

# A Model to Explain the Emergence of Imitation Development based on Predictability Preference

Takashi Minato, Dale Thomas, Yuichiro Yoshikawa, and Hiroshi Ishiguro, *Member, IEEE*

**Abstract**—Imitation is a very complicated function which requires a body mapping (a mapping from observed body motions to motor commands) that can discriminate between self motions and those of others. The developmental mechanism of this sophisticated capability, and the order in which the required abilities arise, is poorly understood. In this article, we present a mechanism for the development of imitation through a simulation of infant-caregiver interaction. A model was created to acquire a body mapping, which is necessary for successful mutual imitation in infant-caregiver interaction, while discriminating self-motion from the motion of the other. The ability to predict motions and the time delay between performing a motion and observing any correlated motion provides clues to assist the development of the body mapping. The simulation results show that the development of imitation capabilities depends on a *predictability preference* (a function of how an agent feels regarding its options of ‘what to imitate,’ given its ability to predict motions). In addition, the simulated infants in our system are able to develop the components of a healthy body mapping in order, that is, relating self motion first, followed by an understanding of others’ motions. This order of development emerges spontaneously without the need for any explicit mechanism or any partitioning of the interaction. These results suggest that this predictability preference is an important factor in infant development.

**Index Terms**—infant development, imitation, body mapping, self-other distinction, predictability preference,

## I. INTRODUCTION

Imitation is a very important function in human infant development, especially for the development of our ability to understand and communicate with others. For example, simulation theory has suggested that the capacity to understand others’ internal state relies on a process which matches the observed behavior with the action of the observer, that is, imitation by the observer [1]. According to Piaget’s developmental theory [2], infants’ imitative behaviors (shown in TABLE I) are observed while the infants learn to coordinate their senses and motor skills in the first two years. Before infants come to be able to imitate other persons in stage 3, they show repetitive behaviors (it seems they are mainly attentive to their own bodies) in stage 2. This process (from stage 2 to 3) has also been observed in other studies [3]. It is suggested that infants develop a sense of ‘self’ after birth [4], that is, the self-knowledge of infants is formed during the developmental process. It may be that infants are unable to distinguish self-produced motions from motions produced by others within their perception in the early developmental

Asada Project, ERATO, Japan Science and Technology Agency, Graduate School of Engineering, Osaka University, Suita, Osaka, 565-0871, Japan, e-mail: minato@atr.jp.

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TABLE I  
INFANT BEHAVIORS IN PIAGET’S STAGES OF COGNITIVE DEVELOPMENT.

Stage (Age)	Infants’ behaviors
Stage 1 (0–1 month)	Infants operate based on reflexes.
Stage 2 (1–4 months)	Infants show primary circular reactions (reproduction of an interesting event initially occurred by chance) involving their own bodies (e.g., repeating the motion of passing their hand before their face).
Stage 3 (4–8 months)	Infants actively experience the effects their behaviors on external objects and repeat actions to bring about a desirable consequence (secondary circular reactions). Infant imitates an adult who is imitating him/her.
Stage 4 (8–12 months)	Infants coordinate actions into new and more complex sequences and start to show intentional, goal-directed behaviors. Infants can imitate behaviors without feedback (e.g., facial gestures).
Stage 5 (12–18 months)	Infants experiment with new behavior in a purposeful, trial-and-error way (tertiary circular reactions). Infants actively imitate new behaviors.
Stage 6 (18–24 months)	Infants develop the ability to use primitive symbols. Infants become capable of deferred imitation and start to solve certain types of problems mentally.

process. However, infants come to repeat their own motions in advance of imitating others even though they are frequently in the presence of other people (caregivers) and they may observe not only self-produced motions but also movements produced by others. In primary circular reactions, infants may be unable to recognize ‘their body’ motions but just respond to interesting events, however, it is considered that these reactions work as self-imitation for the development of infant’s sensorimotor coordination [5]. We infer that the infant acquires the ability to distinguish self from others during this process (the transition from self to mutual imitation). This developmental process is considered to be essential for imitation development. However, not many studies have focused on this mechanism. This paper focuses on the mechanism of the transition from self to mutual imitation in the process of acquiring a body mapping.

Imitation requires a body mapping that associates an observed motion with the corresponding motor commands needed to perform the same action. Although some studies have suggested that infants have an innate body mapping, and there have been some examples of neonates imitating their parents in some manner (ex., [6]), we consider a neonate’s body mapping to be not sufficiently innate and that it is acquired, at least in part, through sensorimotor experiences after birth (ex., [7]). Self-imitation requires a mapping that associates an observed self-motion with the corresponding motor command (hereafter called the ‘self-model’), while other-imitation needs a mapping that associates an observed other-motion with the corresponding motor command (here-

after called the ‘other-model’). The development of imitation capabilities should involve the acquisition of these two models with which self and other’s motions become distinguishable. This paper accounts for it as the development of self-other distinction in the body mapping acquisition.

