Survey and perspective on social emotions in robotics

Chie Hieida and Takayuki Nagaib,c

aDivision of Information Science, Graduate School of Science and Technology, Nara Institute of Science and Technology, Ikoma, Japan; bDepartment of Systems Innovation, Graduate School of Engineering Science, Osaka University, Suita, Japan; cThe University of Electro-Communications, Chofu, Japan

ABSTRACT
This paper presents a review of available research concerning social emotions in robotics. In robotics, the study of emotions has been pursued since a long time. The popular research endeavors in robotics concern the study of robotic recognition, expression, and computational modeling of the basic mechanisms that underlie them. The advancements in research relevant to this domain are in accordance with well-known psychological findings obtained using the category and dimension theories. Many studies are based on these basic theories, which exclusively address the basic emotions. However, social emotions, also referred to as high-level emotions, have been investigated in psychology. We believe that these high-level emotions are worth investigating for the development of next-generation robotic systems – socially aware robots. This paper summarizes the findings concerning social emotions reported through psychology and neuroscience research endeavors along with a survey of studies concerning social emotions in robotics conducted to date. Moreover, this paper discusses future research directions to facilitate the implementation of social emotions in robots.

ARTICLE HISTORY
Received 13 May 2021
Revised 28 August 2021 and 21 November 2021
Accepted 24 November 2021

KEYWORDS
Social emotion; emotional robotics; emotion model; developmental robotics; survey paper

1. Introduction

Emotion, also known as emotional intelligence [1], is an important element that forms the basis of human intelligence. Therefore, the elucidation of its mechanisms and application to robotics is an important research direction. In particular, because of the connection between emotions and the human body, research concerning emotion and robots has attracted increased attention in recent years [2]. However, current endeavors concerning emotional research in robotics have exclusively focused on basic emotions. It is necessary to broaden that focus to include social emotions to create robots that can socially coexist with humans and elucidate complex emotional mechanisms.

This paper focuses on research trends concerning social emotions in robots. There have been few studies focusing on social emotions, but many studies on basic emotions in robotics. Moreover, although the understanding of basic emotions has deepened considerably, our conception of social emotions is inadequate, and no unified definition of them exists, even in emotion studies. In this paper, we first overview the problems regarding the current study of emotions in robotics, followed by a presentation of the general theories of emotions. We then summarize the definitions of social emotions and review the associated psychological and neurological findings. Subsequently, we catalog how social emotions have been studied in robots. Finally, the challenges of social emotion research in robotics in the future are discussed.

Previous research has attempted to survey and review the study of emotions and robots. Cavallo et al. [3] reviewed emotions in social robots, whereas Motherlind et al. focused on reinforcement learning in emotion models [4]. Although these projects did not describe social emotions, they comprehensively summarized emotion research in robotics; therefore, we will refer to them in the text for comparison. Note that these survey papers did not provide a perspective on the learning and development of emotions themselves.

In psychology, the idea of emotional differentiation has existed for several decades. The emotional differentiation model proposed by Lewis [5] is a prime example of such research. Recent studies concerning robotic emotions have demonstrated that there are no fixed basic emotions. Instead, our bodily inference is believed to form the basis of emotions. Moreover, human development and learning play an important role in the development of this inferencing ability [6,7]. As this area of research has progressed, various emotion model studies have been developed. However, most studies concerning
robotics consider emotions to exist from the day the robots are first used, and only few studies have focused on the development of emotions in robots.

We believe that more complex social emotions should be addressed in future robotic research. Therefore, it is necessary to perceive emotions as things which can develop and change, rather than being fixed and pre-existing. This is because it is difficult to comprehensively design complex emotions. These points are also important for promoting a constructive approach to elucidate underlying emotional mechanisms, including social emotions, through robots. In the discussion section, we consider the development of social emotions by comparing them with basic emotions.

2. Direction of proposed research and current status of robot-emotion studies

2.1. Overview of proposed survey

Emotions are remained a topic of extensive research. Moreover, diverse as they are, it is impractical to investigate all emotions at once. In this section, we summarize the objectives of and methodologies employed in extant studies concerning social-emotion research in robots – the main focus of this paper. Subsequently, we describe the current problems and propose appropriate solutions for them.

Figure 1 summarizes the objectives of, problems encountered, and viewpoints presented in extant research concerning robotic emotions. The first purpose of the said research is to apply engineering principles for developing partner robots capable of establishing an emotional connect with people. Additionally, the scientific purpose of such research focuses on understanding the essence of emotions. This is referred to as the ‘constructive approach.’

There exist three major approaches to realize this objective. The first approach aims to manually design emotions using robots. The second approach is developmental in nature and emphasizes on the creation of a bottom-up learning framework based on the idea that humans do not innately possess social emotions. Instead, they acquire them over the course of their lives. The third approach involves laboratory experimentation involving humans to gain knowledge pertaining social emotions. Although the third approach could be considered irrelevant in the context of research concerning social emotions in robotics, it offers an important means to understand the key aspects of social emotions. These laboratory studies can be referred to when considering the actual definitions of social emotions.

When employing the constructive approach, it is possible to utilize the knowledge gained and enhance the same by performing experiments involving robots. In

![Figure 1. Overview of proposed survey summarizing the purpose of, approach followed in, and number of existing research endeavors concerning social-emotions in robots.

Note: Moreover, it describes how extant research was handled in this study, issues encountered, and perspectives are summarized in this figure.](image-url)
In particular, this approach is similar to the developmental approach; that is, these approaches are not completely independent.

A later section discusses several studies investigating these different aspects of social emotions. In fact, in few studies, the researchers have attempted to design social emotions for robots. Furthermore, there exist examples of developmental research, wherein robots can acquire social emotions. Alternatively, several experimental endeavors have endeavored to examine social emotions in humans. The specific contents of such studies are described in detail in a later chapter.

Based on this evaluation of the state of emotion research in robots, the problems considered by the authors are listed in Figure 1, and these problems are discussed based on the survey results obtained in this study.

### 2.2. Emotion studies using existing robots

Some implementations of emotions in existing social robots are summarized in Figure 2. However, all robots in this figure are famous, and their arrangement is based on the author’s subjective assessments. The horizontal axis indicates whether the implementation of emotions represents a design or developmental model.

The vertical axis indicates whether the robot was made to resemble an existing creature or original robot. Realizing a developmental model using a completely original robot is difficult; hence, there exists no research corresponding to the third quadrant. We believe that the area in the second quadrant, which is indicted by the gray color, is important from the viewpoint of performing future research concerning robot emotions. This is because it is difficult for robots to express complex emotions like humans solely by design. Although this, in part, depends on the context in which robots are used, the research represented by the second quadrant are indispensable if one imagines a future wherein robots would establish friendly relationships with humans.

### 3. General theory of emotions

#### 3.1. Definition of emotions

Considering the definition of emotion, to the best of our knowledge, there is no universal consensus on the definition of the term 'emotion.' Damasio, for example, distinguished between emotions and feelings. Emotions were defined as a series of physical reactions, changes in the state of internal organs and skeletal muscles, and changes in internal states. Feelings, alternatively, were defined as the recognition of emotional states [17]. Other definitions of emotions are based on unconsciousness and consciousness, transient and subjective experiences, emotions that are suddenly caused by stimuli, etc. The word ‘affect’ is occasionally used to refer to all emotions, and it has a wide variety of meanings. In this paper, all items are represented using the word 'emotion' without dividing the concept into a further detailed meaning.

#### 3.2. Psychological theories on emotions

There are several different psychological theories of emotion. There are category theories, which regard emotions as categories, and dimensional theories, which represents emotions in an emotional space composed of several dimensions. Ekman’s six common emotions (anger, disgust, fear, happiness, sadness, surprise, and neutral) which exist regardless of culture is an example of category theory [18]. Although subsequent research has disputed this claim, it is still a popular theory. Russell’s circumplex model, conversely, is well-known as a dimensional theory of emotion. Russell stated that emotions are placed in a two-dimensional space consisting of valence and arousal (VA) axes [19].

