificial agent. The core network underlying emotional face processing comprises the amygdalae, fusiform gyrus, superior temporal gyrus, and medial prefrontal cortex [19]. So far, three studies have investigated the pattern of activation in this network during the processing of artificial agents' facial expressions: one using virtual agents [55], and two using the same robotic agent (WE-4RII, a humanoid robot) [24], [25]. Compared to human agents, decreased amygdalae activity was found when viewing emotional facial expressions performed by a robotic agent [25], while no differences were found in amygdalae engagement for virtual agents compared to humans [55]. The latter is in agreement with findings of robust amygdalae activation in a variety of neuroimaging studies using virtual agents to explore social perception, including direct manipulations of emotional expression [56]–[60]. Activity in the fusiform face area, a brain region found in the ventral temporal cortex that is selective for faces [61], was greater for human agents compared to virtual agents [55], but the opposite pattern emerged for robotic agents [24], [25]. While activity in the superior temporal gyrus was greater for expressions made by human compared to virtual agents [55], no difference in superior temporal gyrus activity was found for human versus robotic agents [24], [25].

Interim Summary: Together, the reviewed studies suggest that, while above chance level, accuracy for reading robotic facial expressions is decreased compared to human expressions, and this seems to be the case especially for negative emotions such as fearful expressions. However, one mediating factor that warrants further attention is the physical presence of the robotic agent. The impact of facial expressions made by a collocated robot is higher than that of a visually presented robotic agent. In addition, recognition accuracy of facial expressions made by virtual agents seems to be on a par with that for human agents and largely driven by the depiction of facial muscle movement. At the brain level, no clear differences in the amplitude of activation within the face network have been documented when people observe emotional expressions made by a human compared to a robot, as well as to a virtual agent. While activity in some regions was increased, other regions showed attenuated responses to artificial compared to human agents. So far, the functional consequences of these neurocognitive findings remain unknown. Given the variability in recognition accuracy between emotions, one straightforward and highly likely possibility is that differences in responsiveness within these brain regions depend on the specific emotion being perceived. To date, most studies have looked at differences between agents per se. It remains unknown how neural activity within, for example, the fusiform face area serves as a function of emotion expression.

B. Bodily Expressions

Besides facial expressions, bodily expressions also provide strong and reliable cues to the emotional state of an observed individual [62]. While facial expressions are crucial in signaling the mental state of the individual, bodily expressions signal the action-related component of the emotional state of the individual [63]. In contrast to facial expressions, bodily expressions have long been neglected in the study of human social behavior, and this asymmetry is also visible in HRI research. This is somewhat surprising, as bodily expressions are visible from afar, easily recognizable (for example [64]), and are the dominant channel for certain emotion expressions (e.g., anger, see [65]). Moreover, bodily expressions carry crucial information required for context-dependent emotion recognition (for example [66]). Of course, these same arguments also hold for artificial agents [67], and bodily expressions are especially relevant for robots without dedicated facial articulation (e.g., the robots NAO and Pepper or many nonhumanoid robots). Bodily expressions impact HRI. Even in the absence of emotional content, gestures made by an ASIMO robot have been reported to increase its perceived humanness and likability. Equally importantly, these gestures increased the engagement of the human individual in the interaction [68]. The first and central question, similar to facial expressions of emotion, is whether people are able to recognize bodily expressions of emotion when made by artificial agents.

Using a full-body version of a WE-4R robot [21], [24], [25], Itoh *et al.* [69] investigated the recognition of a variety of emotions. These expressions were made by the upper half of the body (including the face) and were presented to the participants as a movie. Results showed that all basic emotions (including surprise, happiness, sadness, anger, and disgust, but not fear) were accurately recognized. In the absence of a direct comparison with expressions made by a human agent, accurate recognition of a diverse range of emotions, ranging from prototypical emotions to complex emotions, such as shame, pride, and excitement, expressed by a humanoid NAO robot has been reported [70]–[72]. In these studies, the authors first recorded the movements of a human actor with motion capture, a technique that records the movement of the actor multiple times per second with multiple cameras to map limb positions in 3-D and velocity profiles of individual limb movements [70]. The authors then used animations to feed this motion data to a virtual agent and created key poses that served as a basis for bodily expressions made by a small humanoid robot NAO. This procedure leads to correct recognition of emotions, including fearful expressions, and these key poses can even be used to create blended emotions in robots [70], for example, a mix between happiness and pride. Accurate recognition of these emotional body expressions is also observed in children [73]. Interestingly, older adults did not accurately recognize angry and sad bodily expressions made by a physically present Robovie-*X* robot [74].