Some studies have focused on the mechanisms of body mapping acquisition. Oztop and Arbib [8] proposed a model to acquire a body mapping related to grasping motions through a hand state which is a viewpoint-independent image feature. An alternative clue, which aids the learning of the body mapping, is when the learner is imitated by another person. In fact, it has been reported that caregivers frequently imitate their baby in various situations, especially in vocal interaction (ex., [9–13]). Ishihara et al. [14] proposed a model in which infants learn how to vocalize vowels through mutual imitation with caregivers. Yokoya et al. [15] suggested that a body mapping is acquired through the process of being imitated by another person. However, these studies assumed that other persons (caregivers) can already be discriminated from self and that the self-model is acquired first and then followed by the acquisition of the other-model based on the prior learned self-model. This explicit partitioning of interaction does not happen in real world situations; that is, at no point do infants get an opportunity to fully develop their self-model in the absence of any other environmental factors and only then start to have caregivers interact with them. Rather, the infants themselves must possess an innate mechanism that automatically causes the developmental order, beginning with the self-model acquisition and proceeding to the acquisition of the other-model, to emerge spontaneously.

This paper reports a study of a mechanism behind the development of an infant’s body mapping which enables self-imitation and the ability to imitate others through infant-caregiver interaction. This mechanism concerns the acquisition of imitation capabilities and the ability to distinguish self from others in the circumstance of being with a caregiver. We study the mechanism through a computer simulation of infant-caregiver interaction in the standpoint of the constructivist approach called Cognitive Developmental Robotics [16]. Since the study on the mechanism of imitation development is an intricate issue, imitation development was simplified into the acquisition of self-model and other-model through infant-caregiver interaction and, in addition, essential factors for bringing about the transition from self to mutual imitation were explored. We built a minimal model to represent the body mapping and simulated interactions between infant and caregiver. We focused only on the imitative behaviors of the infant and the caregiver in their interaction and did not specify their task explicitly. In order to learn the body mapping, the infant needs to be imitated by the caregiver, and also the infant needs to imitate the caregiver because it is considered that the caregiver’s imitative behavior is elicited when he/she is imitated [17]. At first the infant cannot correctly imitate because of his/her immature body mapping and proceeds to learn the mapping through the imitative interaction. During this interaction, the agents need to choose a motion from one corresponding to self motion (self-imitation) and one corresponding to the other’s motion (imitating other). This

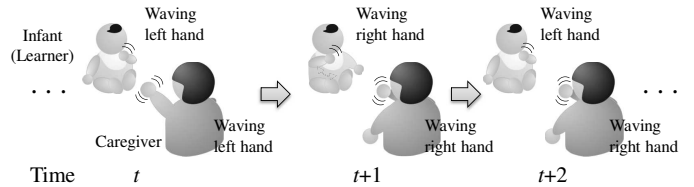


Fig. 1. Model of mutual imitation in infant-caregiver interaction.

motion selection problem possibly relies on the predictability of the observation since it has been observed that infants are highly sensitive to contingency [18, 19]. We propose a mechanism for the motion decision that uses a *predictability preference*, which is the preference for a motion modulated by the predictability. It is expected that the infant does not acquire the body mapping if the caregiver never imitates the infant, because we assume the body mapping is constructed owing to the other’s imitation. It is also expected that the infant is unable to discriminate self from other if the infant and caregiver keep imitating each other with the same motion because the self motor command can be matched equally with both the observed self-motion and the other’s motion. It is inferred that the motion selection affects the course of the interaction and the development of imitation. This paper shows that the predictability preference which is typical for healthy people can lead to the successful learning of body mapping. It is generally desired that a developmental model can reproduce not only typical development but also disordered development when the model has some deficits in order to improve the validity of the model. We also investigate imitation development when the infant has an atypical predictability preference. It is suggested that the predictability preference is one of the most important factors governing the development of body mapping, which involves the development of self-other distinction and imitation, by showing how a typical preference results in a typical developmental process and atypical preferences lead to a disordered body mapping.

## II. A MODEL FOR THE EMERGENCE OF IMITATION DEVELOPMENT

This paper studies a mechanism behind the development of self-imitation and the imitation of others. The main focus is to explore the infant’s mechanism that automatically causes the developmental order to emerge spontaneously. Our model does not include the explicit mechanism of developmental sequence or specific tasks. This differentiates our model from those of the existing studies.