Other examples of extensions to the two-dimensional Russell’s circumplex model include the pleasure-arousal-dominance (PAD) [20] and valence-arousal-stance (VAS) [21] methods. In PAD, the D dimension indicates dominance-submissiveness, which represents the control state of the individual emotion relative to particular situations; it is influenced from others. In VAS, the stance specifies how approachable the perpect is to the agent. The stance dimension indicates an axis, the ends of which correspond to an open stance and closed stance.
Furthermore, Plutchik’s wheel of emotions can be regarded as both a dimensional theory and a category theory [22]. As a dimensional theory, it is represented by a cone-like shape, towards the bottom and apex of which the emotional intensity increases and decreases, respectively. Moreover, the opposite sides of the cone represent opposite emotions. As a categorical theory, this cone-shaped model mainly comprises eight basic emotions, and through their combination, various other emotions can be expressed.

3.3. Neuroscience studies

Recent studies have clarified the importance of the body in emotions, as previously suggested by William James through the peripheral theory of emotions [23]. In recent studies in cognitive neuroscience, the perception of the internal state, also known as interoception, has been reported to be the key to the subjective experience of emotions [24]. According to the emotional quartet theory, a brainstem-centered system corresponds to an emotional system [25]. The brainstem is the oldest brain structure, and the reticular formation plays an important role in this brainstem-centered system. Another important aspect of the relationship between emotions and the body is Damasio’s somatic marker hypothesis, which assumes that emotions efficiently evaluate external stimuli through our own body [26].

As previously mentioned, the body is the origin of emotions and is thus indispensable to the study of emotions. Basic emotions, such as anger, joy, disgust, fear, sadness, and surprise, exist irrespective of culture, even though how these emotions are expressed might be different [18]. This might be because humans share a similar body and environment, which supports the notion that emotions are based on our physical body and environment. The idea of active inference is also related to the body system, such as visual attention, which is related to the evaluation of external stimuli [27,28].

Note that emotions are related to decision-making and causal reasoning [29]. For example, misattribution of a physical reaction, known as the suspension bridge effect, is the false attribution of one’s personal-physical reaction to another person by experiencing the fear of one’s self is in danger while meeting someone [30]. This higher-level cognitive process is believed to be closely related to the system centered on the orbitofrontal cortex, as well as to the reinforcement learning module derived from the corticobasal loop. The relationship between active inference and reinforcement learning is discussed in [31].

Memory-based systems are also considered to be important components of emotions. In the quartet theory, the hippocampal-centered system, which mainly involves the hippocampus and the amygdala, are the important brain structures involved in emotion [25]. Amygdala activity during the experience of emotions is important, and it has extensively been studied. For example, the well-known limbic circuit Yakovlev includes amygdala [32]. Similarly, the Papez circuit is also a well-known limbic circuit that includes the hippocampus [33]. Although these circuits are independent, they interact with each other through the cortex, basal ganglia, and diencephalon, and are closely related [34].

As described above, emotions need to be considered as a network rather than as a localized circuit, because each function is interrelated, and several models have been proposed for this integration. In Damasio’s conceptual model, the amygdala evaluates the information, the hypothalamus induces a physical reaction, and then the physical reaction actually occurs. This is the emotional state. The information is sent to the cerebral cortex as an internal receptive sensation and integrated with external receptive sensations. Emotional feelings are then perceived [26]. In the model of Moriguchi and Komaki, a core affect (i.e. emotional state) is formed based on the interoception representing the physical state of the physical body [7]. Emotions are perceived by integrating and categorizing core affects with information such as contexts and concepts. This is a model that was proposed based on the alexithymia neuroimaging research.

3.4. Social constructivist view of emotions

Social factors have a great deal to do with how people feel. The social constructivists in emotions seek to find the source of emotions in society. The originator of social constructivists in emotions was Averill, who argued that a social level analysis was needed to fully understand emotions [35]. More recently, Boiger emphasized the importance of considering the social world for the science of emotions [36]. Emotion is a complex process, based on biological constraints, but it cannot be fully understood without considering the social impact of the individual’s development. He further stated that emotions are an ongoing, dynamic, and interactive process that embeds three contexts: in-the-moment interactions, relationships, and culture [37].

Culture in particular is crucial for social constructivists. Considerable research has been conducted on the relationship between emotions and culture, and there have been various discussions about the similarities and differences of emotions between cultures [38,39]. The relationship between language and emotion has also been studied. The ultimate relationship between language and emotion is Harré’s ‘Emotionology Principle’ [40]. The idea is that emotions can be understood by identifying
under which conditions the language that expresses these emotions is used.

The perspective that emotions are socially constructed is important, but it would be an extreme view to think that it represents the totality of emotion formation. Emotional mechanisms exist in the cognitive domain, based on the human body as described earlier. This is also a premise in claims of recent social constructivists. Cornelius [41] summarized the social constructivist perspective and discussed how emotions could be studied under the fusion of various views, such as cognitive and psychological perspectives. This integrated perspective seems to be important to fully understand emotions. Aranguren [42] stated that there is a need to separate ontology and methodology in emotional research. This is based on the assumption that ontological emotions that are described by language can lead to oversights regarding the nature of emotions. This is also suggested by emotional studies in nonhuman primates, who lack linguistic abilities.

An important characteristic of the social constructivist’s emotion theory is that it does not explicitly separate basic emotions from social emotions. This is a natural consequence of the idea that emotions are socially constructed. For example, anger is considered to be a sophisticated social emotion in itself. In this paper, we will discuss social emotions in the following chapter, but we will not touch on the perspective of social constructivist. However, the elements of social construction described in this section should be included in the construction of social emotions.

4. What are social emotions?

4.1. Taxonomic definition of social emotions

Until now, we have established general definitions and theories about emotions. From here, we focus on the definition of social emotions. Parkinson et al. listed the following as social emotions [43].

- **Embarrassment**: this is caused by unwanted interpersonal attention and serves to deflect it.
- **Shame**: this is simply a stronger and more enduring form of embarrassment.
- **Guilt**: this tends to focus on a particular incident, rather than a more general moral failing. Further, it is a response to accusations from a close social partner.
- **Jealousy and Envy**: both refer to negative reactions to the good fortune of another person.
- **Love**: this is a statement about the perceived status of a relationship or a promise of commitment. Moreover, it is quite diverse in character: sometimes positive and exciting, sometimes painful, and sometimes calm and serene.
- **Fago**: this represents concern for other people when they are alone, ill, or, by contrast, exhibiting qualities of interpersonal sensitivity and social intelligence.
- **Grief**: this is a feeling of suffering. For example, the experience resulting from the death of someone close.

Hareli and Parkinson defined anything with a social relationship as a social emotion, which is different from the above definition. They stated that both social and non-social perspectives exist, even with similar feelings [44]. In addition, Elster proposed eight social emotions from a combination of three types of characteristics: evaluation of oneself or evaluation of others, evaluation of behavior/evaluation of personality, and evaluation of positive/negative, as summarized in Table 1 [45]. According to this definition, social emotions include those that were traditionally considered as basic emotions. Shame and guilt are common between Parkinson’s social emotion category and Elster’s social emotion category.

Furthermore, moral emotions and self-conscious emotions are considered to be sub-categories of social emotions [44]. Moral emotions are defined as emotions that are intrinsically linked to the interests or welfare of society as a whole, or to persons other than the agent. Moral emotions are easily triggered by the perception of moral violations in the context of interpersonal events, which can lead to moral behavior. This category includes shame, guilt, regret, embarrassment, contempt, anger, disgust, gratitude, envy, jealousy, schadenfreude, admiration, sympathy, and empathy. Self-conscious emotions are emotions that occur when an individual becomes aware that a particular event or situation affects their own self-esteem or well-being. Common examples include shame, guilt, pride, and embarrassment. Lewis, who proposed a theoretical model of emotional development, claimed that self-conscious emotions do not appear until the age of two [5]. This indicates that infants’ awareness of being different from others is related to these emotions. Furthermore, Lewis suggested a relationship between self-conscious emotions and the recognition of themselves in a mirror.

Emotions can also be classified into non-self-conscious emotions and self-conscious emotions wherein the non-self-conscious emotions are the same
as the basic emotions. In addition, Lewis divided emotions into primary and secondary wherein the primary emotions refer to basic emotions. Moreover, there exist expressions for low- and high-level emotions.

Regardless, the existence of other people is common in the aforementioned definitions of social emotions. Social emotions are thus defined by the relationship between others, who are different from oneself but in other ways similar to oneself, and the society, which comprises multiple individuals.

