Affective Developmental Robotics*

How can we design the development of artifcial empathy?

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ABSTRACT

The design of artificial empathy is one of the most essential issues in HRI, and several attempts have been made for specific situations. However, they have shown limited capabilities, and therefore seem far from authentic. In this article, we propose "Affective Developmental Robotics (hereafter, ADR)" towards more authentic artificial empathy based on the concept of cognitive developmental robotics (hereafter, CDR). First, the evolution and development of empathy as revealed in neuroscience and biobehavioral studies are reviewed, starting from emotion contagion to envy and schadenfreude through emotional and cognitive empathy, and sympathy and compassion. Then, these terms are reconsidered from a viewpoint of ADR/CDR, especially, along the developmental trajectory of self-other cognition. Next, a conceptual model of artificial empathy is proposed from a ADR/CDR viewpoint, and discussed with respect to several existing studies. Finally, discussion and future issues are given.

1. INTRODUCTION

The importance of "affectivity" in HRI was pointed out with a brief survey of existing robots from the viewpoint of affective computing [29]. Several attempts have been made for specific contexts (e.g., [18] for survey) in which the designer specified how to realize empathic behaviors to humans, and therefore the capability of empathic interaction seems limited and difficult to extend (generalize) to different contexts.

From a viewpoint of developmental robotics ([20, 3]), such empathic behaviors are expected to be learned through social interactions with humans. Asada et al. [5] argued how to design "artificial empathy" they discussed under cognitive developmental robotics (CDR) [3]. However, their arguments were not precise from a viewpoint of neuroscience and biobehavioral studies. Then, in this article, we propose "Affective Developmental Robotics" (hereafter, ADR) in order to understand the affective developmental process by means of synthetic and constructive approaches, especially towards more authentic artificial empathy.

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First, the evolution and development of empathy in neuroscience and biobehavioral studies are reviewed, starting from emotion contagion to envy and schadenfreude through emotional and cognitive empathy, and sympathy and compassion. Then, these terms are reconsidered from a viewpoint of ADR/CDR, especially, along the developmental trajectory of self-other cognition. Next, a conceptual model of artificial empathy is proposed from a ADR/CDR viewpoint, and discussed with respect to several existing studies. Finally, discussion and future issues are given.

2. EVOLUTION AND DEVELOPMENT OF EMPATHY

We follow the definition of the empathy in a review of neuroscience of empathy from viewpoints of ontogeny, phylogeny, brain mechanisms, context and psychopathology by Gonzalez-Liencres et al. [12]. Their points are:

- The manifold facets of empathy are explored in neuroscience from simple emotion contagion to higher cognitive perspective-taking.
- A distinct neural network of empathy comprises both phylogenetically older limbic structures and neocortical brain areas.
- Neuropeptides such as oxytocin and vasopressin as well as opioidergic substances play a role in modulating empathy.

First two points seem related to each other, that is, emotion contagion is mainly based on the phylogenetically older limbic structures while higher cognitive perspective taking is based on neocortical brain areas. Neuromodulation may amplify (reduce) the level of the empathy both positively and negatively.

A narrow definition of empathy is given as the ability to form an embodied representation of other's emotional state, while at the same time being aware of the causal mechanism that induced the emotional state in the other [12]. This entails that the empathizer has interoceptive awareness of his or her own bodily states and is able to distinguish between self and other, which is a key aspect of the following definitions of empathy-related terms from an evolutionary viewpoint.

2.1 Emotion contagion

Emotion contagion is an evolutionary precursor that enables animals to share their emotional states. The key point is that the animals cannot understand what aroused such emotional states in the other. In this sense, emotion contagion seems automatic, unconscious, and fundamental for higher level empathy.

Waal [8] proposed the evolutionary process of empathy in parallel with that of imitation starting from emotion contagion and motor mimicry. Besides the precise definitions of other terms, motor mimicry needs a sort of resonance mechanism of the physical body which supplies a fundamental structure for emotion contagion.