In order to deal with this issue in the computer simulation, we built a minimal model to represent the body mapping and the infant-caregiver interaction. To simplify the model, we make the following assumptions:

- Body motions are spatially and temporally discretized. The motion segmentation problem, that is, knowing when a discrete motion begins and ends, is also important in infant development. The capabilities of the segmentation and the self-other distinction might develop in parallel and influence each other. However, we assume that the

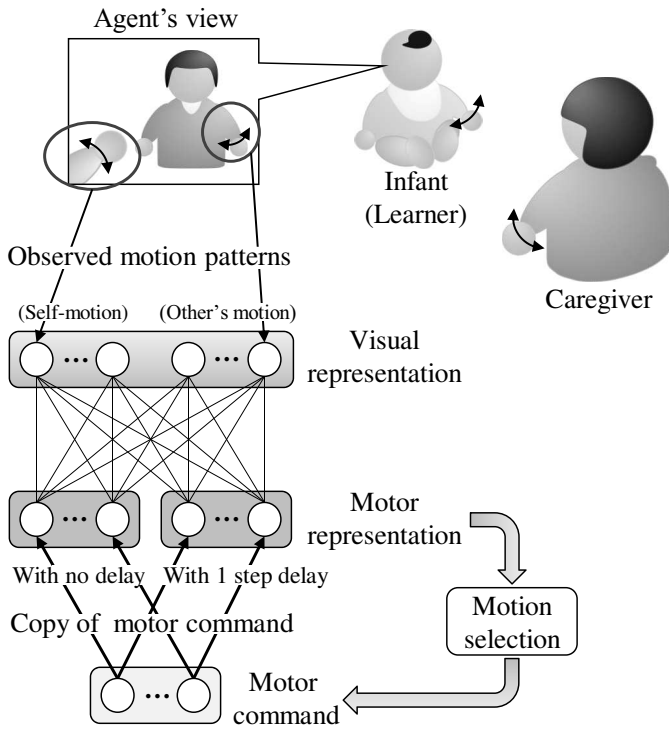


Fig. 2. Model of body mapping.

motion segmentation capability is acquired in advance. This is indeed a large assumption, but was made for the sake of keeping the model tractable.

- Both the infant and the caregiver have homologous body motions.
- The agents show motion either by trying to imitate, or by selecting an action to be performed randomly (here, “agent” denotes infant or caregiver). Also, no explicit task is given to either agent.

The agent’s motion is categorized into imitation or other motions in order to focus only on imitation which is necessary for the body mapping acquisition.

- Both agents perform a body motion at the same time and observe both their own motion and that of the other. An example of infant-caregiver interaction is shown in Fig.1. The caregiver in time step  $t+2$  shows an imitative motion (the caregiver observes the infant’s right hand movement in time step  $t+1$  and shows the same motion in time step  $t+2$ ). To the contrary, the caregiver in time step  $t+1$  does not show an imitative motion, i.e., performs a randomly selected motion (the infant’s motion in time step  $t$  is left hand movement but the caregiver’s motion in time step  $t+1$  is right hand movement). A body motion is assumed to be a motion pattern of arms and legs which can be seen by the agent himself such as a waving hand in front of the face.

The self-other distinction can be explained as an issue to discriminate between observed motions with perfect contingency (observed self-motions), with imperfect contingency (observed other’s imitative motions), and with no correlation to the self-motion. We have this assumption to present situations including these observations.

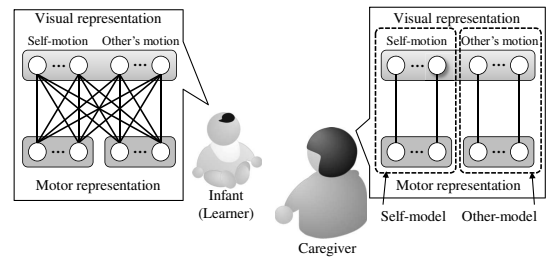


Fig. 3. Body mappings of infant and caregiver.

- The caregiver has a perfect body mapping, while the infant does not know the correct correspondence and cannot initially distinguish between observed self and other motions.  
The infant imitates by executing a body motion which corresponds to the observed body motion according to his/her immature body mapping.
- The infant learns the body mapping using unsupervised learning, that is, without any explicit reward.  
The infant cannot know whether or not his/her imitation is successful because of his/her immature body mapping. It is observed, in fact, that the caregiver indicates that the imitation is successful by giving a reward. However, the reward is not always expected in the infant-caregiver interaction. This paper deals with the extreme case in which no reward is given by the caregiver. The body mapping is learned simply by associating motor commands with observed motions.
- The agent can predict the successive observation from the self motor command by using the body mapping inversely.

The body mapping is represented by a network as shown in Fig.2. The body motions in the observation and the motor command are discretized. An observed body motion is represented by one node in the visual representation layer and the motor commands for a body motion are represented by a single node in the motor representation layer. For the sake of convenience, the observed self-motions are displayed in the left half of the visual representation layer and the observed other’s motions are displayed in the right half, though the learning rules do not discriminate between the sources of the body motions. The meanings of the commands in the motor representation layer are duplicated (i.e., two nodes indicate the same motion command) by which the infant can acquire two mappings: a mapping that associates an observed self-motion with the corresponding self-motor command (self-model) and a mapping that associates an observed other’s motion with the corresponding self-motor command (other-model). When the agent imitates the observed motion, it is done by executing a body motion which corresponds to the observed motion according to the agent’s body mapping.

