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Review article

Development of artificial empathy

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ABSTRACT

We have been advocating cognitive developmental robotics to obtain new insight into the development of human cognitive functions by utilizing synthetic and constructive approaches. Among the different emotional functions, empathy is difficult to model, but essential for robots to be social agents in our society. In my previous review on artificial empathy (Asada, 2014b), I proposed a conceptual model for empathy development beginning with emotional contagion to envy/schadenfreude along with self/other differentiation. In this article, the focus is on two aspects of this developmental process, emotional contagion in relation to motor mimicry, and cognitive/affective aspects of the empathy. It begins with a summary of the previous review (Asada, 2014b) and an introduction to affective developmental robotics as a part of cognitive developmental robotics focusing on the affective aspects. This is followed by a review and discussion on several approaches for two focused aspects of affective developmental robotics. Finally, future issues involved in the development of a more authentic form of artificial empathy are discussed.

Contents

1. Introduction

Empathic behaviors towards humans are expected for social robots to realize true communication, and several attempts have been made to address specific contexts (e.g., see Leite et al., 2013 for survey of context specific behavior design). These attempts have revealed that the scope for empathic interaction seems limited and is difficult to extend (generalize) to different contexts. The importance of "affectivity" in human–robot interactions (HRIs) was recently addressed in a brief survey from the viewpoint of affective computing (Riek and Robinson, 2009). However, a deeper understanding of its meaning

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seems necessary to design more authentic forms of artificial empathy.

Empathic behaviors are thought to be learnt through social interactions with humans in the framework of (cognitive) developmental robotics (Lungarella et al., 2003; Asada et al., 2009). Asada et al. (2009) hypothesized that affective development was a part of cognitive development, and with regard to affective aspects they argued "artificial sympathy" (Asada et al., 2012) and proposed classifying affective developmental robotics as part of cognitive developmental robotics to accurately design artificial empathy (Asada, 2014a,b). Among the several issues argued in the previous review (Asada, 2014b), I focus on two aspects in designing the development of artificial empathy along with several possible approaches.

The rest of the article is organized as follows. The next section provides a summary of the review (Asada, 2014b) beginning with emotional contagion to envy/schadenfreude, followed by an introduction to affective developmental robotics as an approach to the developmental design of artificial empathy. Next, a review and discussion on several approaches for two focused aspects of affective developmental robotics, emotional contagion in relation to motor mimicry and cognitive/affective aspects of empathy follow. Finally, future issues regarding development of a more authentic form of artificial empathy are discussed.

2. Development and evolution of empathy

A previous study attempted to define "empathy" and "sympathy" to clarify the approach for designing an artificial system because these two emotions are often mistaken for each other (Asada et al., 2012). However, their attempt did not accurately discriminate between these terms from a neuroscience and biobehavioral perspective. Asada published a more accurate review of artificial empathy (Asada, 2014b), based on reviews from neuroscience perspectives that include ontogeny, phylogeny, brain mechanisms, context, and psychopathology as outlined by Gonzalez-Liencresa et al. (2013).

First, they claimed that the manifold facets of empathy are explored in neuroscience from simple emotional contagion to higher cognitive perspective-taking, and a distinct neural network of empathy comprises both phylogenetically older limbic structures and neocortical brain areas. These suggest that emotional contagion is mainly based on phylogenetically older limbic structures, while higher cognitive perspective-taking is based on neocortical brain areas. Next, they pointed out that neuropeptides such as oxytocin and vasopressin, as well as opioidergic substances, play a role in modulating empathy. These kinds of neuromodulation may regulate levels of empathy both positively and negatively.

A wide definition of empathy may encompass from emotional contagion to envy/schadenfreude as mentioned in Section 2.1. However, a restricted definition of empathy is simply the ability to form an embodied representation of another's emotional state while simultaneously being aware of the causal mechanism that induced that emotional state (Gonzalez-Liencresa et al., 2013). This suggests that the empathizer has interoceptive awareness of his or her own bodily states and is able to distinguish between the self and others, which is the underlying principle of empathy-related terms from an evolutionary viewpoint. In this regards, the narrow definition may hold true only for cognitive empathy.

2.1. From emotional contagion to envy/schadenfreude

Emotional contagion is an evolutionary precursor that enables animals to share their emotional states. However, animals do not understand what aroused an emotional state in another. Therefore, emotional contagion seems early, automatic, unconscious, and fundamental for later empathy-related mental states such as emotional/cognitive empathy, sympathy, and so on.

Both emotional and cognitive empathy (EE and CE) may only occur in animals with self-awareness such as primates, and perhaps, elephants, and dolphins although presence of self-awareness in these species remains controversial.[1] Neural representations for such complex emotions and self-awareness are localized in the anterior cingulate cortex and the anterior insula (Craig, 2003). EE is an older phylogenetic trait than CE, and allows individuals to form a representation of others' feelings by sharing these feelings through embodied simulation, a process that is triggered by emotional contagion. While, EE considerably overlaps in definitional terms with "theory of mind" (Premack and Woodruff, 1978) which present in apes and humans (Edgar et al., 2012), and requires perspective taking and mentalizing (de Waal, 2008).

Unlike emotional contagion that does not require reasoning about the cause of aroused emotions in others, both EE and CE require distinction between one's own and others' mental states and forms of a representation of one's own embodied emotions.

Sympathy and compassion seem similar to empathy in terms of emotional states, but differ in terms of the responses produced in reference to others' emotional states. Both require the ability to form representations of others' emotions, even though the emotion is not necessarily shared; however, in empathy, the emotional states are synchronized (Goetz et al., 2010). This implies that sympathy and compassion may require the control of one's own emotions in addition to this self-other discrimination (emotion regulation).

There seem to be two kinds of emotion regulation extensions. In in-group/out-group cognition sympathy and/or compassion is shown toward in-group members, whereas opposite feelings are experienced in response to out-group members. This is called envy/schadenfreude and evolved in response to the selection pressure of social coherence among early hunter-gatherers (Gonzalez-Liencresa et al., 2013).