2.2 Emotional and Cognitive Empathy

Both emotional and cognitive empathy (hereafter, EE and CE) occur only in animals with self-awareness such as primates, and even elephants and dolphins. Neural representation for such complex emotion and self-awareness is localized at the anterior cingulate cortex and the anterior insula [6]. The differences between emotional and cognitive empathy are summarized as follows:

- Emotional Empathy (EE):
  - an older phylogenetic trait than cognitive empathy
  - allows individuals to form representation of other's feelings by sharing these feelings through embodied simulation, a process that is triggered by emotional contagion.
- Cognitive empathy (CE):
  - considerably overlaps in definitional terms with "theory of mind" [27]
  - present in apes and humans [9]
  - requires perspective-taking and mentalizing [8].

Compared to emotion contagion that does not requre reasoning about the cause of aroused emotion in others, both EE and CE require the distinction between one's own and other's mental states and to form a representation of one's own embodied emotions. The later styles of EE and CE do not necessarily require that the observer's emotional state match the observed one. They can be seen as sympathy and compassion explained in the next section.

2.3 Sympathy, Compassion and Envy, Schadenfreude

Sympathy and compassion seem similar to empathy in terms of emotional states, but different in ways of the response to other's emotional states. Both require the ability to form representations of others' emotions, even though the emotion is not necessarily shared while in empathy the emotional states are synchronized [11]. This implies that sympathy and compassion may need a control capability of one's own emotion in addition to the self-other discrimination.

More powerful control of one's own emotion can be observed in envy and schadenfreude which describe feelings opposite of the other's emotional state, different from sympathy and compassion. Envy and schadenfreude evolved in response to selection pressures on social coherence among early hunter-gatherers [12].

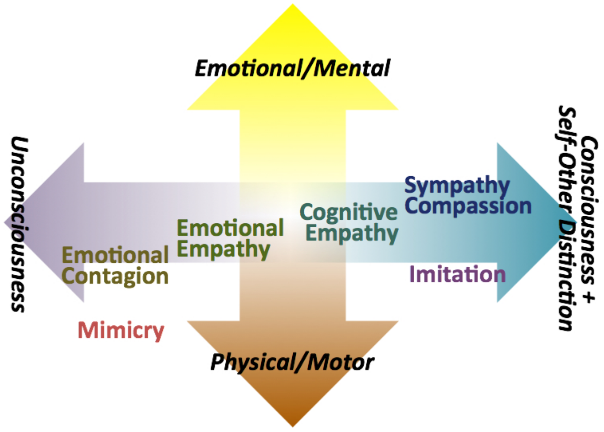

Figure 1: Schematic depiction of the terminology (adopted and modified from Fig. 1 in [12])

2.4 The Relationship among terms

Fig. 1 shows a schematic depiction of the terminology used in the context of empathy so far. The horizontal axis indicates the "conscious level" starting from "unconsciousness (left-most)" to "consciousness with self-other distinction (right-most)." The vertical axis indicates "physical/motor (bottom)" and "emotional/mental (top)" contrast. Generally, these axes show discrete levels such as "conscious/unconscious" or "physical/mental". However, the terminology in the context of empathy could be distributed in the zones where it is not always easy to discriminate these dichotomies. In addition, there are two points to be mentioned:

- In this space, the location indicates the relative weight between both dichotomies, and the arrow to the left (the top) 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) implies the evolutionary process, and the developmental process, as well, if "ontogeny recapitulates phylogeny." Therefore, a whole story of empathy follows a gentle slope from the bottom-left to the top-right.

3. AFFECTIVE DEVELOPMENTAL ROBOTICS

We have been advocating cognitive developmental robotics (CDR) [4, 3], and supposing that the development of empathy could be a part of CDR. Actually, the survey [3] introduced a study of empathy development [38] as one example