Initially, the infant’s connections between the visual representation layer and the motor representation layer are immature (i.e. connected with small random weights), as shown in Fig.3, and develop over the course of the imitation period according to the interaction with the caregiver. A Hebbian

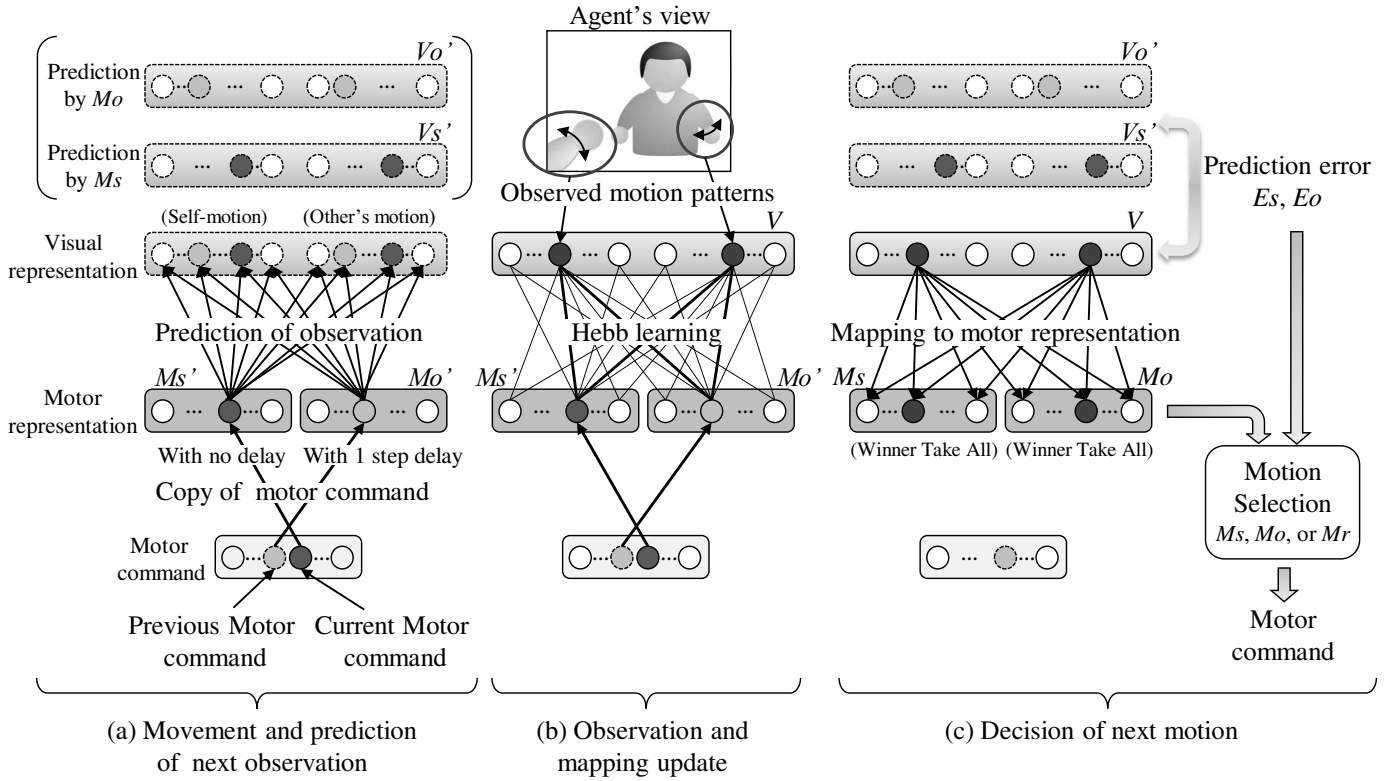


Fig. 4. Motion decision process.

learning rule reinforces associations between the self-motor commands with the corresponding body motion observed at the same time that the motor command is executed. The caregiver has a perfect body mapping in which the self-model and other-model are correctly separated and both layers are correctly connected (Fig.3). The infant acquires the body mapping if he/she associates the correct motor commands with the observed caregiver's imitative motions.

In order to discriminate between observed self generated motions and those of the other, the self-model and the other-model need to be represented separately. One of the clues needed by the learner in order to acquire these separate models is a difference in the delay of observation. When a motor command is executed, the corresponding self generated motion is observed immediately after the execution, while the corresponding other's motion is observed with a one step delay (assuming that the other is imitating). In order to make use of the difference in the delay of observation, the body mapping model is assumed to have a structure in which the motor command is copied back to the motor representation layer in two ways: without delay and with a one step delay. This is equivalent to an efferent copy of a motor command. For the sake of convenience, the motions in the left part of the motor representation layer shown in Fig.2 (motor commands copied without delay) is called the self-related motions, and the motions in the right part (motor commands copied with a one step delay) is called the other-related motions.