4.2. Social emotions and psychology

In psychological research on social emotions, guilt and shame/embarrassment are primarily studied because they have important functionalities for maintaining our social groups.

Niedenthal et al. summarized the emotions that can occur within a group [46]. The authors divided the emotions within the group into group emotions and group-based emotions. The group emotions consisted of emotions that occur as a function of being in a group, such as sharing joy, whereas group-based emotions consisted of emotions that occur from a group, such as individual guilt. In particular, group-based emotions can be used as a predictor of group behavior against social injustices.

According to Hoffman, guilt can be defined as a strong contempt for oneself to injure others unfairly. For instance, based on the parental involvement, their child pays attention to the victim's pain and can recognize and empathize with their situation. Hoffman stated that guilt can cause empathic distress and foster empathy-based guilt [47]. In addition, the guilty conscience that arises by collectively belonging to an ethnic group, nation, group, etc., rather than the act of the individual itself, is called collective guilt [48].

Shame/embarrassment is an unpleasant emotion, and in some cases, it is one of the emotions that can completely disrupt interpersonal interactions and strongly afflict an individual for long time [49]. Shame itself is an emotion with a variety of meanings and is attributed to social evaluation concerns, self-image disagreements, interaction confusion, and reduced self-esteem [50].

Comparing oneself with others is called making a ‘social comparison.’ If jealousy and envy are caused by the awareness of things which an individual sees but does not have, it is considered that a social comparison is involved in the arousal process of these emotions. One of the social comparison theories is the self-evaluation maintenance (SEM) model [51]. This model assumes two processes, the comparison process and the reflection process. The comparison process is a comparison of the content you are interested in, and the reflection process is a comparison of the content that you are not interested in. Currently, jealousy and envy are considered to be related to the comparison process. The circumstance in which others are viewed as superior is the turning point in determining whether one experiences jealousy or envy.

Pride is a positive self-conscious emotion that is experienced when one's behavior, remarks, and traits are superior or desirable, and are positively evaluated by others [52]. The process of experiencing pride, etc., is modeled by Tracy and Robins [53], as illustrated in Figure 3. Specifically, hubristic pride, such as shame, results from internal, stable, uncontrollable, and global attributions. Highly authentic pride, such as guilt, results from internal, unstable, controllable, and specific attributions.

In 1986, Rivera and Grinkis proposed a structural theory based on interpersonal factors [54], as shown in Figure 4. The interpersonal factors of this proposal consist of ‘It–Me,’ ‘Extension–Contraction,’ ‘Belonging–Recognition’ and ‘Positive–Negative.’ The ‘It–Me’ factors refers to a choice of whether to direct a given

![Figure 3. Process model of self-conscious emotions [53].](image-url)
emotion toward another person or toward yourself. The ‘Extension’ factor reflects the distinction between accepting other people or rejecting them. The ‘Contraction’ factor reflects the distinction between wanting to be associated with other people or withdrawing from them. The ‘Belonging’ factor reflects whether the focal person belongs to another person or form a unit together, and the ‘Recognition’ factor involves social recognition and comparison.

### 4.3. Social emotions and brain activity

Koush et al. examined the brain activities associated with positive emotions in a social context using functional magnetic resonance imaging (fMRI) [55]. Their results demonstrated that self-referential positive-social emotion regulation recruited a distributed network of prefrontal, temporoparietal, and limbic brain areas.

Immordino-Yang et al. investigated brain activities related to compassion [56]. Using a compassion- and admiration-inducing procedure, they found that social emotions strongly recruited a neural region comprising the posterior/inferior precuneus and the neighboring retrosplenial cingulate, which are both involved in high-level associations of interoceptive information from visceral sensation and regulation. Functionally, this area is involved in the default network, which has been suggested to correspond to the feeling of self, personal salience, and higher-level consciousness.

Klapwijk et al. conducted an experiment wherein they read scenarios that evoked embarrassment and guilt (social emotions) and disgust and fear (basic emotions) to subjects and measured their brain activity using fMRI [57]. Psychophysiological interaction (PPI) analysis revealed that the right posterior superior temporal sulcus (PSTS) and the right temporoparietal junction (TPJ) showed greater functional connectivity with the dorsomedial prefrontal cortex (DMPFC) during social emotions than with basic emotion. These brain regions were suggested to be involved in mentalizing and acquiring the viewpoints of others.

Grecucci et al. summarized the brain regions related to emotional regulation as a mechanistic study of social emotional regulation [58] (Table 2). First, individual emotion regulation (IER) has been reported to be related to the dorsolateral prefrontal cortex (DLPFC), ventrolateral prefrontal cortex (VLPFC), anterior cingulate cortex (ACC), amygdala, striatum, and orbitofrontal cortex (OFC), among others. The DLPFC is generally believed to control attention and working memory. The ACC is involved in monitoring and controlling ongoing processes. The VLPFC appears to be responsible for choosing an appropriate response to a goal and suppressing inappropriate responses. The area of interest for reassessment is the amygdala, which is believed to be an important structure that supports the refinement of external and internal emotional and negative stimuli. In addition, the striatum and insula have little relationship with IER.

Socially cued emotions are emotions that are caused by interactions with others, such as rejected sadness. Socially cued emotion regulation (SER) involves different brain regions than IER, depending on the social context, SER can involve the medial prefrontal cortex (MPFC), the medial orbitofrontal cortex (MOFC), the posterior cingulate cortex (PCC), and the amygdala. In particular, the MPFC is related to the mentalizing of oneself and others, and the PCC is related to the attribution of others’ emotions. In addition, when emotions are downregulated using mentalization, subjects are shown to have weak emotional responses, less rejection behavior, and less neural activity when they received an unjust offer. This emotional modulation is observed on the insula, which has been found to represent the emotional experience of the viscera.

| **Table 2**. Key brain regions related to emotion regulation [58]. |
|---------------------------------------------------------------|
| **Individual emotion regulation**                             |
| Regulating regions   | Regulated regions   |
| DLPFC               | Amygdala           |
| VLPFC               | Striatum           |
| ACC                 | OFC                |
| **Socially cued emotion regulation**                         |
| Regulating regions   | Regulated regions   |
| VMPFC               | Insula             |
| VLPFC               | Striatum           |
| TPJ                 | Cingulate          |
| Temporal Pole       | Cingulate          |
| ACC                 | Cuneus/Inferior parietal lobule |
| **Interpersonal emotion regulation**                         |
| Regulating regions   |
| Left temporal pole/Inferior temporal gyrus                   |
| Rostral medial prefrontal cortex                             |
| Posterior insula                                            |
| Cingulate gyrus                                             |
| Bilateral caudate                                            |
| Cuneus/Inferior parietal lobule                              |
Furthermore, interpersonal emotion regulation (I-PER) is a strategy for regulating the emotions of others during interactions. The same brain regions are activated as in IER/SER, with the additional activation of other regions, as listed in Table 2.

5. Survey on social emotions in robotics

5.1. Survey based on survey papers of emotional robotics

In this section, emotions research in robotics are briefly summarized. Yan et al. investigated the emotional space of social robots [59]. Cavallo et al. reviewed emotions in social robots and revealed that many studies on social robots are based on Ekman’s basic emotions [3]. Moerland et al. summarized emotion model research using robots and agents targeting reinforcement learning [4]. With reference to the aforementioned literature (101 articles were targeted from three survey papers), Table 3 summarizes the emotion categories that have been addressed by relevant studies, except Ekman’s six basic emotions (anger, disgust, fear, happiness, sadness, surprise, and neutral). The emotion categories described in these studies (and listed in the table) as well as the definitions of social emotions, reveal the presence of shame, pride, and admiration; however, no other social emotions were present. Note that anger, which is difficult to categorize as a social or basic emotion, has been excluded.

In addition, with respect to the dimension theory of emotions, several studies involving robots have used VA, which were famous in Russell’s circumplex model. It cannot be denied that social emotions may be included in VA. However, VA cannot distinguish between social and basic emotions. In addition, there have been studies which used PAD [20,73–76] and VAS [21,77–79].

Although social ‘others’ were involved in these research projects, the existence of others represented the directionality of relationships between the robot and others. There was no axis that represented self/other in the emotional space, as has been proposed in social emotion research.