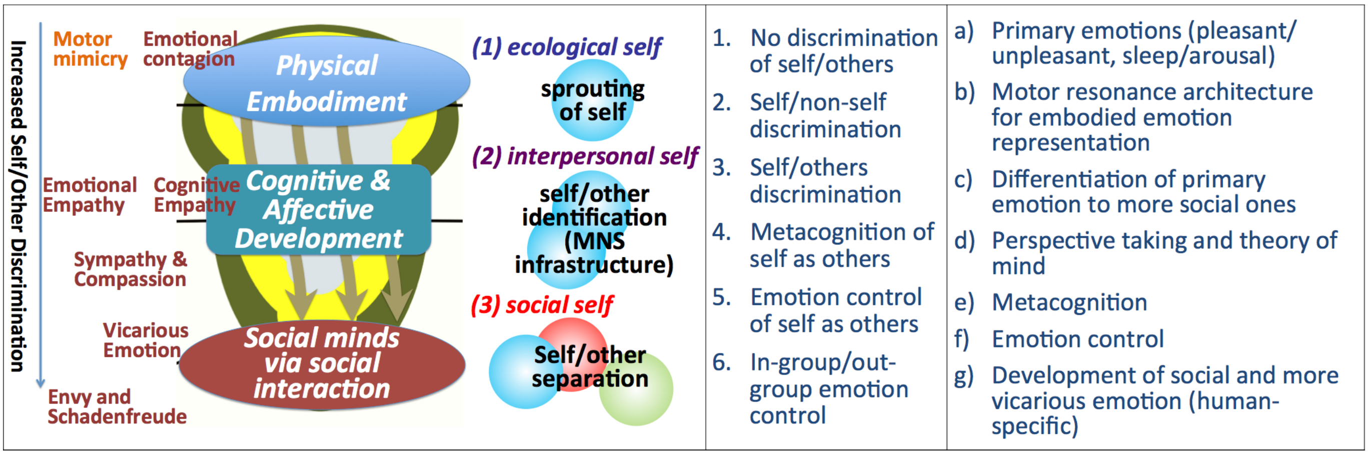

Figure 2: Parallelism of empathy development with self-others cognition (CDR/ADR)

of CDR. Here, in order to focus on this part, we rephrase a part of CDR as Affective Developmental Robotics (hereafter, ADR) [1]. Therefore, ADR just follows the approach of CDR, especially focusing on the affective development. First, we give a brief overview of ADR following CDR, and then discuss how to approach the issue of the empathy development.

3.1 Key concepts of ADR

Just following the CDR, ADR could be stated as follows: affective developmental robotics aims at understanding human affective developmental processes by synthetic or constructive approaches. Its core idea is "physical embodiment" and more importantly "social interaction" that enables information structuring through interactions with the environment including other agents, and affective development is thought to connect both seamlessly.

Roughly speaking, the developmental process consists of two phases: individual development at an early stage and social development through interaction between individuals at a later stage. In the past, the former has related mainly to neuroscience (internal mechanism), and the latter to cognitive science and developmental psychology (behavior observation). Nowadays both sides approach each other: the former gradually starts imaging studies for social interactions, and the latter also involve neuroscientific approaches. However, there is still a gap between them owing to the difference in granularity of the targets of their research questions. ADR aims not simply at filling the gap between them but, more challengingly, at building a new paradigm that provides new understanding of ourselves with a new design theory of humanoids that are symbiotic and empathic with us.

3.2 Relationship in development between self-other cognition and empathy

Self-other cognition is one of the most fundamental and essential issues in ADR/CDR. Especially, in ADR,

1. the relationship between understanding others' minds and the vicarious sharing of emotion is a basic issue in human evolution [35],
2. the development of self-other discrimination promotes the vicariousness, and
3. the capability of metacognition realizes a kind of vicariousness, that is, imagination of self as others (emotion control).

A typical example of 3 can be observed in a situation where we can enjoy sad music [15, 16]. The objective (virtualized) self perceives sad music as sad while the subjective self feels pleasant emotion by listening such sad music. It seems to be a kind of emotion control by metacognition of self as others. The capability of emotion control could be gradually acquired along the developmental process of self-other cognition, starting from no discrimination between self and non-self including objects. Therefore, development of self-other cognition accompanies the development of emotion control which consequently generates various emotional states mentioned in 2.4.

4. TOWARD ARTIFICIAL EMPATHY

The development of self/other cognition could parallel the empathy development. Fig. 2 indicates this parallelism of empathy development with ADR/CDR. The left part shows the correspondence between a ADR/CDR flow and the development of empathy by projecting the terminology in Fig. 1. "Physical embodiment" connects motor mimicry and emotional contagion, that is, motor resonance by mimicry induces embodied emotional representation, that is, emotional contagion.