The simulation proceeds as follows: (a) The agents execute a motor command, (b) The learner updates the body mapping, and (c) The agents select a new motion to perform as shown

in Fig.4.

- The current motor command and the previous motor command are copied to the motor representation layer ( $M_s'$  and  $M_o'$ ) when the motor command is executed. The resulting observations are predicted ( $V_s'$  and  $V_o'$ ) from  $M_s'$  and  $M_o'$  with the inverse mapping of the body mapping.
- The body mapping is updated by strengthening the connection weights between the observed motions ( $V$ ) and the copied motor commands on the motor representation layer ( $M_s'$  and  $M_o'$ ) using a modified Hebbian learning rule.
- The motions corresponding to the observed motions are found by the body mapping ( $M_s$  and  $M_o$ ), and the prediction errors ( $E_s$  and  $E_o$ ) are calculated from  $V$ ,  $V_s'$ , and  $V_o'$ . The next motion is chosen between  $M_s$  and  $M_o$  based on the prediction errors.

Since the agents observe two motions (self-motion and other's motion) at the same time, two motions (self-related motion and other-related motion) are retrieved from the observed motions as shown in Fig.4 (c). When the agents imitate the observed motions they must choose an imitative motion from two motions. The self-related motion means imitating self-motion (self-imitation) and the other-related motion means imitating the other's motion. We hypothesize that the agents choose the motion based on the predictability of the observation. This paper proposes a *predictability preference* for motion decision, which is an innate function relating predictability to action selection. The agents predict the resulting observations from the activations in the motor representation layer by inverting

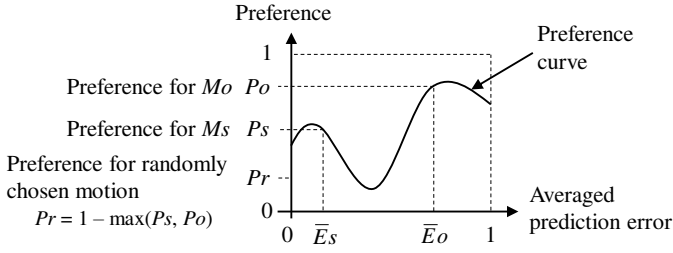


Fig. 5. Decision of imitative motion based on predictability preference.

the body mapping (the self-model and other-model are not discriminated). Two patterns of the observation ( $V'_s$  and  $V'_o$ ) are predicted from the copied current motor command  $M'_s$  and previous motor command  $M'_o$  as shown in Fig.4 (a). When the agents observe the motions, two prediction errors ( $E_s$  and  $E_o$ ) are calculated, which are related to  $M'_s$  and  $M'_o$ , respectively. The preferences for the self-related and other-related motions ( $P_s, P_o \in [0, 1]$ ) are determined based on the prediction errors  $E_s$  and  $E_o$ , respectively. The preference curve modulates the preference of a motion based on the prediction error, as shown in Fig.5. The preference is assumed to be determined not only by the current prediction error but also the prediction errors in the past several steps; here the averaged prediction errors ( $\bar{E}_s, \bar{E}_o \in [0, 1]$ ) are used. In addition, both agents can choose a random motion ( $M_r$ ) as an additional option as well as imitative motions. The preference for the random motion is defined as  $P_r = 1 - \max(P_s, P_o)$  so that  $P_r$  has a high value when both the preferences for imitative motions have low values. The agents probabilistically choose a motion among  $M_s$ ,  $M_o$ , and  $M_r$  in proportion to the ratio of  $P_s$ ,  $P_o$ , and  $P_r$ . If the body mapping is correct, the self-motion is correctly predicted from  $M'_s$ . The other's motion is correctly predicted from  $M'_o$  only when the other imitates. The agent's action selection affects the other's prediction error, and therefore determines the balance between self-imitation, imitating other, and randomly selected motion, which in turn affects the course of the interaction and the development of imitation.

The update uses a modified Hebbian learning rule which takes mutual exclusivity into consideration [20]. Let  $w_{ij}$  be the connection weight between node  $i$  in the perception layer  $p$  and node  $j$  in the motor representation layer  $m$ . The cross-anchoring Hebbian learning rule is given by:

$$\Delta w_{i^*j^*} = \eta ({}^p d_{i^*j^*} {}^p a_{i^*} \cdot {}^m d_{i^*j^*} {}^m a_{j^*} - w_{i^*j^*}). \quad (1)$$