There have been few robot studies that are directly based on social emotions. For example, Tsiouri et al. conducted a comparative study to investigate how humans perceive emotional cues expressed by humanoid robots through five communication modalities (face, head, body, voice, and locomotion) [80]. This study addressed three emotions: happiness, sadness, and surprise. The authors argued that these three emotions are social emotions according to the definition of Harelli et al. [44].

5.2. Survey based on categories of social emotions

We also conducted a mechanical survey of articles on robots using keywords regarding the social emotions (embarrassment, shame, guilt, jealousy/envy, love, fago, grief, pride, pridefulness, admiration, liking, and contempt) that were described in Section 4. The target articles include those published in the early 2000s. Consequently, shame, jealousy/envy, love, grief, pride, admiration, and contempt were found in the emotion recognition and expression of robots, as summarized in Table 4. Regarding embarrassment and guilt, psychological experiments have been conducted in which specific scenarios were presented to humans to evaluate whether humans have those feelings toward robots [81,82]. However, we could not identify any research wherein the existence of that emotion was actually incorporated as part of the robot system.

From Table 4, El-Nasr et al. addressed pride, shame, and admiration in robots [62]. In that study, pride was defined as an action done by the agent that was approved by the available standards, shame was an action done by the agent that was disapproved by the standards, and admiration was an action done by another agent that was approved by the agents’ standards. In [63], pride, shame, and admiration were used in the system to determine an agent’s facial expression from human facial expressions and audio information. In addition, Hegel et al. had

| Table 3. Emotion category in robots and agents research (excluding basic emotions). |
|-----------------------------------------------|
| Emotion                      | Research          |
|-----------------------------------------------|
| Joy                           | [60–63]           |
| Hope                          | [60,62,64,65]     |
| Frustration                   | [66–68]           |
| Distress                      | [60,63]           |
| Relief                        | [61,62]           |
| Gratitude, Reproach, Admiration, Pride, Shame, Gratification, Remorse | [62,63] |
| Boredom                       | [69]              |
| Contentment, Elation, Panic   | [71]              |
| Cooperative, Slight Annoyed   | [72]              |
| Disappointment                | [62]              |
| Resentment, Sorry for, Glossing| [65]              |

| Table 4. Social emotions and robots. |
|--------------------------------------|
| Emotion                | Research                                |
|------------------------|-----------------------------------------|
| Shame                  | EL-Nasr et al. [62]; Moussa et al. [63]; Hegel et al. [83] |
| Jealousy/Envy          | Oliveira et al. [84]                    |
| Love                   | Samani [85]                             |
| Grief                  | Huahu et al. [86]; Terada et al. [87]   |
| Pride                  | EL-Nasr et al. [62]; Moussa et al. [63]; Oliveira et al. [84] |
| Admiration             | EL-Nasr et al. [62]; Moussa et al. [63]; Oliveira et al. [84]; Terada et al. [87] |
| Contempt               | Oliveira et al. [84]; Jung [88]         |
robots express shame via LEDs on the robot’s cheeks as the robot that performed different facial expressions [83].

Oliverira et al. presented groups of two people and two robots with a card game to play. For the robots, two characteristics of competence and warmth were divided into two levels, high and low. The researchers designed behavior for the robots corresponding to each characteristic, and the reaction of human beings to the behavior of the robot was investigated. Here, jealousy/envy was expressed as high competence and low warmth, pride and admiration were expressed as high competence and high warmth, and contempt was expressed as low competence and low warmth [84].

Regarding love, previous researchers have attempted to validate user verification of love between humans and robots with reference to human-human affection [85]. Here, the robot received audio, visual, tactile, and acceleration information and interacted with a person using motion, audio, and LED. In addition, in the research by Huahu et al., robots recognized grief as emotional recognition from human utterances [86]. Jung explained that ‘turning against’ is recognized as contempt from an affective standpoint in the interactions between robots and humans [88].

Terada et al. used a glowing robot to express grief and admiration [87]. In the study by Terada et al., experiments were based on Plutchik’s wheel of emotions. In Plutchik’s Wheel of Emotions, grief and admiration are listed as part of the basic emotions [89] (Table 5). In Plutchik’s model, there are other applied emotions, such as shame, guilt, envy, love, pride, and contempt (Table 6).

These are composed of a combination of basic emotions. Plutchik’s model is similar to dimensional theories, such as the VA mentioned above, and in this model social emotions are not separated from basic emotions.

### 5.3. Mapping between existing robots and social emotions

Figure 5 was obtained by applying the research presented in Table 4 to the space shown in Figure 2 in the introduction. Although some of the studies shown in Figure 2 have taken social emotions into consideration, they do not clearly implement social emotions and thus are not

---

**Table 5. Basic emotions of Plutchik’s wheel of emotions.**

| Emotion | Content |
|---------|---------|
| Joy     | Basic emotion |
| Trust   | Basic emotion |
| Fear    | Basic emotion |
| Surprise| Basic emotion |
| Sadness | Basic emotion |
| Disgust | Basic emotion |
| Anger   | Basic emotion |
| Anticipation | Basic emotion |
| Ecstasy | |
| Admiration | |
| Terror  | |
| Amazement | |
| Grief   | |
| Loathing| |
| Rage    | |
| Vigilance| |
| Serenity| |
| Acceptance | Week joy |
| Apprehension | Week fear |
| Distraction | Week surprise |
| Perversion | Week sadness |
| Boredom | Week disgust |
| Annoyance | Week anger |
| Interest | Week anticipation |

**Table 6. Higher-level emotions of Plutchik’s wheel of emotions.**

| Emotion      | Blend                      |
|--------------|----------------------------|
| Love         | Joy + Trust                |
| Submission   | Trust + Fear               |
| Alarm/Awe    | Fear + Surprise            |
| Disappointment| Surprise + Sadness        |
| Remorse      | Sadness + Disgust          |
| Contempt     | Disgust + Anger            |
| Aggressiveness| Anger + Anticipation       |
| Optimism     | Anticipation + Joy         |
| Guilt        | Joy + Fear                 |
| Curiosity    | Trust + Surprise           |
| Despair      | Fear + Sadness             |
| Unbelief     | Surprise + Disgust         |
| Envy         | Sadness + Anger            |
| Cynicism     | Disgust + Anticipation     |
| Pride        | Anger + Joy                |
| Hope         | Anticipation + Trust       |
| Delight      | Joy + Surprise             |
| Sentimentality| Joy + Surprise             |
| Shame        | Joy + Sadness              |
| Outrage      | Surprise + Anger           |
| Pessimism    | Sadness + Anticipation     |
| Morbidness   | Disgust + Joy              |
| Dominance    | Anger + Trust              |
| Anxiety      | Anticipation + Fear        |

---

**Figure 5.** Approach to robot’s social emotions.
shown in Figure 5. Looking at this result, we can see that there has been no study in the second quadrant, which we identified in the introduction as being particularly important. Although many emotion modeling studies have been conducted, we were unable to find any studies which clearly implemented social emotions. However, because there are a few studies which have addressed the topic of social emotions, we believe that the number of studies investigating social emotions in robots will increase as a result.

6. Discussion

Based on our observations, there have been few robot studies on social emotions. Even in the studies which have focused on social emotions, they did not differentiate basic emotions from social emotions. Instead, they treated the two types of emotions as conforming to the same dimension, and designed expressions and recognition procedures based on these rules. Thus, present social robot research conflicts with the results from psychological–neurological findings. We believe this is not necessarily an incorrect wrong direction of research, considering that robots address social emotions superficially. A simple system can be constructed by assuming that all emotions are in the same layer without separating complex emotions from the more basic emotions, and if the goal is to simply convey the emotional expression to others, this purpose may be achieved even with a simple rule-based implementation. However, it is difficult to determine whether all complex, higher-level emotions can be realized by manually designing their rules. It is difficult to imagine that such an approach would be able to replicate sufficiently complex emotional behavior. Moreover, as mentioned above, there is a gap between the current psychological–neurological findings and the implementation of social emotions in current robots. To achieve emotional development, we must fill that gap. Here, we discuss future challenges based on surveys from this perspective.