The middle of Fig. 2 shows six points along the developmental process of self/other cognition, starting from no discrimination between self and others. The first three points correspond to emotional contagion, EE and CE. In cases of sympathy and compassion, one's emotional state is not synchronized with that of other's, but different emotional state is induced. In case of listening sad music [15, 16], the

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

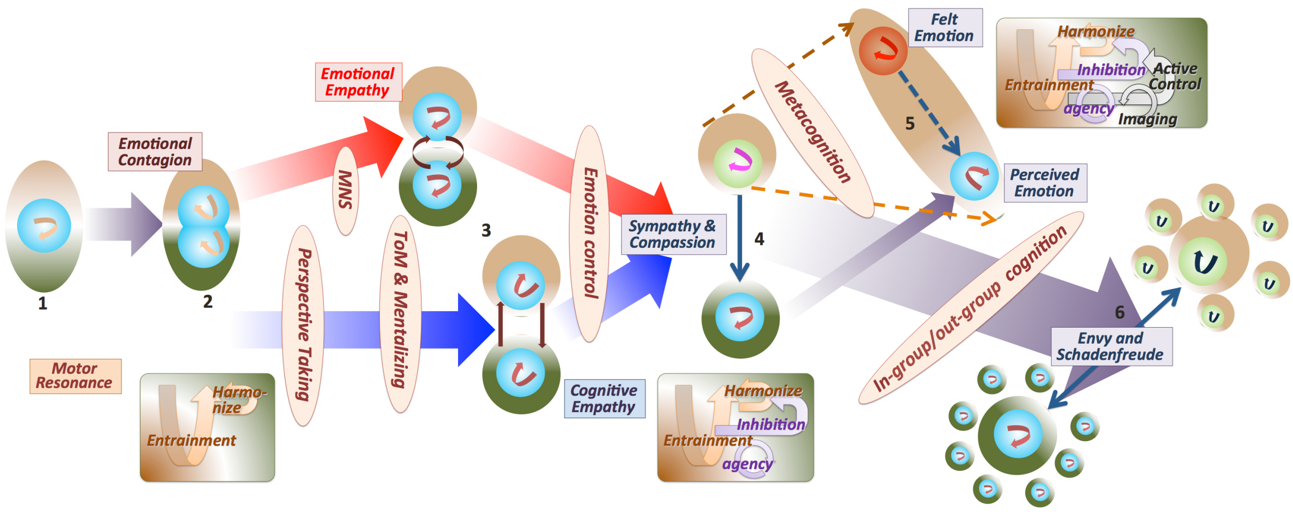

Figure 3: An overview of the development of artificial empathy

listener's objective (virtualized) self perceives sad music as sad while the subjective self feels pleasant emotion. Further, the concept of self-other discrimination can be extended to the in-group/out-group concept, and higher order emotional states such as envy and schadenfreude.

The right side of Fig. 2 shows the list of requirements or functions which are supposed to trigger (promote) the development of both empathy and self-other discrimination when designing the above process as an artificial system.

5. ADR/CDR APPROACHES

There are many design issues towards artificial empathy. Fig. 3 shows a conceptual overview of the development of artificial empathy by ADR/CDR approaches following the arguments above. The numbers correspond to that in the middle of Fig. 2.

A flow from the left to right indicates the direction of evolution and development in terms of self-other cognition and emotion control. Small circles with curved arrows indicate internal emotional states of the agent starting from no discrimination of self-other (1) to completely separated agent representations with different emotional states (6). The orientations of curved arrows indicate the emotional states, and they are synchronized between self and other, e.g., until EE and CE (3). The undelying structure needed until EE and CE is synchronization with the environment including other persons to harmonize with as shown at the left-botton in Fig. 3. However, after that they can be de-synchronized (different emotions) by the capability in emotion control.

Sympathy and compassion are such examples for emotional states being different between self and other (4). Intuitively, sympathy is more EE-dominant while compassion is more CE-dominant since sympathetic concerns seem more emotional while compassion can be realized after understanding other's state logically. However, the difference is actually not so large since both sympathy and compassion need perceiving other's internal states and understanding its cause. In addition to the fundamental structure of synchronzation, inhibition of harmonization with perceived emotion based on the establishment of agency (self-other discrimination) is needed as shown at the middle bottom in Fig. 3.