This is the update rule for the connection between the most activated nodes, where  $\eta$  is the learning rate,  $i^*$  and  $j^*$  are the most activated nodes in their respective layers,  ${}^p a_{i^*}, {}^m a_{j^*} \in [0, 1]$  are their respective activations and  ${}^p d_{ij}$  and  ${}^m d_{ij}$  are the dynamic anchoring rates, given by the following equations:

$${}^p d_{ij} = \exp\left(-\frac{\sum_{k, k \neq j} w_{ik}}{p\sigma^2}\right), \quad (2)$$

$${}^m d_{ij} = \exp\left(-\frac{\sum_{k, k \neq i} w_{kj}}{m\sigma^2}\right), \quad (3)$$

where  ${}^p\sigma$  and  ${}^m\sigma$  are parameters that determine the degree of

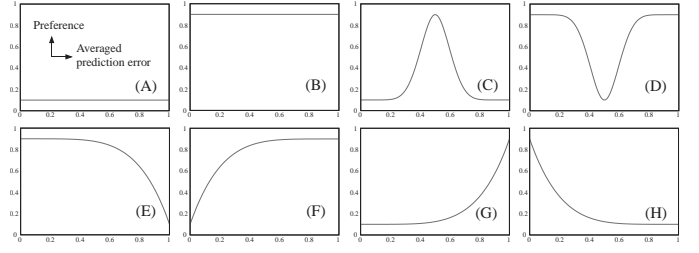


Fig. 6. Test patterns of preference curve.

anchoring. The remaining connections are updated as follows:

$$w_{ij^*}(t) = w_{ij^*}(t-1) - \eta_p (1 - {}^p d_{ij^*}) \Delta w_{ij^*}, \quad (4)$$

$$w_{i^*j}(t) = w_{i^*j}(t-1) - \eta_m (1 - {}^m d_{i^*j}) \Delta w_{i^*j}, \quad (5)$$

where  $\eta_p$  and  $\eta_m$  are constant coefficients of the competition. This means that learning is greater when there is more mutual exclusivity. For situations where such behavior is desired, that is, if the task calls for mutually exclusive networks, and this is known *a priori*, this modified Hebbian learning rule can result in a significant speedup in learning. This learning procedure is applied four times per time step, once for each combination of self/other observations and self/other motor representation pairs.

### III. SIMULATIONS FOR EMERGENCY OF IMITATION DEVELOPMENT

#### A. Simulation settings

In order for the learner to acquire the body mapping and imitation capability, he/she needs to elicit imitative motions from the caregiver. Too much imitation from the caregiver might make it difficult for the learner to discriminate their own motions from those of the caregiver, whereas too little imitation will not allow the learner to fully develop a correct mapping for self and other motions. A good caregiver should be able to strike the right balance of imitation to allow the infant to develop their body mappings naturally, and the learner needs to be able to elicit the right balance of imitation. In our model, the preference curve determines this balance of imitation. We hypothesize that a typical, healthy preference leads to a typical developmental process and an atypical preference can only result in a disordered body mapping.

We investigated the effects of using different shaped preference curves on the developmental process of the body mapping. In this simulation, we tested eight distinct preference curves for the learner. The profiles of the curves are qualitatively different, as shown in Fig.6.

The prediction error of the preference curve (the abscissa in Fig.5) essentially indicates a measure of novelty in the resultant observation. We set the range of preference values to  $[0.1, 0.9]$  so as to avoid extreme cases (e.g., the agent *always* preferring the self-related motions). The meanings of the preference curves are:

- A *Nothing*: Mostly choose random behavior, regardless of predictability
- B *Everything*: Mostly try to imitate, regardless of predictability