6.1. Current status of emotions research using robots

Section 2.2 summarized existing emotion studies using robots. Subsequent survey of research on robots dealing with social emotions revealed that most of the studies listed here clearly did not implement social emotions. We could not find any research that dealt with social emotions in the second quadrant of Figure 5, which is of particular importance. This indicates that, although there have been some successful design implementations, the number of such projects is small and robot research dealing with social emotions has not been conducted. For example, in pepper, research is being carried out from a broad perspective using emotion maps, but only basic emotions are being implemented. This may represent a limitation of implementation by design.

‘Jealousy’ has been implemented in lovot. This is a complete design; however, it has not been verified as to whether it is actually perceived as jealousy by humans, so it cannot be cited as a valid example of research dealing with social emotions. It is unlikely that such an emotional design implementation is able to capture the essence of jealousy. In different situations, lovot does not express jealousy and is unaware of the fact that lovot is itself jealous. Furthermore, this jealousy behavior does not benefit the robot itself. Emotions are believed to be inherently built into the survival system, and one is thought to develop emotions as a means toward some reward. A system that is not rooted in this survival system cannot be said to play the original role of emotions. In that sense, developing the research in the second quadrant shown in Figure 2 would be a useful method that may clarify the essence of social emotions.

6.2. Is it yet possible to design robots with social emotions?

Unfortunately, at present, it is not easy to provide robots with social emotions by implementing a developmental model of emotions. Therefore, creating social emotions by design to build a partner robot is a reasonable method so long as we acknowledge its applicability in limited situations and with simple behaviors. In fact, the above example of lovot is a realization of this style of approach, but its success or failure is not clear at present.

Which emotional categories should be adopted when taking a design approach? In this paper, we have listed various emotion categories; however, we cannot determine which of these is the correct answer. This is because, in essence, the emotional category is considered to emerge through interactions, and from the standpoint of this paper, there is no ground truth. From the viewpoint of emotion emergence, we consider a space in which multidimensional information, such as extraceptions and/or interoceptions, is conceptualized through verbal communication as an emotional space. The basis of emotions is a concept of interoceptions.

From this perspective, a problem is encountered in describing emotions only by language category, which has been previously identified by social constructivists [42]. However, we do not claim that the traditionally presented categories are incorrect. The dimensional theory is also the result of dimensionality reduction in one aspect, and emotions are believed to essentially
be expressed in a higher dimensional space. Therefore, when taking the approach of designing social emotions for a robot, which emotion category should be used depends on the application.

Now, the social constructivist claims can directly apply to emotional design approaches when using robots. Designing emotions on robots can be regarded as attempting to realize the social functions of emotions. This is exactly the idea of the social constructivist, and such a design must pursue the social constructivist view of emotions. Considering the descriptions in Section 3.4, we can see that emotions in current robots are based on a type of ‘Emotionology Principle.’ The idea of the emotionology principle is that it is easier to understand than natural language processing (NLP). NLP basically attempts to identify the meaning of words in relationships. For example, in the case of Word2Vec technology, a neural network learns the semantic distance between words based on how each word is used in sentences [90]. Similarly, the emotionology principle argues that the essence of emotions can be understood by examining in detail the situations in which emotional words are used. Social emotions can be designed by writing down all these situations and defining the reaction in each situation. However, this is a complex task which cannot be done manually.

Alternatively, the great success of NLP today is supported by machine learning technology and huge language resources. Chatbot systems, which were previously believed to be impossible, are being developed to considerable performance levels [91]. Is the same applicable in the context of implementing emotions in robots? Here, there are two main problems. First is the question of whether a large amount of relevant emotion data can be collected. For example, this would require collecting a large amount of human physiological data and first-person view images to identify the agent’s behavior and their situation at the time that they experience different emotions. The second is the issue of individuality. Considering these problems, it is difficult to determine if the design of social emotions using machine learning is an easy direction for future research, although it at least seems like a possible approach.

In any case, the constructive approach is more important than the design approach for revealing the mechanisms of social emotions of individuals. This perspective has been considered for the remainder of the paper.

6.3. What is missing in current studies on social emotions in robotics?

First, let us summarize the difference between psychological and neurological findings, and the implementation of social emotions in current robots. From the definition of social emotions, Elster classified social emotions based on the criteria of self-other evaluations, as summarized in Table 1. The self-conscious emotion, which is a sub-category of social emotions, conveys that self-awareness is the awareness of being different from others; that is, self-other discrimination, is significant. Thus, regarding social emotions, the existence of others is considered an important factor in creating social emotions. However, the papers listed in Table 4, which currently deal with social emotions, do not include the elements of others in their definitions of emotions. These studies assume a context of human–robot interaction (HRI), at which point each robot behaves in the social context of the interaction.

From a perspective based on psychological findings, factors such as others, groups, and evaluations through others, influence the emergence of social emotions. For example, in the ‘It–Me’ axis shown in Figure 4, social emotions are categorized according to different factors, such as whether the emotion is directed toward oneself or the other. According to neurological findings, the insula (which acts as a hub in emotional activities), PSTS, TPJ, and DMPFC (which is involved in mentalizing and acquiring the perspective of others) are involved in interpersonal and social emotions. According to Table 2, the active brain regions are different between individual emotions and social-interpersonal emotions; further, common but different activities occur in the brain for these different emotion types. However, the robotics studies surveyed in this paper do not mention these important points, such as acquiring the perspective of others. Because these studies focused on HRI, they are believed to address interpersonal emotions, which are a subset of social emotions.

6.4. Challenges towards implementation of social emotions

What are the necessary elements to implement social emotions in robots? From the current discussions, we believe that elements of self-other discrimination, the acquisition of the viewpoint of others, and mentalizing are necessary. Thus, the mirror neuron system [92] plays an important role. These elements have been studied as constructive approaches in cognitive developmental robotics [93,94]. However, current research has not progressed to studying social emotions.

The important point is that social emotions are deeply involved in the separation of self and others from their identification, which is the root of human sociality. That is, the understanding of others based on the mirror neuron system and the acquisition of the perspective
of others. Therefore, whether robots can realize these functions that humans have, to have or develop social emotions, is crucial. For example, the simplest engineering realization of a mirror neuron system would be to use human pose estimation techniques such as OpenPose [95, 96]. By using such an algorithm, the movements of others can be projected and recognized on the movements of one’s own joints.

Furthermore, the Generative Query Network (GQN) [97] is a technology that can generate viewpoint images at various positions in the three-dimensional world. For example, using GQN it is possible to estimate the appearance of the world at a particular position from the position information of others. Therefore, in principle and from an engineering perspective, the viewpoint of others can be acquired. These recent technological advances through deep learning are crucial factors for creating social emotions. In the future, it will be necessary to study, through robots, mechanisms that develop into social emotions by linking self-other discrimination, acquisition of the perspective of others, and mentalizing centered on the mirror neuron system with emotions, which all involve conceptualizations of the physical body.

Additionally, the study of empathy in robots is important. For example, Asada proposed a developmental model of artificial empathy [98] and described the development of self-other cognition. First, self-awareness occurs by manipulating objects. After synchronization with other persons using mirror neurons, the other person behaves differently, and self-other discrimination occurs. Further, Asada explained that this factor could generate emotions, such as envy and schadenfreude. Empathy would therefore be considered as a type of synchronization mechanism, although it is believed that various emotions are generated when changing from synchronization to desynchronization.

### 6.5. Challenges facing emotion development in robots

The authors constructed an emotion model to create social emotions with robots [10]. In this study, we argued that when an action is output, an emotional category is formed by categorical input (for example, language) from another person. We simulated emotional differentiation using a task that mimics the interaction between a caregiver and a child. In that study, only basic emotions were addressed; however, according to the idea of Lewis mentioned above, after the emergence of basic emotions, self-other discrimination is performed, and then social emotions can emerge. Therefore, we believe that social emotions can be achieved by realizing the separation of self and others with this model.

Simply put, there is a possibility that social emotions can emerge by integrating the self-other separation algorithm, as described in Section 6.4, for example, [94], with the authors’ algorithm. Whether it has human-like basic emotions and social emotions depends on the body and environment of the robot in which it is implemented. The design of the robot body, including soft robots for human-like emotions, is an important research direction.

Furthermore, this is a problem related to the intelligence of robots that integrate various senses and decisions, not just emotions. Thus, we believe that it is necessary to study which types of bodies, environments, interactions, and algorithms produce which types of intelligence with an actual robot. We believe it is necessary to connect the robot technology realized in this manner to the moral problems, as discussed in Section 6.7.