One factor that has received some attention in the design of artificial agents' bodily expressions of emotion is the impact of action or motion parameters. Emotions that we express and observe in real life are dynamic and evolve across time. Perhaps unsurprisingly, recognition accuracy of artificial agents' expressions is increased when emotional expressions are dynamically presented [36], [75]. Of course, movement made by a robot is nonbiological in nature, by virtue of a robot being an artificial, nonbiological agent, and most robot movements follow a constant velocity profile and are perfectly linear in nature. Human movements, in contrast, begin slowly, speed up in the middle, and decelerate at the end, and are not completed in a perfect line. It is known from research on action observation that biological and nonbiological motion impact the perception of these actions [76]. For example, while an early study found impaired automatic imitation (the copying of observed movements) during observation of nonbiological robotic motion [77], this process appears to be intact when people observe robotic motion that has been programmed to resemble biological motion as closely as possible [78]–[80]. Interestingly, these potential differences appear to be driven less by form, and more by motion factors [81], [82], as well as people's expectations about the human or artificial nature of the agent they are watching or interacting with [83] and [84]. Brain regions in a dedicated action observation network are not only more responsive to rigid, robotic-like actions compared to more familiar, natural human actions, but this same pattern also holds whether the robotic actions are performed by a human or a robotic agent [82].

A question thus arises as to what the impact of motion parameters is on the perception of bodily expressions made by a robotic agent. Initial evidence suggests that a participant's focus on different body parts, and assessment of motion (speed and magnitude) influences recognition of emotions displayed by a Robovie-*X* robot [74]. A careful investigation of these factors was undertaken by Novikova and Watts [67]. They manipulated movement energy (strength and tempo), intensity (suddenness of the movement), duration and frequency in a small toy robot, while participants were asked to rate the perceived valence (from negative to positive), arousal (from low to high), and dominance (from low to high control of the situation). Energy, duration, and frequency, but not intensity, of the movement were shown to influence the perceived valence, arousal and dominance of the expression. Intensity of the movement only determined arousal. While these parameters allow for sophisticated bodily expressions of emotion, a question emerges as to whether this is necessary, as people are already able to recognize happiness and anger from simple motion patterns made by a nonhumanoid KaMERo robot [85].

While few studies have looked at the processing of emotional faces made by artificial agents in the human brain, no direct investigation has been undertaken for bodily equivalents. The neural network involved in body perception partly overlaps with the neural network implicated in face perception. Together, they are referred to as the person perception network (see Fig. 2). Two regions in this network, the extrastriate body area (EBA) and fusiform body area (FBA), underlie the processing of the shape and posture of the body [86], while a third region, the posterior superior temporal sulcus (pSTS) is involved in processing bodily motion [87], [88] and the nature of the interaction [89]. While it remains unknown how expressive bodily motions or postures performed by artificial agents shape activity within these regions, one relevant study has contrasted human–human interaction (HHI) with human–robot interactions [90]. The authors presented participants in with pictures of HHI or HRI that were either instrumental or emotional in nature. When participants were asked to judge if one of the agents was helping the other, the robots (NAO) pictured in the HRIs were perceived as more helpful in nature. However, HRIs were also perceived as more eerie and less believable, and participants rated the robotic agents as less capable of having emotions and intelligence compared to humans. The authors also examined activity within regions of the person perception network. No clear differences emerged for face- or body-selective regions (FBA and EBA). The only difference in the person perception network was found in the response profile of the pSTS, where HRI compared to HHI activated this region to a lesser extent. These results overlap with several previous studies that investigated perception of computer-generated agents or emotional point-light displays, where the movement of the individual is represented by several dots [91], [92].