The second type requires metacognition, which realizes a kind of vicariousness, that is, an imagination of the self as others. A typical example is a situation where we enjoy sad music (Kawakami et al., 2013a,b). The objective-(virtualized) self perceives sad music as sad (perceived emotion), while the subjective-self feels pleasant emotions by listening to such music (felt emotion). This seems to be a form of emotion control by metacognition of the self as others.

2.2. Schematic diagram of empathy-related terms

Fig. 1 shows a schematic depiction of the terminology used in the context of empathy thus far. The horizontal axis indicates the "conscious level" spanning from "unconscious" (left) to "conscious with self-other distinction" (right). The vertical axis indicates "physical/motor" (bottom) and "emotional/mental" (top) contrasts. Generally, these axes show discrete levels such as "conscious/unconscious" or "physical/mental." However, terminology in the context of empathy could be distributed in the zones where discrimination between these dichotomies could be difficult. In addition, there are three points of mention:

- In this representation, the location indicates the relative weight between both dichotomies, and the arrow to the left (the top)

[1] e.g., visit http://www.world-of-lucid-dreaming.com/10-animals-with-self-awareness.html.

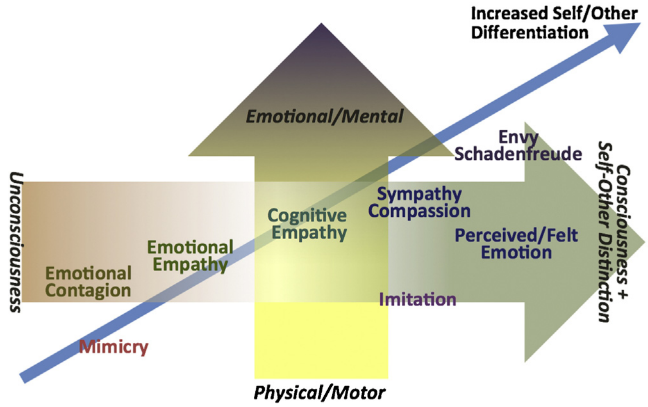

Fig. 1. Schematic depiction of empathy terminology.
Adapted from Fig. 2 in Asada (2014b).

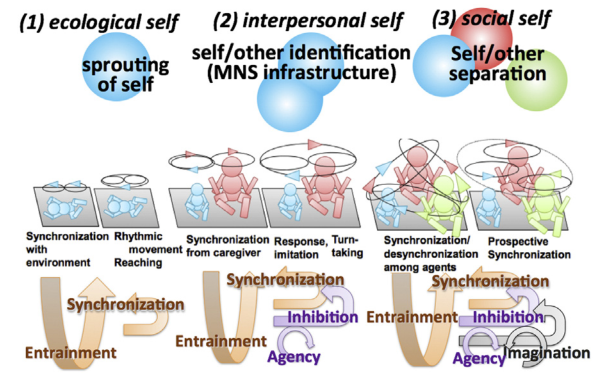

Fig. 2. The developmental process of establishing the concept of the self and other(s) and their expected underlying mechanisms.

implies that the conscious (mental) level includes the unconscious (physical) one. In other words, the conscious (mental) level exists on the unconscious (physical) level but not vice versa.

- The direction from left (bottom) to right (top) indicates the evolutionary process, as well as the developmental process if "ontogeny recapitulates phylogeny." Therefore, a whole story of empathy follows a gentle slope from the bottom-left to the top-right.
- The above arrow also indicates the developmental process of self/other differentiation (de Waal, 2008), the details of which are discussed in Asada (2014b).

3. Affective developmental robotics

Asada et al. advocated cognitive developmental robotics (CDR) (Asada et al., 2001, 2009), assuming that empathy development could be a part of CDR. Actually, one survey (Asada et al., 2009) introduced a study of empathic development (Watanabe et al., 2007) as an example of CDR. For our purposes, we will rephrase a part of CDR as affective developmental robotics (ADR).[2] Therefore, ADR follows the approach of CDR, particularly focusing on affective development. First, we give a brief overview of ADR following CDR and then discuss how to approach issues of empathic development.

3.1. Concepts and approaches of ADR

Based on the assumptions of CDR, ADR aims to understand human affective developmental processes with synthetic or constructive approaches. Its core idea is "physical embodiment," and more importantly, "social interaction" that enables information structuring through interactions with the environment. This includes other agents, and affective development is thought to seamlessly connect both aspects. The most related disciplines are neuroscience (micro structure for internal mechanisms) and developmental psychology (macro structure based on behavior observations), aspects both have been overlapping with each other in social neuroscience.

Two main approaches are (A) computational model construction for affective development including verification with virtual/real agents and (B) offering new means or data to better understand the human developmental process, including providing a robot as a reliable reproduction tool in (psychological) experiments.

3.2. Development of self-other cognition

The top panel of Fig. 2 shows the developmental process of establishing the concepts of self and other(s), partially following Neisser's definition of the "self" (Neisser, 1993). The term "synchronization" is used to explain how this concept develops through interactions with the external world, including other agents. As Fig. 1 shows, the target for synchronization changes starting from physical objects, then, other's movements, and finally other's mental states. Accordingly, the behavior changes from physical primitive movements such as early rhythmic motions, actions consisting of primitive movements, and actions caused by mental states such as empathic/sympathetic facial expressions and even altruistic behaviour. We hypothesize that the three stages of self-development that are actually seamlessly connected. More details of these stages process are discussed in (Asada, 2011).

3.3. Relationship between development of self-other cognition and empathy

During the three stages in Fig. 2, synchronizations in different levels occur.

1. Emotional contagion: as described in later sections, emotional contagion is closely related to motor mimicry, an automatic reaction of imitating the other's primitive movements. Therefore, the level of this type of synchronization is in terms of primitive movements such as cyclic ones.
2. Emotional and cognitive empathy: through emotional contagion (motor mimicry) and development of self-awareness and perspective taking, a variety of mental states are induced by observing (estimating) the other's mental state. The induced mental state is the same as that of the others. In this sense, this type of the synchronization is in terms of the mental state.
3. Sympathy and compassion: unlike emotional and cognitive empathy, the induced emotional states of sympathy and compassion are different from the other's one. This means that once the agent understands the other's state (synchronization), and then he or she feels different ones, such as pity or sorrow (de-synchronization).