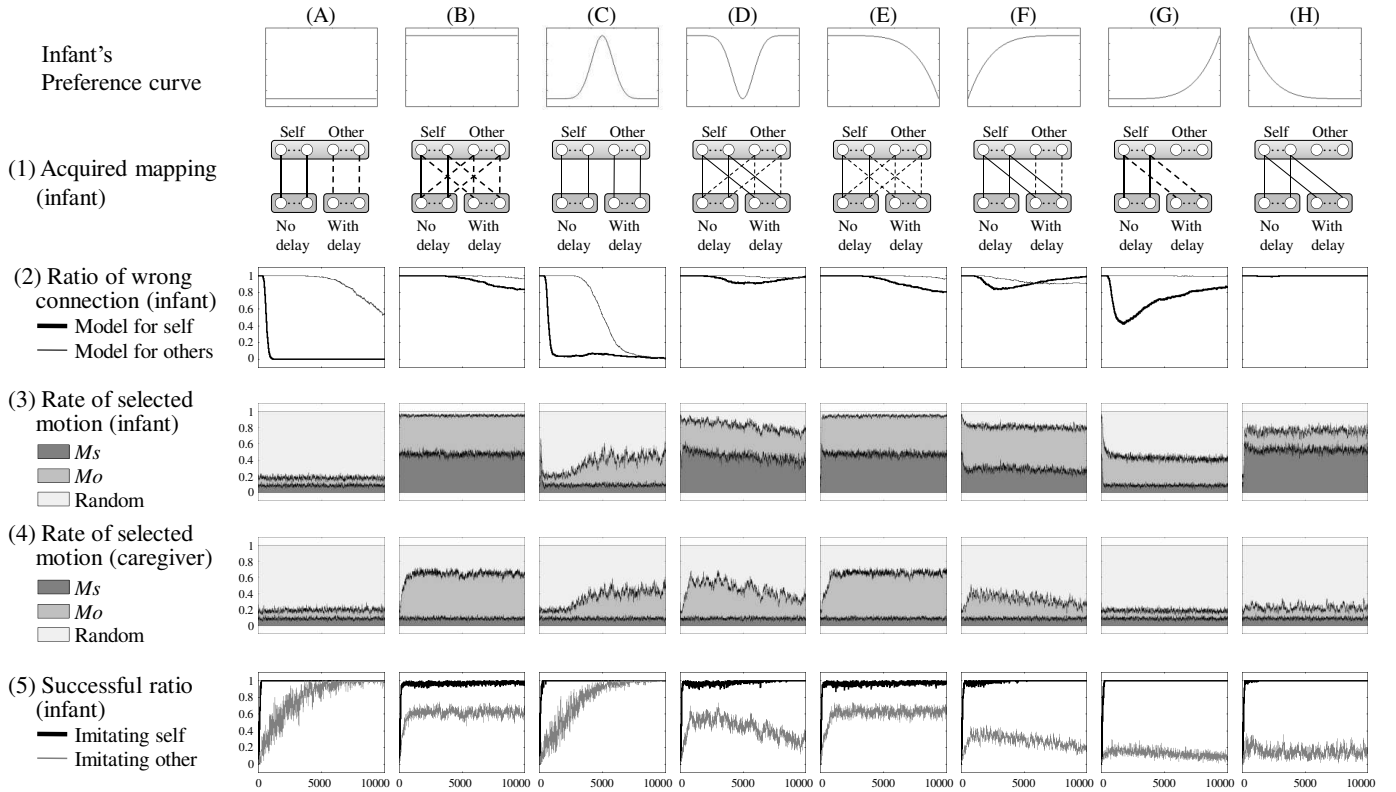


Fig. 7. Simulation results (caregiver uses preference curve (C)).

C *Comfort zone*: Prefer neither too much familiarity, nor too much novelty

D *Extremes*: Prefer very familiar or very novel situations

E *Novelty avoiding*: Dislike very novel situations

F *Familiarity avoiding*: Dislike very familiar situations

G *Novelty greedy*: Prefer very novel situations

H *Familiarity greedy*: Prefer very familiar situations

Preference curve (C) simulates a Wundt curve where greatest pleasure comes from a moderate amount of stimulus novelty, which is considered to be a person's intrinsic preference [21]. It shows a characteristic that the agent does not prefer motions from which successive results can be accurately predicted (i.e., results are too-familiar) and cannot be completely predicted (i.e., results are too-novel). This curve shows an inverted-U relationship between novelty (opposite of familiarity) and preference. Many studies have argued the inverted-U relationship (ex., [22,23]) and have shown that this kind of relationship appears in psychological experiments (ex., [24,25]). The caregiver was assumed to be a typical healthy person, and was therefore given this preference curve.

The simulation assumes that the agents have  $N_a$  patterns of body motion ( $N_a = 30$  in this work). The range of the connection weights of the body mapping is  $[0, 1]$ , and the learner's initial weights are set randomly in the range of  $[0, 0.1]$ . The caregiver has a value of 1.0 on the correct connections and 0.0 on the wrong connections; these are fixed and do not change during the simulation. In the prediction phase, we assume that the agent predicts motions whose values are greater than a threshold (0.1) in the visual representation layer after the inverse mapping is calculated ( $V'_s$  and  $V'_o$  in

Fig.4 (a)). The prediction errors  $E_s$  and  $E_o$  are calculated as the ratio of the number of predicted but unobserved motions to the total number of predicted motions. The averaged predicted errors  $\bar{E}_s$  and  $\bar{E}_o$  are calculated from the errors in the last 20 steps. In this work, the learning rate  $\eta$  was set at 0.05,  $\eta_p$  and  $\eta_m$  were 0.5, the weights  $w_{ij}$  were clamped to the range  $[0, 1]$  and  $p\sigma$  and  $m\sigma$  were both set to  $N_a^{\frac{1}{2}}$ , which, in this work, was 2.34.

## B. Results

The averaged simulation results of 20 trials are shown in Fig.7. One trial is terminated at 10000 time steps. The caregiver always uses preference curve (C), and each column of the figure shows the graphs when the infant is using curves (A)-(H). Each row in the figure shows the following results:

(1) Acquired mapping of the infant.