Interim Summary: While work in this domain is still very much in its naissance, evidence collected to date suggests

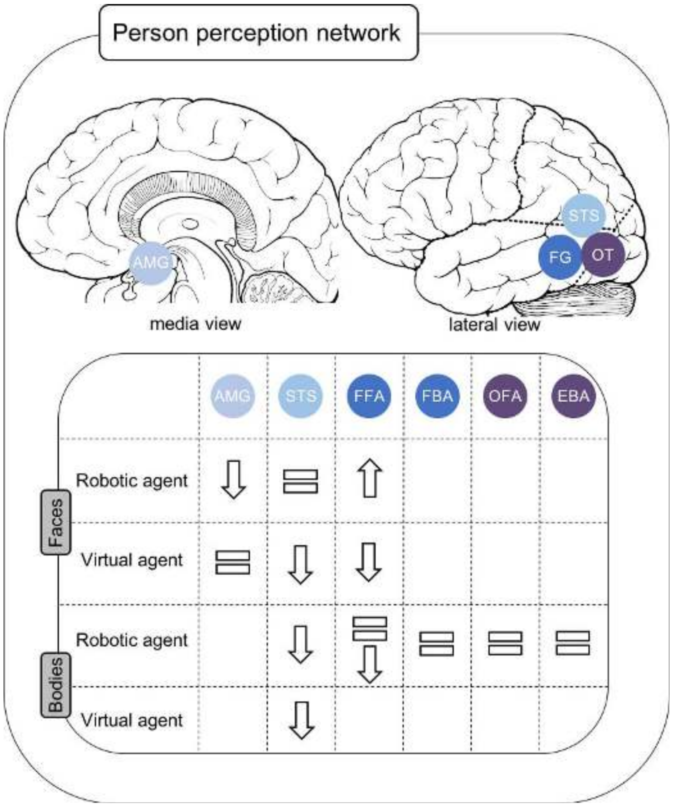

Fig. 2. Person perception network and the observation of emotion in artificial agents. Symbols indicate increased (upward arrow), decreased (downward arrow), and similar (equal sign) activity compared to human agents. AMG: amygdalae, STS: superior temporal sulcus, FG: fusiform gyrus, OT: occipitotemporal cortex, FFA: fusiform face area, FBA: fusiform body area, OFA: occipital face area, EBA: extrastriate body area.

that human observers are able to accurately recognize bodily expressions of emotion displayed by robots. Recognition of these emotions is likely influenced by the robotic agent's motion. No firm conclusions can yet be made for recognition of bodily expressions displayed by virtual agents. While one study found accurate recognition [93], another study found that emotions were perceived as blunted when expressed by a virtual agent, regardless of whether the agent's appearance was realistic or simple [70]. Combined with the neuroimaging results for artificial faces, the reviewed findings suggest that brain regions in the person perception network process emotional expressions made by robotic agents similarly as human expressions (Fig. 2). However, further work is required to more completely document the similarities and differences between bodily expressions of humans and robotic agents, as well as virtual agents, by directly contrasting individual emotions. Moreover, outstanding questions concern how subtle differences in activity in the person perception network might relate to recognition of facial and bodily emotional expressions by artificial agents.

III. Consequences of Emotion in Artificial Agents

In the previous section, we discussed how human observers perceive emotional expressions made by virtual agents and robots. While these studies provide key insights into the behavioral and brain processes mediating this perception, such as an agent's presence and motion, most of the research discussed so far has focussed on passive observation. However, it is important to keep in mind that the application of emotional behavior in artificial agents will have an equally, if not more, significant impact on the interaction and user experience during human-artificial agent encounters. People readily react to emotions expressed by artificial agents, for example, by petting a relatively passive haptic creature robot when it expresses sadness [17]. To better understand how emotional expressions made by artificial agents shape ongoing interactions, we need to study real interactions [94], during which the artificial agent influences the human interaction partner, and vice versa. In this section, we review the consequences of interacting with an emotional artificial agent. We highlight both positive and negative reactions to emotions displayed by artificial agents during these interactions.