The formation of these different (de-)synchronizations accompanies the developmental process of self-other cognition as mentioned below.

Fig. 2 (bottom) indicates the mechanisms corresponding to these three stages. The common structure is a mechanism of "entrainment." The target with which the agent synchronizes may change from objects to others, and along with these changes, more

[2] ADR starts from a part of CDR but is expected to extend beyond the current scope of CDR.

substructures are added to the synchronization system in order to obtain higher concepts and control of self/other cognition.

In the first stage, a simple synchronization with objects is realized, while in the second stage, a caregiver initiates the synchronization. A representation of the agent (agency) is gradually established, and a substructure of inhibition is added for turn-taking. Finally, more synchronization control skill is added to switch from one person (e.g., father) to another (e.g., mother) as mentioned above. Imaginary actions toward objects could be realized based on the sophisticated skill of switching. These substructures are not added but are expected to emerge from previous stages.

Table 1 shows the summary of the relationships among self-development, self/other discrimination (and its requirements), empathy terminology, and imitation terminology (Asada, 2014b). The imitation terminology comes from de Waal (2008) which claims the parallel evolution of imitation and empathy along with self/other discrimination, and we apply this process to the developmental process of empathy.

4. Two key aspects towards artificial empathy

From the perspective of affective developmental robotics, the early two stages are important for designing artificial empathy. These are emotional contagion and emotional/cognitive empathy.

4.1. The connection between emotional contagion and motor mimicry

As mentioned in Section 2.1, emotional contagion is automatic (unconscious). An example is an experiment with mice where one mouse-A observes another mouse receiving an electric shock accompanied by a tone. Eventually, mouse-A freezes in response to the tone even though it had never experienced the shock (Chen et al., 2009). Here, the freezing behavior is triggered by its emotional reaction and might be interpreted as a sign of emotional contagion.

de Waal (2008) proposed the evolutionary process of empathy in parallel with that of imitation starting from emotional contagion and motor mimicry. Both emotional contagion and motor mimicry are based on a type of matching referred to as perception–action matching (PAM). Beyond the precise definitions of other terms, motor mimicry requires a sort of resonance mechanism from the physical body that supplies a fundamental structure for emotional contagion (Uithol et al., 2011), and the relationship between motor mimicry and emotional contagion is the first key stage to connect physical and mental synchronizations.

Hatfield et al. (2000) defined primitive emotional contagion as the tendency to automatically mimic and synchronize facial expressions, vocalizations, postures, and movements with those of another person's and, consequently, to converge emotionally. Later, Hatfield et al. (2009) proposed a mechanism of emotional contagion consisting of three phases: mimicry, feedback, and contagion. Based on this mechanism, people tend to automatically mimic the facial expressions, vocal expressions, postures, and instrumental behaviors of those around them, and thereby to feel a weak reflection of others' emotions, and finally experience others emotions.

Sonnby-Borgstrom (2002) proposed that mimicry enables one to automatically (unconsciously) share and understand another's emotions regardless of conscious interpretation of the emotional situation. Upon classification of subjects into high- and low-empathic groups and measuring facial electromyogram (EMG) responses upon exposure to "happy" and "angry" face pictures, the high-empathic groups exhibited a positive correlation between the exposed picture and their induced emotion. Similar situations can be seen in case of the chameleon effect, which refers to unconscious mimicry of the postures, mannerisms, facial expressions, and other behaviors of one's interaction partners, such that one's behavior passively and unintentionally changes to match that of others in one's current social environment. This effect is supposed to act as a social glue because unconscious behavioral mimicry increases affiliation, which serves to foster relationships with others (Chartrand and Bargh, 1999; Lakin et al., 2003). On the other hand, subjects of the low-empathic group exhibited inverted "smiling reactions" in response to "angry" face pictures indicating that these reactions through facial feedback may act as a defense against negative feelings.

Initial evidence for involuntary pupillary contagion was found in a functional magnetic resonance imaging (fMRI) study (Harrison et al., 2006). Participants were presented with photos of sad faces with various pupil sizes. Their own pupil size was significantly smaller when they viewed sad faces with small, rather than large pupils, and the Edinger–Westphal nucleus in the brainstem, which controls pupil size, was specifically engaged by this contagious effect. Activation in this subcortical structure provides evidence that pupillary contagion occurs outside of awareness and may represent a precursor of empathy. Their data identify the neural substrates through which subconscious mirroring of another's pupil size may enhance empathic appraisal and understanding of their feelings of sadness. This study also shows the strong overlap between mimicry and emotional contagion.

These observations seem to assume that mimicry represents some sort of automatic or hardwired motor resonance with another person's affective display. However, an influence of top-down processes on mimicry is suggested. Therefore, mimicry seems to serve a social function in increasing rapport and fondness between self and others (Singer and Lamm, 2009).

There are cases in which mimicry occurs without an emotional component and other cases in which emotions are automatically elicited by observing others' emotional states without the involvement of motor mimicry. Therefore, mimicry and emotional contagion are regarded as important, yet distinct and neither necessary nor sufficient processes for the experience of empathy (Singer and Lamm, 2009).

Sperry argued that the perception–action cycle is the fundamental logic of the nervous system (Sperry, 1952). Perception and action processes are functionally intertwined; perception is a means to action and vice versa.

The discovery of mirror neurons in the ventral premotor and parietal cortices of the macaque monkey (Gallese et al., 1996) provided neurophysiological evidence for direct matching between action perception and action production (Rizzolatti and Sinigaglia, 2008). The MNS seems closely related to motor mimicry because it recognizes an action performed by another and produces the same action, which is referred to as motor resonance that could induce emotional contagion. Furthermore, this relates to self-other discrimination, action understanding, joint attention, imitation, and theory of mind (a detailed discussion is given in Asada, 2011).