### 6.6. Social constructivist view of emotions when employing developmental approach

As mentioned in Section 3.4, emotions are formed under the influence of social interactions and culture. Society and culture seem to have a great influence, especially on social emotions. Therefore, incorporating such social influences into the technical elements mentioned in Section 6.4 is indispensable for the study of social emotions.

From the developmental psychology perspective, specifically in Vygotsky’s view, children need the help of others, especially in the zone of proximal development (ZPD). ZPD represents the difference between what a child could accomplish when acting alone and with support from another person and/or cultural artifacts [99]. At first, children cannot perform tasks without others’ help, but eventually, they internalize their knowledge and perform tasks on their own. Vygotsky’s concept can be used to explain the acquisition of high-level functions, such as language, which cannot be learnt unless taught. In other words, high-level functions are generally learnt with the help of others and gradually internalized [100]. This indicates that the involvement of others is important during the development process. Therefore, the existence of these other people and society is indispensable for developing social emotions. In the context of machine learning, this could be related to curriculum learning [101]. In the curriculum consideration, it is indispensable to have people interact with each other.

However, it is difficult to constructively reproduce the relationship with society and culture in an experimental setting. This is also related to language learning, and it is believed to be necessary to build intelligence as a whole. For that purpose, the approach of symbol emergence in robotics (SER) is of great help [102, 103]. Even in SER, the
relationship between society and culture is a problem that has just begun to be addressed. Therefore, to incorporate emotional problems, it is necessary to solve many of the existing problems, including the improvement of robot performance. The concept of sharing among multiple individuals handled by SER includes ‘intersubjectivity.’ It is useful to approach emotions considering these factors. More importantly, it is necessary to clarify new findings and problems by comparing the emotions realized by engineering with the emotions examined in humans. In doing so, the constructive approach will play an essential role.

6.7. Moral emotions in robotics

In the section on the definition of social emotions, moral emotions were introduced as a subcategory of social emotions; however, they are not covered in this study. Moral emotion is an interesting topic in view of recent attention to morality in HRI [104–106]. Moral emotions are triggered by the perception of moral violations in the context of interpersonal events, and they can guide moral behavior. Moral emotion is an important factor in encouraging the moral behavior of the robot. This category includes shame, guilt, regret, embarrassment, contempt, anger, disgust, gratitude, envy, jealousy, schadenfreude, admiration, sympathy, and empathy. Empathy, which is treated as an element that creates social emotions, is treated as a part of moral emotions. Moreover, other complicated emotions, such as schadenfreude, are also included in moral emotions. However, how to address these differences in each definition remains controversial.

The following can be considered as issues in future moral emotion research in robotics: (1) Is it possible to make a robot moral, and for robots to understand morals, by implementing moral emotions? (2) Can we better understand the mechanism of moral emotion through robots? (3) Can we understand how to nurture people’s morals and make people behave more morally? Considering the coexistence of humans and robots, it is necessary to discuss both sides of the morals of humans and robots in an integrated manner.

7. Conclusions

This survey paper examined research on social emotions in the area of robotics. We discussed the definitions of social emotions, psychological–neurological findings, how social emotions are treated in robotics, the gap between robotics and knowledge in other research fields, and challenges for implementing social emotions in robots. This research field is still developing. A major issue is how to implement social emotions in robots while considering their relationship with basic emotions. We believe this will help elucidate the mechanisms underlying emotional development. Furthermore, we hope to better understand the morals of humans and robots through social emotions, and to explore ways which lead to a better future in which humans and robots can coexist harmoniously.

Note

1. There exist several definitions of learning and development. In the context of this study, development can be defined as the acquisition of functions, and each acquisition process can be considered learning. In other words, emotional development implies the acquisition of emotional functions through learning. Because development is supported by learning, this study does not distinguish between the two.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by JSPS KAKENHI Grant-in-Aid for Early-Career Scientists (20K19907), JSPS KAKENHI Grant-in-Aid for Scientific Research on Innovative Areas (20H05565) and JSPS KAKENHI Grant-in-Aid for Scientific Research (A) (21H04420).

Notes on contributors

Chie Hieida received her BE, ME, and PhD degrees from the University of Electro-Communications in 2013, 2015, and 2019, respectively. From 2016 to 2019, she was a research fellow of the Japan Society for the Promotion of Science. From 2016 to 2019, she was a specially appointed researcher at the Symbolic Intelligent Systems Research Center, Institute for Open and Transdisciplinary Research Initiatives, Osaka University. Since 2020, she has been with the Division of Information Science, Graduate School of Science and Technology, Nara Institute of Science and Technology as a assistant professor. She has received IEEE Robotics and Automation Society Japan Chapter Young Award. Her research is focused on modeling of emotions for robots.

Takayuki Nagai received his BE, ME, and PhD degrees from the Department of Electrical Engineering, Keio University, in 1993, 1995, and 1997, respectively. Since 1998, he had been with the University of Electro-Communications (UEC), and from 2018 he has been a professor of the graduate school of Engineering Science, Osaka University. From 2002 to 2003, he was a visiting scholar at the Department of Electrical Computer Engineering, University of California, San Diego. He also serves as a specially appointed professor at Artificial Intelligence Exploration Research Center, UEC. He has received IROS Best Paper Award Finalist, Advanced Robotics Best Paper Award, Advanced Robotics Best Survey Paper Award, JSJAI Best Paper Award, etc. His research interests include intelligent
robotics, cognitive developmental robotics, and robot learning. He aims at realizing flexible and general intelligence like human by combining machine learning and robot technologies.