A. Empathy and Other Positive Reactions

As the design goal of many social robots is to engage people in social exchanges, questions arise concerning the extent to which emotional expressions by these agents can facilitate and influence these interactions. Simple emotional reactions in the absence of more complex facial and bodily expressions have been shown to lead to increased enjoyment during HRI with a pet-like Keepon robot [95]. Many everyday interactions feature collaborative tasks that require both sides to actively engage with one another and contribute toward a shared goal. This requires artificial agents taking a more active role. A study by Pais *et al.* [96] used a twofold experimental procedure to test the impact of an emotionally responsive robot on subjective and objective engagement during HRI. First, they tested participants' recognition of a large set of expressions made by the iCub robot. This was followed by a task in which the human participant trained the robot to manipulate objects. The three facial expressions most accurately recognized (happy, content, and annoyed) were used to provide feedback to the human user. While objective performance did not increase when receiving facial feedback, subjective evaluation of the training was improved when the robot provided this facial feedback during training. Specifically, participants reported being more comfortable and satisfied with the robot after the training when the emotion-based feedback was provided. Another intriguing example on the impact of emotion communication on HRI comes from a study featuring a physically present BERT2 robot [16]. During the collaborating with the human, the robot was programmed to work perfectly without expressing emotion, or to make a mistake and correct it without apologizing, or to make a mistake and correct it while apologizing and making a sad facial expression. In contrast to expectations from previous literature [97], the authors found that participants preferred the flawed, but emotionally responsive robot over the flawless but emotionless robot or flawed, but nonexpressive robot. While this already indicates human interaction partners' tolerance of errors when an artificial agent responds in an emotionally appropriate manner, other research goes even further by examining people's empathic responses to emotional artificial agents.

Empathy, derived from the German word Einfühlung (literally translating to "to feel into another"), is assumed to be driving force behind social behavior [98], [99]. Several studies suggest that humans exhibit empathy toward artificial agents [18], [100]–[106], especially for physical present agents. A study by Kwak *et al.* [100] involved children actively teaching a head-shaped Mung robot word pairs. Whenever the robot made a mistake, it received a shock, and the robot expressed a painful vocal reaction and displayed a bruise. The participants reported more empathy for the physically present robot compared to the virtual robot. A similar finding has been reported in a study where participants conversed with either a virtual or physically present small humanoid NAO robot and reported more empathy toward the physically present robot [102].

There is some indication that children are more inclined than adults to engage in empathic behavior during interaction with artificial agents. Weiss *et al.* [101] found that adults, while interested in an AIBO robot's abilities, preferred to observe the robot from a distance. However, children often directly interacted with the robot, with nine out of ten children attributing emotional states, such as sadness and happiness to the robot upon being asked. Moreover, a field study using a similar setup found that young children between 4 and 7 years of age showed empathic behavior such as comforting toward a Sparky robot when it made fearful or sad facial expressions [104]. Another study with 9–15-year old children reported similar findings during an interaction with a Robovie robot [18]. At one point during the HRI, the experimenter put the robot in a closet, who protested this action. Semi-structured interviews revealed that the majority of children not only attributed intelligence toward the robot but also believed it had feelings, thought it was unfair to put it in the closet and reported that they would try and comfort the robot if it told them it was sad.

Interim Summary: Emotionally expressive artificial agents can evoke positive reactions during HRI. People are more inclined to engage with agents that are capable of expressing emotions in a clear way, even in the presence of a faulty program. Moreover, these emotional cues can, especially for children, result in feelings of empathy toward a robotic agent.

B. Aggression and Other Negative Reactions

A major concern in robotics is the possibility of negative reactions to a robot, especially outside of a fully controlled laboratory environment. Some scholars have argued that humans may view robots as belonging to a social outgroup, depending on social context and robot design [107], [108]. This has the potential to result in negative and even aggressive behaviors directed toward robots. A field study noted that people are not only interested in engaging with nonhumanoid Piero robots they encountered but also actively try to damage it through aggressive behavior [109]. This kind of behavior seems to be particularly pronounced among children. Boys from 7 until early teenage years reacted in an aggressive manner through verbal or physical abuse when confronted with a small pet-like Sparky robot [104]. Only when the authors changed the robot's emotion to angry and programmed the robot to approach the boys head-on did the boys behave more respectfully toward the robot. Aggressive or negative behavior, such as hitting the robot, blocking its path or throwing objects at it, especially occurred if multiple children are present around a robot or when there were less adult bystanders in the vicinity [110].