In humans, motor resonance in the premotor and posterior parietal cortices occurs when participants observe or produce goal-directed actions (Grezes et al., 2003). This type of a motor resonance system seems hardwired or at least functional very early in life (Sommerville et al., 2005).

4.2. The relationship between emotional and cognitive empathy

According to de Waal's model (de Waal, 2008), EE develops (evolves) earlier than CE; therefore, the latter might involve the former in a type of hierarchy (see Fig. 1). However, several studies have reported that their relationship is not inclusive and that they are different systems, having different roles, and located within different brain regions.

Table 1
Summary of the relationship among self-development, self/other discrimination, empathy terminology, and imitation terminology (Asada, 2014b).

Self-development (based on Neisser, 1993)	Self/other discrimination (Asada, 2014a) and its requirements (–)	Empathy terminology (Gonzalez-Liencresa et al., 2013)	Imitation terminology (de Waal, 2008)
Ecological self (Kuniyoshi and Sangawa, 2006; Mori and Kuniyoshi, 2007)	No discrimination – *Primary emotions* (Russell, 1980) Self/non-self-discrimination – *MNS/motor resonance architecture*	Emotional contagion (Chen et al., 2009; de Waal, 2008; Chartrand and Bargh, 1999)	Motor mimicry (Gallese et al., 1996; Rizzolatti and Sinigaglia, 2008) Motor resonance (Sommerville et al., 2005; Agnew et al., 2007)
Interpersonal self (Meltzoff, 2007; Nagai and Rohlfing, 2009; Inui, 2013; Kuhl et al., 1997)	Self-awareness – *Differentiation of primary emotion* Complete self/others discrimination – *Perspective taking* (Moll and Tomasello, 2006) *and ToM* (Premack and Woodruff, 1978)	Emotional empathy (Craig, 2003; Shamay-Tsoory et al., 2009) Cognitive empathy (Premack and Woodruff, 1978; Edgar et al., 2012; de Waal, 2008; Smith, 2006)	Coordination Shared goals
Social self (Asada, 2011)	Emotion regulation of self as others – *Emotion regulation* Metacognition of self as others – *Metacognition* (Schraw, 1998) In-group/out-group emotion control – *Development of social and more vicarious emotion* (Amodio and Frith, 2006)	Sympathy/compassion (Goetz et al., 2010) Perceived/felt emotion (Kawakami et al., 2013a,b) Envy/schadenfreude (Gonzalez-Liencresa et al., 2013)	Emulation Imitation (de Waal, 2008)

As mentioned in Section 2.1, neural representations for complex emotions and self-awareness are localized in the anterior cingulate cortex and anterior insula (Craig, 2003). Bush et al. (2000) reviewed neuroimaging studies of the anterior cingulate cortex (ACC) and hypothesized that the ACC is a part of a circuit involved in a form of attention that serves to regulate both cognitive and emotional processing. Its two major subdivisions have distinct functions. These include a dorsal cognitive division (ACcd) and a rostral–ventral affective division (ACad, rostral and ventral areas). They carried out a meta-analysis of reviewed studies, and illustrated that controls for affective and cognitive tasks are separately located in these two regions.

Shamay-Tsoory et al. (2009) found that patients with lesions in the ventromedial prefrontal cortex (VMPFC) exhibit deficits in CE and theory of mind (ToM), while patients with lesions in the inferior frontal gyrus (IFG) show impaired EE and emotion recognition. For instance, Brodmann area 44 (in the frontal cortex, anterior to the premotor cortex) was found to be crucial for EE, and the same area was previously identified as part of the MNS in humans (Rizzolatti, 2005). Shamay-Tsoory et al. (2009) summarized the differences between these two separate systems (see Table 2).

Fana et al. (2011) reported some differences in the recruited brain regions when subjects were unaware of being tested for empathy (which they called affective-perceptual), than when they were asked to pay attention to empathy-related cues (cognitive-evaluative). While both conditions activated the above-mentioned areas (i.e., the dorsal anterior cingulate cortex [dACC], anterior mid-cingulate cortex [aMCC], supplementary motor area [SMA] and bilateral insula), the cognitive-evaluative condition additionally activated the dorsal aMCC, while the affective-perceptual condition activated the right anterior insula.

Table 2
Two separate systems for emotional and cognitive based empathy.

Emotional empathy	Cognitive empathy
Simulation system	Mentalizing system
Emotional contagion	Perspective-taking
Personal distress	Imagination (of emotional future outcomes)
Empathic concern	Theory of mind
Emotion recognition	
Core structure	Core structure
IFG BA 44	VM BA 10, 11
Development	Development
Infants	Children/adolescents
Phylogenetics	Phylogenetics
Rodents, birds	Chimpanzees

Adopted from Fig. 6 in Shamay-Tsoory et al. (2009).

These studies discussed above claim that emotional and cognitive aspects are in separate brain regions and therefore independently processed. However, they seem closely related to each other. One case is metacognition by which one can observe him-/herself from another's perspective. Therefore, the individual self is separated into two states: the observing and observed self. The former may correspond to the subjective (real) self and the latter the objective (virtualized) self. A typical phenomenon in this case can be seen when enjoying sad music. Sad music is perceived as sad by the objective self, while listening to this music itself is felt as pleasant by the subjective self (Kawakami et al., 2013a,b, 2014). In this case, the relationship between emotional and cognitive aspects is complicated. The perceived emotion itself is a target of the felt emotion, and the situation itself is organized by a cognitive process (metacognition).

Pessoa published a book entitled "The cognitive-emotional brain" (Pessoa, 2013) that described how several brain regions committed to different functions with functional diversity maps and fingerprints of brain regions. He claimed that there was no dichotomy of cognitive versus emotional; rather, he proposed a dynamic network structure. This seems suggestive for ADR to design artificial empathy because a unified architecture of such a dynamic network is more attractive than the integration of independent function modules. While we have not yet devised and developed such a network, the following sections describe several attempts in this direction.