The above discrepancy of empathy between self and other (de-synchronization) is extended in two ways, internally and externally. The internal extension is as follows: the self emotion space is divided into two (5), one is subjective (top) and the other is objective (virtualized: bottom) that could be projection of other person's emotional state. Perception of emotional state of objective self (perceived emotion) seems more CE-dominant since it seems objective decision while feeling itself seems more subjective (felt emotion). The external extension is as follows: both self and other have their own populations (6), and inside the same group, all members are synchronized. However, they are de-synchronized with members of another grooup. If two groups are competitive (evolutionally, due to natural selection), hostile emotions to the opponent group may happen. A group can be regarded as an extended self (or other). In both cases, the capabilities in imagination of virtualized self (5), and more control of self emotion (6) are needed to emerge such various emotional states as shown at the top-right in Fig. 3.

Hereafter, we review previous works and existing studies, some of which were not categorized as ADR, but seem related to the topics discussed here.

5.1 Emotional Contagion, MNS, and EE

Designing a computational model which can explain the developmental process shown in Fig. 3 is very challenging, and such a model does not exist yet. In the following, we review examples of existing studies from ADR/CDR viewpoints.

Emotion contagion and motor mimicry are related to each other via PAM (physical embodiment), and motor resonance seems to have a key role to connect them. Mori and Kuniyoshi [24] proposed one of the most fundamental structures for behavior generation based on neural oscillation through the interaction among neural oscillators, a muscleskelton system of the whole body, and the external world which can be the endometrium in the case of fetal simulations, and the horizontal plane under the force of the earth's gravity in the case of neonatal simulation. Oscillatory movements of the fetus or the neonate happen in these external worlds, and self-organization of ordered movements is expected through such interactions, which leads to the interaction with other agents through multiple modalities such as vision or audition (motor resonance).

Mimicry is one kind of such interactions, and may induce emotional contagion which links to emotional empathy. In this process, a part of the mirror neuron system (MNS) could be included [34]. Mirror neurons in monkeys only respond to goal oriented actions (actions of transitive verbs) with a visible target, while in the case of humans they seem to also respond to actions of intransitive verbs without any target ([30]). This is still a controversial issue that needs more investigation [1]. One plausible interpretation is as follows. In the case of monkeys, due to higher pressure to survive, goal oriented behavior needs to be established and used early. In contrast, humans owe much to caregivers, such that pressure is reduced and therefore the MNS works not only for goal oriented behavior but also behavior without goals. Consequently, much room for learning and structuring for generalization is left, and this leads to more social behavior acquisition and extension to higher cognitive capabilities.

Nagai et al. proposed a computational model for the early development of MNS, which originates from immature vision [25]. The model gradually increases the spatiotemporal resolution of a robot's vision while the robot learns the sensorimotor mapping through primal interactions with others. In the early stage of development, the robot interprets all observed actions as equivalent due to lower visual resolution, and thus associates the non-differentiated observation with motor commands. As vision develops, the robot starts discriminating actions generated by itself from those by others. The initially acquired association is, however, maintained through development, which results in two types of associations: one is between motor commands and self-observation and the other between motor commands and other-observation. Their experiments demonstrate that the model achieves the early development of the self-other cognition system, which enables a robot to imitate others' actions. Considering the strong link between empathy and imitation, this model can be regarded as the process from 1 to a point just between 2 and 3 in Fig. 3.

Different from non-human primates, human's MNS could work for non-purposeful actions such as play. Kuriyama et al. [17] show a method for interaction rule learning based on contingency and intrinsic motivation for play. The leaner obtains new interaction rules through interaction with a caregiver. Such non-purposive mother-infant interaction could play a crucial role in acquiring MNS-like functions and also early capabilities of imitation, such as mimicry. The chameleon effect could be partially explained by the consequence of this learning.

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 [31]. Assuming that human infants are born with this fundamental form of emotion, how can they have variations of emotional states such as happiness and anger?

In developmental psychology, intuitive parenting is regarded as the maternal scaffolding based on which children develop empathy when caregivers mimic or exaggerate the child's emotional facial expressions [10]. Watanabe et al. [38] 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 expresses its own internal state facially if synchronization evokes a response to the caregiver's internal state.

5.2 Perspective taking, theory of mind and emotion control

In addition to MNS, cognitive empathy requires "perspective taking and mentalizing" [8], both of which share functions with the "theory of mind" [27], another most difficult issue for not only empathy development but more generally human development.