References

[1] Goleman D. Emotional intelligence. London: Bloomsbury Publishing PLC; 1996.
[2] Man K, Damasio A. Homeostasis and soft robotics in the design of feeling machines. Nat Mach Intell. 2019 Oct;1:446–452.
[3] Cavallo F, Semeraro F, Fiorini L, et al. Emotion modelling for social robotics applications: a review. J Bionic Eng. 2018;15(2):185–203.
[4] Moerland TM, Broekens J, Jonker CM. Emotion in reinforcement learning agents and robots: a survey. Mach Learn. 2018 Feb;107(2):443–480.
[5] Lewis M. Embarrassment: the emotion of self-exposure and evaluation. In: Self-conscious emotions: the psychology of shame, guilt, embarrassment, and pride. New York: Guilford Press; 1995. p. 198–218.
[6] Barrett FL. How emotions are made: the secret life of the brain. Boston: Houghton Mifflin Harcourt; 2017.
[7] Moriguchi Y, Komaki G. Neuroimaging studies of alexithymia: physical, affective, and social perspectives. Biopsychosoc Med. 2013;7(1):8.
[8] Ogata T, Matsuyama Y, Komiya T, et al. Development of emotional communication robot: Wamobea-2r-experimental evaluation of the emotional communication between robots and humans. In: Proceedings. 2000 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2000) (Cat. No. 00CH37113); Vol. 1. IEEE; 2000. p. 175–180.
[9] Pfeifer R. Emotions in robot design. In: Proceedings of 1993 2nd IEEE International Workshop on Robot and Human Communication. IEEE; 1993. p. 408–413.
[10] Hieida C, Horii T, Nagai T. Deep emotion: a computational model of emotion using deep neural networks. Preprint; 2018. arXiv:1808.08447.
[11] Mitsuosshi S. Pepper’s emotions – towards artificial ego-. J Jpn Soc Artif Intell. 2021;36(1):34–42. In Japanese.
[12] Wada K, Shibata T, Kawaguchi Y. Long-term robot therapy in a health service facility for the aged-a case study for 5 years. In: 2009 IEEE International Conference on Rehabilitation Robotics. IEEE; 2009. p. 930–933.
[13] Breazeal CL. Designing sociable robots. Cambridge: MIT press; 2002.
[14] Zecca M, Endo N, Momoki S, et al. Design of the humanoid robot kobian-preliminary analysis of facial and whole body emotion expression capabilities. In: 2008 8th IEEE-RAS International Conference on Humanoid Robots. Humanoids 2008. IEEE; 2008. p. 487–492.
[15] GrooveX. Official website. [Accessed 2021 Jul]. Available from: https://lovot.life/.
[16] Hieida C, Matsuda H, Kudoh S, et al. Action elements of emotional body expressions for flying robots. In: 2016 11th ACM/IEEE International Conference on Human-Robot Interaction (HRI). IEEE; 2016. p. 439–440.
[17] Damasio A. Looking for spinoza: joy, sorrow, and the feeling brain. San Diego, CA: Harcourt; 2003.
[18] Ekman P, Wallace FV. Constants across cultures in the face and emotion. J Pers Soc Psychol. 1971;17(2):124–129.
[19] Russell JA. A circumplex model of affect. J Pers Soc Psychol. 1980;39(6):1161.
[20] Mehrabian A, Russell JA. An approach to environmental psychology. Cambridge: The MIT Press; 1974.
[21] Breazeal C, Scassellati B. How to build robots that make friends and influence people. In: Proceedings 1999 IEEE/RSJ International Conference on Intelligent Robots and Systems. Human and Environment Friendly Robots with High Intelligence and Emotional Quotients (Cat. No. 99CH36289); Vol. 2. IEEE; 1999. p. 858–863.
[22] Plutchik R. A psychoevolutionary theory of emotions. Soc Sci Inform. 1982;21(4-5):529–553.
[23] James W. What is an emotion? Mind. 1884;os-IX(34):188–205. DOI:10.1093/mind/os-IX.34.188.
[24] Terasawa Y, Fukushima H, Umeda S. How does interoceptive awareness interact with the subjective experience of emotion? an FMRI study. Hum Brain Mapp. 2013 Mar;34(3):598–612.
[25] Koelsch S, Jacobs AM, Menninghaus W, et al. The quartet theory of human emotions: an integrative and neurofunctional model. Phys Life Rev. 2015;13:1–27. Available from: http://www.sciencedirect.com/science/article/pii/S1571064515000500.
[26] Damasio AR, Everitt BJ, Bishop D. The somatic marker hypothesis and the possible functions of the prefrontal cortex [and discussion]. Philos Trans R Soc B Biol Sci. 1996;351(1346):1413–1420.
[27] Friston KJ, Daunizeau J, Kilner J, et al. Action and behavior: a free-energy formulation. Biol Cybern. 2010 Mar;102(3):227–260. DOI:10.1007/s00422-010-0364-z.
[28] Seth AK, Friston KJ. Active interoceptive inference and the emotional brain. Philos Trans R Soc B Biol Sci. 2016;371(1708). Available from: http://rstb.royalsocietypublishing.org/content/371/1708/20160007.
[29] LeDoux J. The emotional brain: the mysterious underpinnings of emotional life. New York: Simon and Schuster; 1998.
[30] Dutton DG, Aron AP. Some evidence for heightened sexual attraction under conditions of high anxiety. J Pers Soc Psychol. 1974;30(4):510–517.
[31] Friston KJ, Daunizeau J, Kiebel SJ. Reinforcement learning or active inference? PLoS ONE. 2009 Jul;4(7):1–13. DOI:10.1371/journal.pone.0006421.
[32] Yakovlev P. Motility, behavior and the brain; stereodynamic organization and neural co-ordinates of behavior. J Nerv Ment Dis. 1948;107:313–335. Available from: https://ci.nii.ac.jp/naid/10018974380/.
[33] Papez J. A proposed mechanism of emotion. Arch Neurol Psychiatry. 1937;79:217–224. Available from: https://ci.nii.ac.jp/naid/10012838531/.
[34] Mendoza J, Foundas A. Clinical neuroanatomy: a neurobehavioral approach. New York: Springer New York; 2007. Available from: https://books.google.co.jp/books? id=HsvUwLcRrO8C.
[35] Averill JR. Chapter 12 – a constructivist view of emotion. In: Plutchik R, Kellerman H, editors. Theories of emotion. Academic Press; 1980. p. 305–339. Available from: https://www.sciencedirect.com/science/article/pii/B9780125587013500181.
[36] Boiger M, Mesquita B. Emotion science needs to account for the social world. Emot Rev. 2012;4(3):236–237. DOI:10.1177/1754073912439789
[37] Boiger M, Mesquita B. The construction of emotion in interactions, relationships, and cultures. Emot Rev. 2012;4(3):221–229. DOI:10.1177/1754073912439765
[38] Mesquita B, Frijda N. Cultural variations in emotions: a review. Psychol Bull. 1992 Sep;112:179–204.
[39] Lim N. Cultural differences in emotion: differences in emotional arousal level between the east and the west. Integr Med Res. 2016;5(2):105–109. Available from: https://www.sciencedirect.com/science/article/pii/S2213422016300191.
[40] Harré R. Emotions as cognitive-affective-somatic hybrids. Emot Rev. 2009;1(4):294–301. DOI:10.1177/1754073909338304
[41] Cornelius R. Theoretical approaches to emotion. ISCA Tutorial and Research Workshop on Speech and Emotion; 2000 Jan. p. 3–10.
[42] Arangether M. Reconstructing the social constructionist view of emotions: from language to culture, including nonhuman culture. J Theory Soc Behav. 2017;47:244–260. doi:10.1111/jtsb.12132.
[43] Parkinson B, Fischer A, Manstead AS. Emotion in social relations: cultural, group, and interpersonal processes. New York: Psychology Press; 2005.
[44] Hareli S, Parkinson B. What’s social about social emotions? J Theory Soc Behav. 2008;38(2):131–156.
[45] Elster J. Strong feelings: emotion, addiction, and human behavior. Cambridge: The MIT Press; 1999.
[46] Niedenthal PM, Brauer M. Social functionality of human emotion. Annu Rev Psychol. 2012;63:259–285.
[47] Hoffman ML. Empathy and moral development: implications for caring and justice. Cambridge: Cambridge University Press; 2001.
[48] Manstead A, Oatley K. Collective guilt: international perspectives. Cambridge: Cambridge University Press; 2004.
[49] Miller RS. Is embarrassment a blessing or a curse. In: The self-conscious emotions: theory and research. New York: Guilford Press; 2007. p. 245–262.
[50] Higuchi M, Fukada H. Comparison of four factors related to embarrassment in nontypical situations. Psychol Rep. 2008;102(1):328–334.
[51] Tesser A, Campbell J, Smith M. Friendship choice and performance: self-evaluation maintenance in children. J Pers Soc Psychol. 1984;46(3):561.
[52] Fischer KW, Tangney JP. Self-conscious emotions and the affect revolution: framework and overview. In: Self-conscious emotions: the psychology of shame, guilt, embarrassment, and pride. New York: Guilford Press; 1995. p. 3–22.
[53] Tracy JL, Robins RW. Self-conscious emotions: where self and emotion meet. In: The self. New York: Guilford Press; 2007. p. 187–209.
[54] De Rivera J, Grinkis C. Emotions as social relationships. Motiv Emot. 1986;10(4):351–369.
[55] Koush Y, Pichon S, Eickhoff SB, et al. Brain networks for engaging oneself in positive-social emotion regulation. NeuroImage. 2019;189:106–115.
[56] Immordino-Yang MH. Me, my “self” and you: neuropsychological relations between social emotion, self-awareness, and morality. Emot Rev. 2011;3(3):313–315.
[57] Klapwijk ET, Goddings AL, Heyes SB, et al. Increased functional connectivity with puberty in the mentalising network involved in social emotion processing. Horm Behav. 2013;64(2):314–322.
[58] Grecucci A, Theuninck A, Frederickson J, et al. Mechanisms of social emotion regulation: from neuroscience to psychotherapy. In: Emotion regulation: processes, cognitive effects and social consequences. New York: Nova Science Publishers; 2015. p. 57–84.
[59] Yan F, Iliyasu AM, Hirota K. Emotion space modelling for social robots. Eng Appl Artif Intell. 2021 Apr;100:Article 104178.
[60] Jacobs E, Broekens J, Jonker C. Emergent dynamics of joy, distress, hope and fear in reinforcement learning agents. In: Adaptive Learning Agents Workshop at AAMAS2014; 2014.
[61] Shi X, Wang Z, Zhang Q. Artificial emotion model based on neuromodulators and Q-learning. In: Deng W, editor. Future control and automation. Lecture notes in electrical engineering, Vol. 172. Berlin: Springer; 2012.
[62] El-Nasr MS, Yen J, Loerger TR. Flame-fuzzy logic adaptive model of emotions. Auton Agent Multi Agent Syst. 2000;3(3):219–257.
[63] Moussa MB, Magnenat-Thalmann N. Toward socially responsible agents: integrating attachment and learning in emotional decision-making. Comput Animat Virtual Worlds. 2013;24(3-4):327–334.
[64] Moerland TM, Broekens J, Jonker CM. Fear and hope emerge from anticipation in model-based reinforcement learning. In: IJCAI, New York; 2016. p. 848–854.
[65] Lahnstein M. The emotive episode is a composition of anticipatory and reactive evaluations. In: Proceedings of the AISB’05 Symposium on Agents that Want and Like, Hatfield; 2005. p. 62–69.
[66] Hasson C, Gauvies P, Bouchenna S. Emotions as a dynamical system: the interplay between the meta-control and communication function of emotions. Palady. 2011;2(3):111–125.
[67] Huang X, Du C, Peng Y, et al. Goal-oriented action planning in partially observable stochastic domains. In: 2012 IEEE 2nd International Conference on Cloud Computing and Intelligence Systems; Vol. 3. IEEE; 2012. p. 1381–1385.
[68] Tsankova DD. Emotionally influenced coordination of behaviors for autonomous mobile robots. In: Proceedings First International IEEE Symposium Intelligent Systems; Vol. 1. IEEE; 2002. p. 92–97.
[69] Goerke N. Emobot: a robot control architecture based on emotion-like internal values. London: INTECH Open Access Publisher Rijeka; 2006.
[70] Blanchard AJ, Canamero L. From imprinting to adaptation: building a history of affective interaction. 2005. Available from: http://cogprints.org/4939/.
[71] Doshi P, Gmytrasiewicz P. Towards affect-based approximations to rational planning: a decision-theoretic perspective to emotions. In: Working Notes of the Spring Symposium on Architectures for Modeling Emotion: Cross-Disciplinary Foundations; 2004.
[72] Gmytrasiewicz PJ, Lisetti CL. Emotions and personality in agent design. In: Proceedings of the First International
Joint Conference on Autonomous Agents and Multiagent Systems: Part 1, Bologna; 2002. p. 360–361.