5. Several approaches in ADR/CDR

From an ADR/CDR perspective, the following issues should be discussed:

- What is the fundamental mechanism connecting emotional contagion and motor mimicry?
- EE could be an extension of emotional contagion with more capabilities in terms of self-awareness and self-other cognition.

- The main issues in designing CE are perspective-taking and theory of mind, which are essential in self-other cognition.

In this section, we review previous studies, some of which were not categorized as ADR but seem related to the topics discussed here.

5.1. Emotional contagion and motor mimicry

Damasio and Carvalho (2013) stated that a lack of homeostasis in the body triggers adaptive behavior via brain networks, such as attention to a stranger's next move. This implies that a homeostasis-like structure is needed to design embodied emotional representations. One of the pioneering WAMOEBA (Waseda-Ameba, Waseda Artificial Mind on Emotion Base) studies (Ogata and Sugano, 2000) proposed a robot emotional model that expresses emotional states connected to self-preservation based on self-observing systems and hormone parameters. This system was adaptive toward external stimuli to maintain bodily feeling stability. Therefore, the best action is sleeping to minimize energy consumption unless external stimuli arise or battery charging is needed.

This study is pioneering in terms of emotion being linked to self-preservation or instinct, with robots being capable of displaying emotional expressions based on these emotion models. Here, the term "instinct" means the survival paradigm embedded by the robot designer in advance to correspond to biological evolution. However, it is not clear how a robot can share an emotional state with humans. Because almost all robot behaviors are explicitly specified by the designer, there is little scope for robots to learn or develop the capacity to share their emotional states with humans.

Emotional contagion and motor mimicry are related to each other, and motor resonance seems to play a key role in connecting the two. Kuniyoshi and Sangawa (2006) proposed one of the most fundamental structures for behavior generation based on interactions among many different components including 198 neural oscillators, a musculoskeltal system with 198 muscles, and an endometrial environment in the case of fetal simulations. Mori and Kuniyoshi (2007) extended the environment to the horizontal plane under the force of the Earth's gravity in the case of neonatal simulation. Fetal or neonatal oscillatory movements occur in these external worlds, and self-organization of ordered movements is expected through these interactions. This leads to additional interactions with other agents through multiple modalities, such as vision or audition (motor resonance). The neural architectures proposed in previous studies (Kuniyoshi and Sangawa, 2006; Mori and Kuniyoshi, 2007) are typical examples for the underlying mechanism at the first stage of the developmental process of the self/other cognition (see Fig. 2, bottom left). This type of architecture is expected to be expanded in later stages by adding more substructures focused on social interactions.

Mimicry is one such interaction that may induce emotional contagion, which is linked to EE. A part of the MNS could also be included in this process (Shamay-Tsoory et al., 2009). Mirror neurons in monkeys only respond to goal-oriented actions (actions of transitive verbs) with a visible target, while in the case of humans, the MNS also seems to respond to the actions of intransitive verbs without targets (Rizzolatti and Sinigaglia, 2008). This is still a controversial issue that needs more investigation (Agnew et al., 2007).

Nagai et al. proposed a computational model for early MNS development that originates from immature vision (Nagai et al., 2011), by which two types of associations were learned: one is between motor commands and self-observation, and the other is between motor commands and other-observation. Their experiments demonstrate that the model achieves early development of the self-other cognitive system, which enables a robot to imitate others' actions. Their model could be considered as a bridge between the first and second stages of the developmental process of the self/other cognition shown in Fig. 2, from the left to the center at the bottom. By adding vision modality to the neural system (Kuniyoshi and Sangawa, 2006; Mori and Kuniyoshi, 2007), we may expect a seamless connection between the first and the second stages of the development of self/other cognition.

Unlike from non-human primates, the human's MNS can work for non-purposeful actions such as play. Kuriyama et al. (2010) revealed a method for interaction rule learning based on contingency and intrinsic motivation for play. This study partially depends on the fundamental MNS capability and therefore seems to be a successor of the Nagai's model (Nagai et al., 2011). This may correspond to a substructure to be added at the second stage of the developmental process of self/other cognition (see Fig. 2, bottom center) although a direct connection with Nagai's model or Kuniyoshi's model (Kuniyoshi and Sangawa, 2006; Mori and Kuniyoshi, 2007) does not seem straightforward.

5.2. Emotional and cognitive empathy

The above studies have not been directly related to emotional states such as pleasure (unpleasant) or arousal (sleep), which are regarded as the most fundamental emotional axes (Russell, 1980). Assuming that human infants are born with this fundamental form of emotion, how can they have variations in emotional states such as happiness and anger? In developmental psychology, intuitive parenting is regarded as a maternal scaffolding on which children develop empathy (Gergely and Watson, 1999). A typical example is when caregivers mimic or exaggerate a child's emotional expressions. This is considered a good opportunity for teaching children how to feel in realtime (Rochat, 2001), and most adults possess this skill. Children are thus able to understand the meaning of facial expressions and develop sympathy toward others as the process is reinforced through emphasis on their caregivers' facial expressions. This is because children empirically learn the connection between their internal state and the facial expressions of others. Watanabe et al. (2007) modeled human intuitive parenting using a robot that associates a caregiver's mimicked or exaggerated facial expressions with the robot's internal state to learn an empathic response. The internal state space and facial expressions are defined using psychological studies and change dynamically in response to external stimuli. After learning, the robot responds to the caregiver's internal state by observing human facial expressions. The robot then facially expresses its own internal state if synchronization evokes a response to the caregiver's internal state.

Considering the neural substrates related to empathy reported in past studies (e.g., Fana et al., 2011; Shamay-Tsoory et al., 2009; Liddell et al., 2005), a draft of the neuroanatomical structure for the above computational model is depicted in Fig. 3. The findings of past studies may not be consistent as the experiments were conducted with different task paradigms and measures. Rather, this structure is intended to give an approximate network structure. During learning, the caregivers' facial expressions, which the learner happens to encounter during an interaction, are supposed to be processed in the inferior frontal gyrus (IFG) and/or insula and then mapped onto the dorsal anterior cingulate cortex (dACC). The dACC maintains the learner's emotional space that drives facial muscles to express one's own emotional states. After learning, the corresponding facial expression is immediately driven by the caregiver's facial expression.