Early development of perspective taking can be observed in 24-month old children as visual perspective taking [23]. Children are at Level 1 when they understand that the content of what they see may differ from what another sees in the same situation. They are at Level 2 when they understand that they and another person may see the same thing simultaneously from different perspectives. Moll and Tomasello found that 24-month old children are at level 1 while 18-month-olds are not. This implies that there could be a developmental process between these ages [23].

A conventional engineering solution is the 3-D geometric reconstruction of self, other, and object locations first, and then the coordinate transformation between egocentric and allocentric coordinate systems. This calibration process needs precise knowledge of parameters such as focal length, visual angle, and link parameters based on which object (others) location and size are estimated. However, it does not seem realistic to estimate these parameters precisely in the age between 18 and 24 month old.

More realistic solutions could be two related ones among which the second one might include the first one. Both share the knowledge what the goal is.

The first one is the accumulation of goal sharing experiences with a caregiver. Suppose reaching behavior to get an object. An infant has successful experiences, but sometimes fails to reach a distant object. In this case, a caregiver may help the infant from the backside, on its side, and then face to face situation. The infant collects these experiences including views of its own behavior and the caregiver's. Based on the knowledge about the same goal, these views are categorized as the same goal behavior just from different views (different perspectives). A circumstantial evidence for view-based recognition can be seen in face cells in the inferior temporal cortex of a monkey brain (chapter 26 in [28]) which selectively activate according to the face orientation. Appearance-based vision could be a engineering method for object recognition and spatial perception[2]. Yoshikawa et al. [39] propose a method of incremental recovery of the demonstrator's view using a modular neural network by which the learner can organize spatial perception for the view-based imitation learning with the demonstrator in different positions and orientations. Recent progress in big data processing provides better solution to this issue.

The second one is an approach which equalizes different views based on the value that can be estimated by reinforcement learning. That is, different views have the same value according to the distance to the shared goal by self and others. Suppose that the observer has already acquired the utilities (state values in reinforcement learning scheme). Takahashi et al. [36] show that the observer can understand/recognize behaviors shown by a demonstrator based not on a precise object trajectory in allocentric/egocentric coordinate space but rather on an estimated utility transition during the observed behavior. Furthermore, it is shown that the loop of the behavior acquisition and recognition of observed behavior accelerates the learning and improves the recognition performance. The state value updates can be accelerated by the observation without real trial and error while the learned values enrich the recognition system, since they are based on estimation of the state value of the observed behavior. The consequence of the learning resembles to MNS function in monkey brain, that is, regarding the different actions (self and other) as the same goal-oriented actioin.

5.3 Emotion Control, Metacognition and Envy, Schadenfreude

Emotion control triggers the development from 3 to 4 in Fig. 3: one understands other's emotional state (synchronize) first, and then shifts the own emotional state to a similar but different one (de-synchronize) such as in sympathy and compassion. In the figure, sympathy appears EE dominant while compassion CE dominant, but actually both include cognitive processes (understanding other's state). Therefore the different dominance does not seem as significant as shown in the figure.

Generally, two components of metacognition are considered: knowledge about cognition, and regulation of cognition [33]. Among four instructional strategies for promoting the construction and acquisition of metacognitive awareness, regulatory skills (self-monitoring) seem related to the emotional state 5 in Fig. 3 where a de-synchronized other's emotional state (the bottom of 4) is internalized as a target (the bottom of 5) to be controlled inside one's own emotional state. This target represents the self as others (objective or virtualized self) while the subjective self (the top of 5) monitors this objective self. In case of sad music [15, 16], a cognitive process perceives sad music as sad, which therefore seems objective. During this process, not simply switching between self (subjective) and others (objective) in 4, but more control power comes from cortex. The medial frontal cortex (MFC) is supposed to be the neural substrate for social cognition. Especially, the anterior rostral region of the MFC (arMFC) maintains roughly three different categories: self-knowledge, person knowledge and mentalizing [2].

5.4 Expressions

Facial and gestural expressions are a very important and indispensable part of artificial empathy. The classical work of WE-4RII shows very rich facial and gestural expressions, and observers evoke the corresponding emotions (same or different) [21, 22]. Although their design concept and technology were excellent, the realism of interactions depends on the skill of the designer.

We need more realistic research platforms in two ways as explained in the ADR approach. One is the design of realistic robots with the computational model of affective development. The other are ones for emotional interaction studies between an infant and its caregiver. For these purposes, Affetto, that has the realistic appearance of a 1- to 2-year-old child, has been designed and built [14, 13].