It remains unknown what processes and mechanisms drive these kinds of reactions. Anxiety or negative affect toward robots [107], the perception of a robot as an outgroup member [111]–[114], or even the threat a robot could pose to human-uniqueness might all lead to negative reactions and even aggression in real-world contexts. For example, while a human-like appearance can facilitate the attribution of a mind to a robot, it might also increase perceived threat to human identity [115]. This highlights a difficult issue in the design of artificial agents, such as embodied robots. On the one hand participants can more easily engage with emotional artificial agents, and this can even lead to feelings of empathy toward the agent. On the other hand, this can also evoke negative feelings and interactions. With increased sophistication of artificial agents' social and emotional capacities, one important question is how far humans might go in abusing artificial agents.

This question has been investigated by studies using a similar approach to a classical psychology study known as the Milgram Obedience experiment [116]. In the original Milgram study, participants were instructed to collaborate with the experimenter to investigate the effects of punishment on learning. To this end, participants were instructed, enforced by the experimenter, to administer electric shocks of increasing voltage to an ostensible learner whenever the learner made a mistake in the learning task. At a certain threshold of 300 V, the learner no longer responded to the task and kicked the wall in protest, yet the average maximum shock had a voltage of 312 V. Twenty-six out of 40 participants were willing to deliver the maximum intensity of 450 V to the learner. This paradigm has subsequently been used to test whether and to what extent people will punish artificial agents (Fig. 3). A study by Bartneck and Hu [117], featuring a physically present toy robot, led to even more pronounced results than the original study. Similar to the original Milgram study, participants were instructed to teach the robot 20 word combinations and give the robot learner shocks when it made a mistake. Despite its verbal protest (for example, "that was too painful, the shocks are hurting me") and painful facial expression, all participants administered the highest electric shock of 450 V. In a follow-up experiment, the authors showed that people are even obedient when asked to kill a Crawling Microbug robot [117].

Do people behave the same way toward a virtual agent? A study by Slater *et al.* [118] used a similar setup in virtual reality as the previous studies, with one important change: participants either heard and saw the virtual learner or did not hear or see the virtual learner and were only able to communicate though text. When the learner was not visible,