[73] Lim A, Okuno HG. The mei robot: towards using mother-erse to develop multimodal emotional intelligence. IEEE Trans Auton Ment Dev. 2014;6(2):126–138.

[74] Bera A, Randhavane T, Manocha D. The emotionally intelligent robot: improving socially-aware human prediction in crowded environments. In: Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition Workshops, Long Beach; 2019.

[75] Fang B, Zhang Q, Wang H, et al. Personality driven task allocation for emotional robot team. Int J Mach Learn Cybern. 2018;9(12):1955–1962.

[76] Claret JA, Venture G, Basañez L. Exploiting the robot kinematic redundancy for emotion conveyance to humans as a lower priority task. Int J Soc Robot. 2017;9(2):277–292.

[77] Jing H, Lun X, Dan L, et al. Cognitive emotion model for eldercare robot in smart home. China Commun. 2015;12(4):32–41.

[78] Lun X, Xin L, Xiujuan Y, et al. Cognitive regulation and emotion modeling for micro-expression. Int J Control Autom. 2016;9:361–372.

[79] Liu X, Xie L, Wang Z. Empathizing with emotional robot based on cognition reappraisal. China Commun. 2017;14(9):100–113.

[80] Tsourtici C, Weiss A, Wac K, et al. Designing emotionally expressive robots: a comparative study on the perception of communication modalities. In: Proceedings of the 5th International Conference on Human Agent Interaction, Bielefeld; 2017. p. 213–222.

[81] Bartneck C, Bleeker T, Bun J, et al. The influence of robot anthropomorphism on the feelings of embarrassment when interacting with robots. Paladyn. 2010;1(2):109–115.

[82] Aymerich-Franch L, Kishore S, Slater M. When your robot avatar misbehaves you are likely to apologize: an exploration of guilt during robot embodiment. Int J Soc Robot. 2019;12:217–226.

[83] Hegel F, Eysel F, Wrede B. The social robot ‘flöbi’: key concepts of industrial design. In: 19th International Symposium in Robot and Human Interactive Communication. IEEE; 2010. p. 107–112.

[84] Oliveira R, Arriaga P, Correia F, et al. The stereotype content model applied to human-robot interactions in groups. In: 2019 14th ACM/IEEE International Conference on Human-Robot Interaction (HRI). IEEE; 2019. p. 123–132.

[85] Samani H. The evaluation of affection in human-robot interaction. Kybernetes. 2016;45(8):1257–1272.

[86] Huahu X, Jue G, Jian Y. Application of speech emotion recognition in intelligent household robot. In: 2010 International Conference on Artificial Intelligence and Computational Intelligence, Sanya; Vol. 1; 2010. p. 537–541.

[87] Terada K, Yamauchi A, Ito A. Artificial emotion expression for a robot by dynamic color change. In: 2012 IEEE RO-MAN: The 21st IEEE International Symposium on Robot and Human Interactive Communication. IEEE; 2012. p. 314–321.

[88] Jung MF. Affective grounding in human-robot interaction. In: 2017 12th ACM/IEEE International Conference on Human-Robot Interaction; HRI. IEEE; 2017. p. 263–273.

[89] Athar A, Khan MS, Ahmed K, et al. A fuzzy inference system for synergy estimation of simultaneous emotion dynamics in agents. Int J Eng Sci. 2011;2(6):35–41.

[90] Mikolov T, Chen K, Corrado G, et al. Efficient estimation of word representations in vector space. 2013.

[91] Xu J, Szlam A, Weston J. Beyond goldfish memory: long-term open-domain conversation. 2021.

[92] Rizzolatti G, Sinigaglia C. Mirrors in the brain: how our minds share actions and emotions. Oxford: Oxford University Press; 2008.

[93] Nagai Y, Kawai Y, Asada M. Emergence of mirror neuron system: immature vision leads to self-other correspondence. In: 2011 IEEE International Conference on Development and Learning (ICDL), Frankfurt; Vol. 2; 2011. p. 1–6.

[94] Lanillos P, Pagés J, Cheng G. Robot self/other distinction: active inference meets neural networks learning in a mirror. CoRR. 2020;abs/2004.05473. Available from: https://arxiv.org/abs/2004.05473.

[95] Cao Z, Hidalgo Martínez G, Simon T, et al. Openpose: realtime multi-person 2d pose estimation using part affinity fields. IEEE Trans Pattern Anal Mach Intell. 2021;43(1):172–186.

[96] Kudo Y, Ogaki K, Matsui Y, et al. Unsupervised adversarial learning of 3d human pose from 2d joint locations. 2018.

[97] Eslami SMA, Jimenez Rezende D, Besse F, et al. Neural scene representation and rendering. Science. 2018;360(6394):1204–1210. Available from: https://science.sciencemag.org/content/360/6394/1204.

[98] Asada M. Towards artificial empathy. Int J Soc Robot. 2015;7(1):19–33.

[99] Lantolf JP. Sociocultural theory and second language learning. Vol. 78. Oxford: Oxford university press; 2000.

[100] Diaz RM, Neal CJ, Amaya-Williams M. The social origins of self-regulation. 1992.

[101] Soviany P, Ionescu RT, Rota P, et al. Curriculum learning: a survey. 2021.

[102] Taniguchi T, Nagai T, Nakamura T, et al. Symbol emergence in robotics: a survey. Adv Robot. 2016;30(11–12):706–728. DOI:10.1080/01691864.2016.1164622.

[103] Taniguchi T, Mochihashi D, Nagai T, et al. Survey on frontiers of language and robotics. Adv Robot. 2019;33(15-16):700–730. DOI:10.1080/01691864.2019.1632223.

[104] Brsic D, Kidokoro H, Suehiro Y, et al. Escaping from children’s abuse of social robots. Vol. 2015. 2015 Mar. p. 59–66.

[105] Nomura T, Kanda T, Kidokoro H, et al. Why do children abuse robots? Interact Stud. 2016 Dec;17:347–369.

[106] Bartneck C, Keijser M. The morality of abusing a robot. Paladyn. 2020;11(1):271–283. DOI:10.1515/pjbr-2020-0017.