The above process may correspond to the second stage of the developmental process of self/other cognition (Fig. 2). More precisely, it may correspond to the early phase of the second stages since the reaction seems to be like that of an MNS-like system. Moreover, mapping from the caregivers facial expression to one's

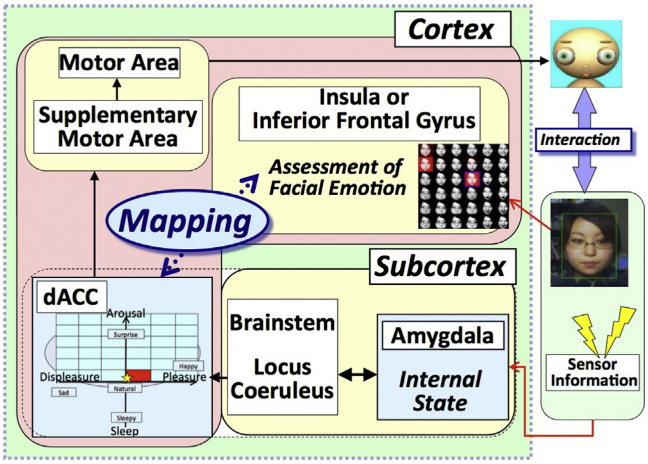

Fig. 3. A neuroanatomical structure for the computational model in Watanabe et al. (2007).

own emotional state requires at least self-awareness as shown in Table 1. However, at this stage, perspective taking and or mentalizing do not seem complete, yet. These issues are argued in the following section.

In addition to the MNS, CE requires “perspective-taking and mentalizing” (de Waal, 2008), both of which share functions with “theory of mind” (Premack and Woodruff, 1978). This is another difficult issue for not only empathy development but also general human development.

Early perspective-taking development can be observed in 24-month old children as visual perspective taking (Moll and Tomasello, 2006) while it cannot be observed in 18-month old children. This implies that there could be a developmental process that takes place between these ages (Moll and Tomasello, 2006).

The 3-D coordinate transformations based on geometric reconstruction of self, others and object locations is a conventional engineering solution, but it does not seem realistic to estimate the precise parameters needed to reconstruct them between the ages of 18 and 24 months. More realistic solutions could be two related ones among which the second one might include the first one. Both share the knowledge of what the goal is.

The first possibility is the accumulation of goal-sharing visual experiences with a caregiver. Circumstantial evidence for view-based recognition can be seen in face cells in the inferior temporal cortex of a monkey brain (Chapter 26 in Purves et al., 2012), which are selectively activated according to facial orientation. Appearance-based vision could be an engineering method for object recognition and spatial perception.[3] Yoshikawa et al. (2001) proposed a method of incremental recovery of the demonstrator’s view using a modular neural network. In it, the learner can organize spatial perception for view-based imitation learning with the demonstrator in different positions and orientations. Recent progress in big data processing provides better solutions to this issue.

The second is an approach that equalizes different views based on a value that can be estimated by reinforcement learning (Takahashi et al., 2010). The learning consequence resembles the MNS function in the monkey brain (i.e., regarding the different actions (self and other) as the same goal-oriented action).

5.3. Expressions

Facial and gestural expressions are a very important and indispensable part of artificial empathy. A pioneering work of WE-4RII shows very rich facial and gestural expressions, and observers evoke the corresponding emotions (same or different) (Miwa et al., 2003, 2004).[4] Although their design concept and technology are excellent, the realism of interactions depends on the skill of the designer.

We need more realistic research platforms (in two ways) as explained by the ADR approach. One is the design of realistic robots with the computational model of affective development. The other includes platforms for emotional interaction studies between an infant and his/her caregiver. For these purposes, The Affetto project has been effective (Ishihara et al., 2011; Ishihara and Asada, 2014). “Affetto” has a child-like (1- to 2-year-old) body size, shape, softness, and appearance. Realizing the structures and functions required for a human-like impression or behaviors in a small body is technically challenging. It involves synergistic hardware integration based on effective and efficient space utilization. In addition to hardware design, we are trying to establish methods to utilize the robot as a child developmental simulator for cognitive developmental robotics and as a stimulus-presenting device for psychological experiments of interpersonal cognition. Fig. 4 shows an example of “Affetto.”

5.4. Social behavior analysis

Another aspect of ADR is (B) offering new means or data for better understanding of the human developmental process. As mentioned in Section 3, robot could be used as reliable tools in psychological experiments to ensure reproducible and unbiased results.

Recently, Takahashi et al. (2014) showed how social interactions with different agents affect the impressions of mental capabilities such as mind-holderness and mind-readerness. They prepared five kinds of social agents: a human, an android (Actoroid F), a mechanical humanoid (infanoid), a pet-like robot (Keepon), and a computer that were opponents of the matching-penny game presented in an fMRI scanner. Principal component analysis (PCA) of the answers for the impression questions showed that the first and third components correspond to the mental function score (mind-holderness) and the entropy (higher values indicate a complex strategy for the game: mind-readerness). Fig. 5 shows the result of the impressions in two-dimensional space in terms mind-holderness (x-axis) and mind readerness (y-axis). The human, the android, and the humanoid have positive correlations between mind holderness and mind readerness. On the other hand, Keepon (the computer) has negative one: high (low) mind holderness while low (high) mind readerness.

fMRI results indicated that these two aspects of social impressions correspond well to activity in two distant brain region networks. The dorso-medial cingulum network and the anterior–ventral temporo-parietal junction (TPJ)/posterior–superior temporal sulcus (pSTS) are activated by the impression of mind-holderness (red) and mind-readerness (blue), respectively (Fig. 6). Social interaction with a mind holder or mind reader may distinctly shape the internal representation of our social brain, which may in turn determine how we behave towards various agents that we encounter in our society.