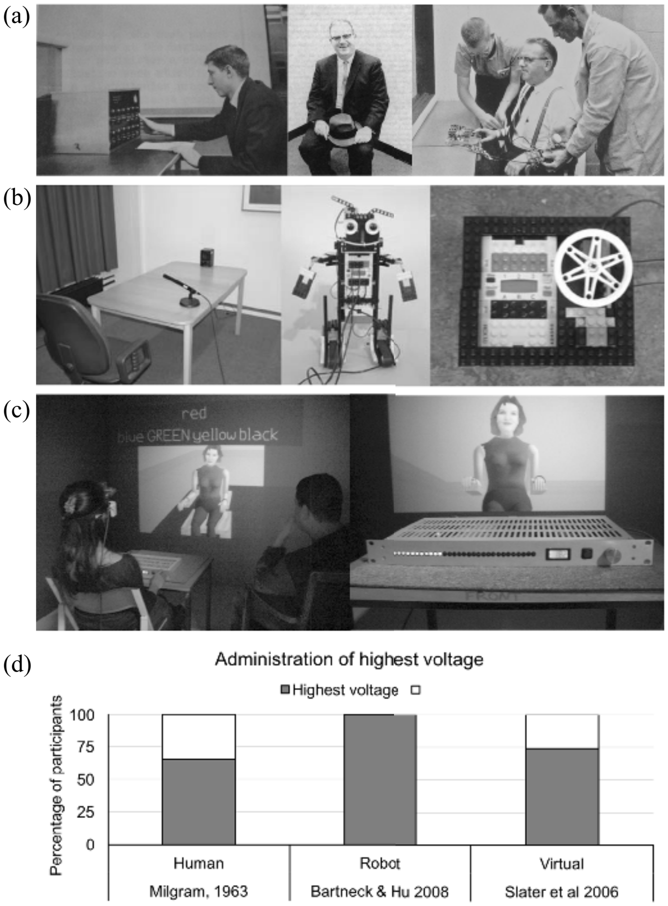

Fig. 3. Milgram obedience experiment and type of agent. Illustration of the Milgram procedure with a human (a), robot (b), and virtual human victim (c). In all studies participant were part of a learning paradigm as an instructor, with the victim being the learner. They were instructed to give the victim shocks after incorrect responses. The voltage increased after each incorrect response. While 65% of the participants continued until the highest voltage in the original experiment with a human victim, 100% and 74% of the participants continued until the highest voltage with a robot or virtual victim (d). Note the visual only condition is reported for Slater *et al.*, 2006. Images from [116], [138], (a) [117] (b), and [118] (c).

all participants administered the final shock, but when the learner was visible, only 74% of participants delivered the maximum voltage. Even though all participants were aware that the learner was a virtual agent, the visual and vocal expression of pain in response to the shock were sufficient to trigger discomfort and stress in participants, resulting in increased arousal and even withdrawal from the experiment. This is similar to the original study, in which participants were also described as highly agitated, with a third of the participants withdrawing from the experiment at some point [116].

Interim Summary: The research reviewed in this section shows that people (and in particular, children) can behave abusively toward robots even when the robot displays distress. Moreover, participants will readily punish artificial agents for their mistakes when instructed to do so. However, one underdeveloped area in the literature concerns the paucity of research examining how people respond to robots expressing negative emotions. Future work could explore how adults and children respond to artificial agents with more diverse emotional responses, instead of the often-used friendly versus neutral dichotomy.

IV. Challenges and Outlook

One major limitation to drawing a general picture of how people perceive and respond to emotion in artificial agents, which likely became increasingly apparent throughout this review, is the wide variety of artificial agents currently used in research (see Fig. 1). While this large and eclectic collection of agents allow us to investigate different manifestations of emotional behavior across diverse artificial agents, it also makes it very difficult for any single study or line of research to generalize to artificial agents more broadly. Generalization of results is a pillar of ecological validity and can only be achieved if a series of studies uses a comparable set of stimuli—in this case, either the same artificial agent, or an artificial agent that is the same across studies with only one factor being varied at a time (such as how the robot moves, looks, expresses emotion, etc.).

In recent years, a growing number of robotics laboratories are using social robots that are becoming increasingly available on the commercial market, such as the Pepper or NAO robots. Follow-up research using the same robotics platform(s) as previously published work is already a major step in the right direction. While an in-depth exploration of this limitation goes beyond the scope of this review, it should nonetheless be considered for future human–robot research, so that the field is better positioned to produce scientific results of adequate scope and generalizability. Another possible way forward to further address this limitation involves laboratories with access to these more common social robots working together to replicate each experiment featuring an artificial agent with a second, different emotional artificial agent. Replicating and expanding results over a broader set of agents will foster direct comparisons between agents used in the same experimental designs, as well as enable researchers to draw more generalizable conclusions for the field as a whole.

Ever since the early study of Ekman and Friesen [119], debate continues as to whether emotions are universal. While some researchers report evidence for universality [120], [121], results from other studies argue for cross-cultural specificity in emotion perception [122]–[125]. As robots and other artificial agents are developed and deployed all around the globe, this discussion must be expanded to include artificial agents as well. So far, this issue has received little attention. As Rehm convincingly argues [126], the impact of cultural influences should be taken into account during the development of artificial agents and subsequent testing and evaluation by users. Indeed, one study found both cross-cultural similarities and differences in the perception of bodily expressions made by virtual agents [127]. Future research should incorporate cultural dimensions and evaluate the universal aspect of emotions by using the same agents in emotional interactions with diverse cultural groups, as well as use emotional expressions adapted to specific groups.

Another area of particular interest for further research concerns the impact of negative emotions displayed by artificial agents during HRI. Research so far has focussed on either pre-existing stereotypes and negative attitudes about artificial agents [107] or on humans abusing artificial agents [104], [109]. Some research has investigated the effects of faulty robots [102], but unless technical failures are specifically framed as being causes for negative emotions by the agent, they might attributed to external causes and not the agent's malintent. To our knowledge, only one study so far as examined angry robot behavior, albeit only in emergencies and without posing any danger to participants at any time [104]. In this paper, the use of an aggressive movement pattern was sufficient to reduce robot abuse. Future research can explore the implications of verbal aggression, cheating, or other potentially negative behavior performed by the artificial agent.