6. DISCUSSION

We have discussed the development of empathy along with that of self-other cognition from a viewpoint of constructive approach (ADR/CDR) expecting that ADR/CDR can fill the gap between neuroscience and developmental psychology. However, this attempt needs more arguments. Here are some points.

The terminology in the context of empathy is reviewed, and a conceptual model of empathy development is proposed in terms of self-other discrimination (Fig. 3). A neural architecture for the empathy development model [38] is proposed based on the existing findings which are not completely consistent due to the differences in the task design, the context, and the measuring equipments. Rather than detailed neural substrates which might be different depending on the context and the target emotion, we may hypothesize that a whole functional structure comprises a network through which cortical and subcortical areas work together. Since the subcortical areas develop earlier than the cortical areas do, the former probably works first then the second does in each situations where one may encounter with an event. From such a viewpoint, more imaging studies for children and behavioural studies, especially focusing on interaction using constructive methods with robots are needed to reveal the underlying developing structure.

The theory of mind (ToM) and MN activities have been investigated in several imaging studies with different approaches such as written stories and comic strips. This is an important discrepancy as the involvement and/or requirement of language in ToM is debatable since Broca's area in humans is supposed to be a homology of the monkey brain region close to F5 where mirror neurons are found. Studies for severe aphasic patients (e.g., [37]) have been reported normal ToM processing. This heavily implies that language capacity is not an essential requirement for ToM [1], and probably not for empathy, too. Therefore, in the conceptual model in Fig. 3, the language faculty is not included.

[2]as a general reference, please visit http://www.cs.rutgers.edu/∼elgammal/classes/cs534/lectures/appearance-based%20vision.pdf

In the computational or robot model mentioned so far, we have not considered emotional states coming from visceral organs. Damasio and Carvalho [7] state that a lack of homeostasis in the body will trigger adaptive behavior via brain networks, such as attention to the stranger's next move. This implies that a homeostasis-like structure seems needed to design embodied emotional representations. One of the pioneering WAMOEBA studies [26] proposed a robot emotional model which expresses emotional states connected to self-preservation based on self-observing systems and hormone parameters. This system was adaptive to external stimuli to keep the body feelings stable. Therefore, the best action is sleeping to minimize the energy consumption unless the external stimuli arise. However, animals' behavior, and especially humans', is generated not only by such a fundamental structure to survive, but more actively by so-called intrinsic motivation [32].

In the machine learning and developmental robotics community, intrinsic motivation has been recently obtaining increasing attention as a driving structure of various behaviors [19]. Their interest seems how to formalize it from a viewpoint of information theory supposing its existence, not caring how it develops. The relationship between empathy and intrinsic motivation has not been intensively investigated, yet. We may consider a certain structure of intrinsic motivation to develop the artificial empathy. Explicit or implicit? That's an issue to be attacked.

7. CONCLUSION

Towards artificial empathy, we argued how it can follow a developmental pathway like the natural one. After reviewing the terminology in the context of empathy development, a conceptual constructive model for the artificial empathy is proposed. Here are concluding remarks.

1. The development of empathy and imitation could be parallel. Emotional contagion, the early style of the empathy linking to motor mimicry, is shared with other animals. Emotional contagion extends to emotional empathy, sympathy (compassion), and higher ones owing to mainly subcortical brain regions (along the developing time course, dependency on subcortical areas becomes less).
2. Under the control by cortical areas, cognitive empathy develops to compassion (sympathy) (along the developing time course, control projection from the cortical area becomes more).
3. Affective developmental robotics (ADR) is proposed, and a conceptual constructive model of empathy development is devised in parallel with self-other cognition development in which the concept of self emerges, develops, and divides (emotion control seems to manipulate these).
4. A number of existing studies in ADR/CDR are discussed in the context of the empathy and self-other cognition development, and possible extensions are discussed.
5. The proposed constructive model is expected to shed new insight on understanding the development of empathy, which can be directly reflected by the design of the artificial empathy.
6. Still, there are many issues to be attacked, and more investigations such as imaging studies with children and behavioral ones using robots for systematic experiments are needed.
7. One of such issues is about intrinsic motivation to emerge various behaviors, and its relationship with empathy during the developmental process is an interesting topic to be challenged.

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