Mind holderness and mind readerness may correspond to emotional and cognitive aspects of empathy thought their relationship

[3] Visit http://www.cs.rutgers.edu/ elgammal/classes/cs534/lectures/appearance-based%20vision.pdf as a general reference.

[4] also visit http://www.takanishi.mech.waseda.ac.jp/top/research/index.htm.

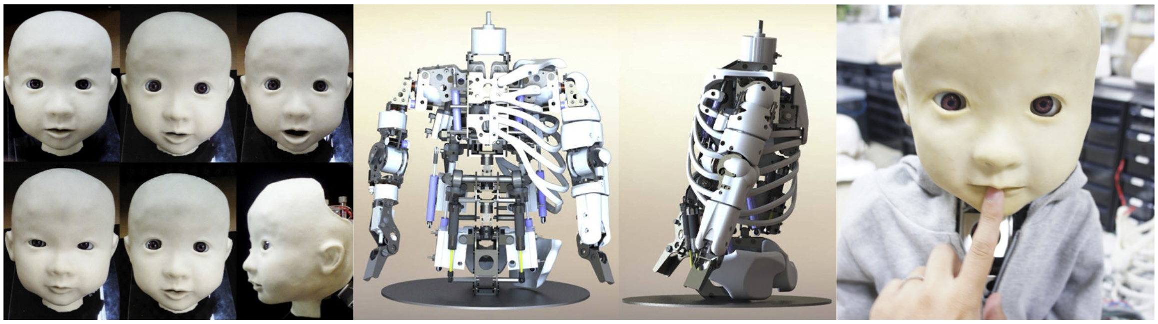

Fig. 4. Affetto: facial expressions (left), internal structure of the upper torso (center), and an example of physical touch (right).

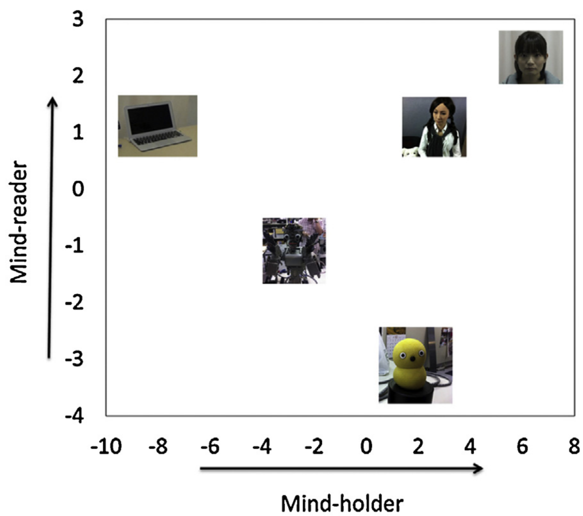

Fig. 5. Location of each opponent in two-dimensional space. The *x*-axis indicates "mind-holderness," and the *y*-axis indicates "mind-readerness" (see text). The score of PCA components for each opponent represents the mean value for all participants (Takahashi et al., 2014).

and network structure are far from our current understanding. Further, the second component of PCA does not correspond to any mental property or any specific brain activity. Future analysis and modeling are expected to reveal the corresponding properties.

6. Discussion

Based on our previous review (Asada, 2014b), this article focused on the issues of emotional contagion, motor mimicry, and cognitive versus emotional aspects. In the former issue, we discussed the possibility of a mechanism to connect physical and mental synchronization. To do so minimally requires an entraining system that realizes physical synchronization with the environment. Fetal and neonatal simulations (Kuniyoshi and Sangawa, 2006; Mori and Kuniyoshi, 2007) are the first step, and these simulations should be extended to interactions with other agents. In order to support such simulations, we need neuroscientific evidence for synchronization. Recently, Hirata et al. (2014) built a hyperscanning magnetoencephalogram (MEG) system with two MEG scanners in one shield room, one for children and another for adults, and a video display system that enables each subject to observe the opponent in approximately real time (with some delay), in static mode, or any other common video clips (see Fig. 7). The measurement and analysis of this hyper scanning data are expected to provide basic knowledge about mother–infant synchronization, and model verifications.

Studies assessing severely aphasic patients (e.g., Varley et al., 2001) have reported normal ToM processing. This heavily implies that language capacity is not an essential requirement for ToM (Agnew et al., 2007) and probably is not needed for empathy, either.

As mentioned in Section 5.1, self-observing systems and hormone parameters in WAMOEBA (Ogata and Sugano, 2000) were promising for designing artificial emotion, and the best action was sleeping to minimize energy consumption unless external stimuli arose. However, animal behavior, especially in humans, is generated not only by this fundamental structure necessary for survival, but also more actively by so-called intrinsic motivation (Ryan and Deci, 2000). Actually, falling is a leading cause of accidental injury and death in children under five (Joh and Adolph, 2007). Nevertheless, they seem to explore their environment using their immature behaviors.

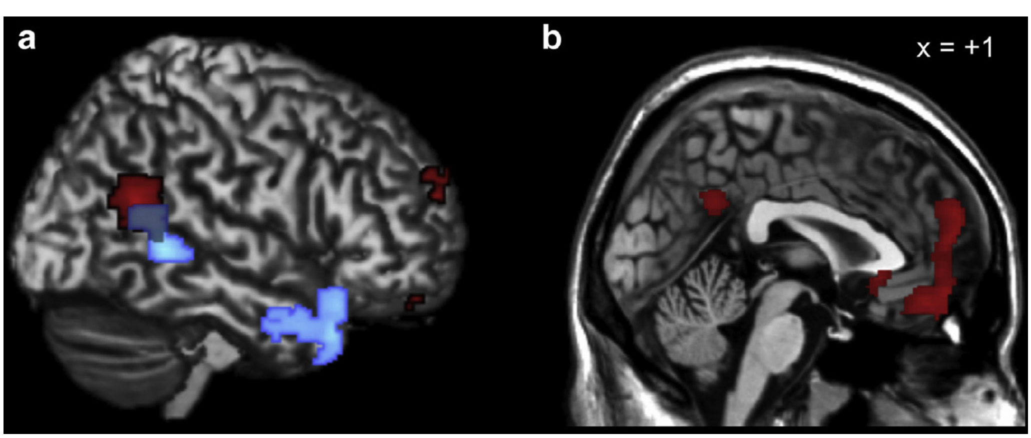

Fig. 6. fMRI of brain regions where activities were modulated by "mind-holderness" (red) and "mind-readerness" (blue) (Takahashi et al., 2014). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