Another question concerns how human observers integrate different and possibly mixed emotional channels from artificial agents. Ultimately, an advanced social robot will have several channels to communicate its emotional state in an authentic and clear way. In embodied artificial agents such as robots, emotions can be expressed vocally or from facial and body cues [9]. Regarding bodily cues, gestures and body movements play a crucial role in accurate emotion expression [21], [128] and the use of different colored lights can improve the perceived accuracy of expressed emotions [129]. Emotions are largely expressed by a combination of facial, vocal, and bodily signals, and a well-developed literature documents how these different cues interact [19], [63], [130]. While studies on perception of artificial agents' emotion have mainly focussed on one channel, there is some indication that recognition accuracy and evaluation increases for a robot that uses multiple channels, for example, facial and bodily expressions [16], [21]. As human emotions are largely expressed by a combination of facial, vocal, and bodily signals, future studies should use a combination of these signals to study the expression and perception of emotion in artificial agents. A related question concerns whether discrete or prototypical emotions expressed by artificial agents, for example, anger or happiness, are superior to mixed or blended emotions. People are still able to recognize mixed emotions expressed by a robot [70], and these types of subtle emotions might communicate feelings and context to a great extent during HRI [131]. Similarly, for an artificial agent that is part of a real-world environment, this context might play a crucial role in the perception of emotional expressions made by the artificial agent by a human observer. Indeed, contextual effects on emotion perception have been reported in human emotion communication [66], [132], [133]. Future research should therefore integrate multiple channels and included mixed emotions as well as context in order to approach the richness of emotions in everyday life.

Despite its apparent importance for conveying emotional content, the voice of artificial agents has thus far been underrepresented in research. In order to understand the impact of an artificial agent with "real" emotions, the voice needs to be considered as well. The evidence so far has shown that nonlinguistic utterances of robots (such as beeping noises) can convey affective content [134], that robots with a gendered human voice are anthropomorphized more than those with robotic voices [135] and that gender stereotypes are activated by gendered computer voices [136]. Lastly, participants can reliably identify the accent of a synthetic computer voice [137]. These studies already provide a solid start but future research should expand beyond mere observation to determine how these voice cues affect active or collaborative human–agent interaction.

TABLE II
GUIDING PRINCIPLES FOR THE DEVELOPMENT AND EVALUATION OF EMOTIONAL ARTIFICIAL AGENTS

1. Emotion
It should be clear if the emotional expression is a prototypical emotion or build-up from multiple discrete emotions, if it is a one-cue emotion or build-up from facial, bodily and vocal expressions, and if it is a context-dependent or –independent emotion
2. Design
The parameters influencing the execution and recognition of the expression, such as presence and motion of the agent, should be known
3. Robustness
It is preferable that the emotional expression is transferable to other robotic or virtual agents resulting in similar performance or the use of one agent across multiple studies
4. Recognition
The emotion expressed by the artificial agent should be reliably recognized by people across age, gender, and culture, or a specified user group
5. Reaction
The reaction of the user should fall within the predefined behavioural reaction space

V. CONCLUSION

The arrival of sophisticated artificial agents capable of meaningful emotion communication marks an exciting new horizon in HRI. In the present review, we aimed to provide an overview of the research on the perception of and reaction to artificial agents' emotional expression. Humans can, to some extent, accurately perceive the emotions expressed by these artificial agents, especially facial expressions of virtual agents, positive facial expressions of physical present robotic agents and bodily expressions. Crucially, these emotions can lead to positive as well as negative reactions among human perceivers. While people can feel empathy for the suffering of an artificial agents, they might also exhibit aggression toward these agents in certain contexts. As a whole, the reviewed literature provides direct guiding principles for the further development of emotional expressions in artificial agents and evaluation thereof (Table II). With the development of ever more advanced agents in the foreseeable future, it will be increasingly important to investigate the replicability and generalizability of findings across agents, study the impact of cultural influences, multichannel emotion communication, and vocal cues of emotion.

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