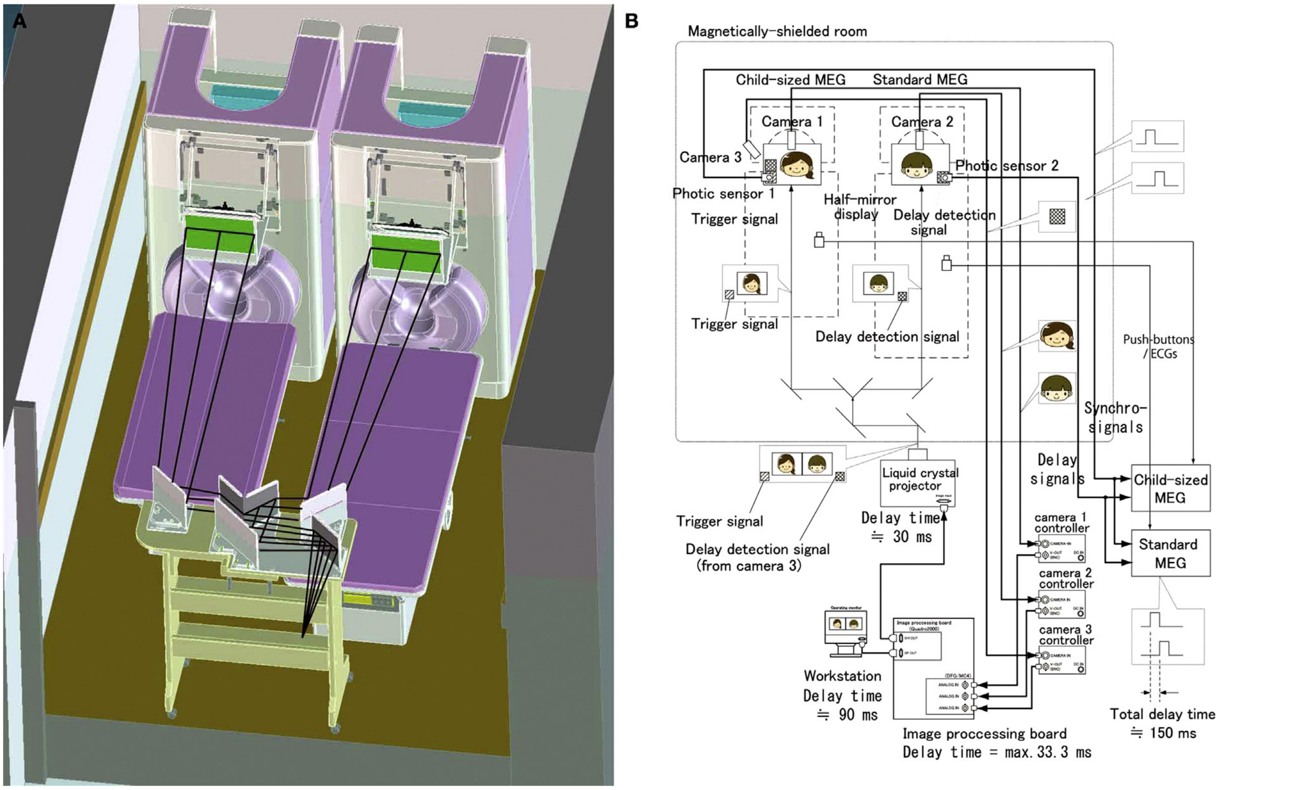

Fig. 7. Schematic and block diagrams of the hyperscanning MEG system.(A) Standard (right) and child-sized (left) MEGs, and (B) an audio–visual presentation and recording system (Hirata et al., 2014).

In the machine-learning and developmental robotics community, intrinsic motivation has received increased attention as a driving structure of various behaviors (Lopes and Oudeyer, 2010). The relationship between empathy and intrinsic motivation is yet to be intensively investigated. We might consider a certain structure of intrinsic motivation as a means to develop artificial empathy. Whether explicit or implicit is to be addressed in future studies.

With regard to the cognitive and emotional aspects, Decety and Lamm (2006) proposed a model in which bottom-up (i.e., direct matching between perception and action) and top-down (i.e., regulation, contextual appraisal, and control) information processes are fundamentally intertwined in the generation and modulation of empathy. Bottom-up processes account for direct emotion sharing, which are automatically activated (unless inhibited) by perceptual input. Executive functions implemented in the prefrontal and cingulate cortices serve to regulate both cognition and emotion through selective attention and self-regulation. This metacognitive level is continuously updated by bottom-up information, and in return controls the lower level by providing top-down feedback. Top-down regulation, through executive functions, modulates lower levels and adds flexibility, making the individual less dependent on external cues. The metacognitive feedback loop also plays a crucial role in taking into account one's own mental competence in order to react (or not) to the affective states of others. This model should be supplemented by top-down processes that are not classically associated with executive function and its associated neural structures, in particular those in the medial and dorsolateral prefrontal cortices.

This system has not been implemented in a functional artificial system, but it seems valuable to attempt to do so. If implemented, contextual factors such as early experiences with primary caregivers (attachment), current mood states, and other environmental contingencies could be considered since theses factors are capable of modulating empathy (Gonzalez-Liencresa et al., 2013). This would require a systematic definition for empathy, sympathy, and personal distress (several papers argue the relationship between empathy and personal distress (e.g., Shamay-Tsoory et al., 2009; Bush et al., 2000; Lamm et al., 2007) because they seem closely related.

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