The network shows the qualitative features of the mapping acquired by the learner. Solid lines means that over 80% of the correctly corresponding connections have strong weight (more than 0.5), dashed lines means that 20% to 80% have a strong weight, and with less than that no lines are drawn.

(2) Ratio of wrong connections in the infant's mapping.

The graph shows ratios of the number of motions which are not correctly connected in the learner's self-model and other-model. The abscissa shows the simulation time step  $[0, 10000]$  (the same for each row). Here, we count a correct connection as follows: when a connection from a node in the visual representation layer has maximal

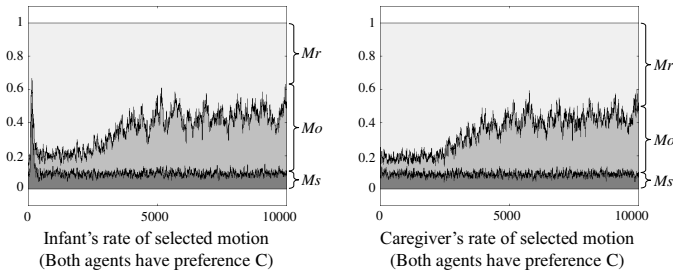


Fig. 8. The rates of selected motion for preferences C (same as those in Fig.7).

weight among the connections from the node, it is correctly connected to the corresponding node in the motor representation layer, and the difference between its weight and the second maximal weight is more than a threshold (0.5), we count it as a correct connection. The threshold is used to check exclusivity of the connection.

(3) Rate of selected motion in the infant's action selection. The graph shows rates of the number of times the self-related motion  $M_s$ , the other-related motion  $M_o$ , and the random motion  $M_r$  are selected by the learner in the last 20 steps (the sum of them is always 1.0).

(4) Rate of selected motion in the caregiver's action selection.

The same as (3) for the caregiver.

(5) Successful ratio of infant's imitation.

The graph shows successful ratios of imitation when the learner selects  $M_s$  and  $M_o$  in the last 20 steps.

In the simulation modeled in the paper, only infants with preference curve (C) can successfully acquire the correct body mapping in which the self-model and other-model are clearly separated, as can be seen in Fig.7 (1). It can be seen that the successful ratios of self-imitation and imitation of the caregiver converge to 1.0 (Fig.7 (5)-(C)), which means that the learner acquires the capability of correct imitation. When the agents have preference curves (B), (D), (E), or (F), the observed motions are correctly associated with the self-motor commands but the self-motions and other's motions are not distinguishable. When the agents have preference curves (A), (G) or (H), the observed self-motions are correctly associated with the self-motor commands but some observed other's motions are not associated with any motor commands (the weights are not zero but are too small to be considered exclusive). This means that the learner is unable to construct a model of the other.

The learner becomes able to imitate self-motions after about 300 steps with any preference curve as can be seen in Fig.7 (5), even though some wrong connections remain due to the exclusivity of the connections being insufficient. This is because the self-motions are always somewhat correlated with the corresponding motor commands. However, the success of the developmental process depends greatly on the preference curve.

*a) Typical developmental process:* The learner using preference (C) frequently chooses self-related motions for the first 300 steps but then the frequency quickly decreases

as can be seen in the left of Fig.8. Then, the frequency of the other-related motions increases relative to the self-related motions, and the learner acquires the other-model. This indicates a developmental process in which the infant's self-imitation appears early on, and disappears once the self-model is acquired. Then the mutual imitation between the infant and the caregiver begins. The resultant processes, therefore, involve the process of transition from self to mutual imitation, that is, the developmental process of the infant's self-other distinction. It is also explained that in this transition an attentional shift from perfect contingency (self-motions) to imperfect contingency (other's imitative motions) occurs owing to preference (C).

The self-imitation in the results is quickly inhibited. It is inferred that the learner confuses the self-model and the other-model if he/she continues to self-imitate. It can be also said that the self-model and the other-model are confused if the caregiver keeps repeating the same imitative motion. We can see from the graph on the right of Fig.8 that the caregiver in these results frequently shows random motions. In the long run, he/she displays all motions. This is due to the low preference for motions from which the agent can accurately predict a successive observation (i.e., motions which elicit too-familiar motions), and this characteristic could be necessary for a typical development.

In this simulation, the self-model is quickly acquired because a correct pair of the motor command and the observation of self-motion is always presented to the infant's learning system. On the other hand, the learning of the other-model takes longer because a correct pair of the command and the observation of other's motion is not always presented to the learning system. Moreover, after the infant's self-imitation is inhibited, the other-model is slowly learned owing to the caregiver's occasional imitation (because the caregiver's preference to the imitation is low) until the mutual imitation becomes dominant. This also could happen in the infant developmental process if the learning is an unsupervised manner. However, some rewards are actually expected in the learning of the body mapping and the learning can be accelerated compared to our results. The self-model is acquired in about 1,000 steps and the other-model is acquired in about 8,000 steps, however, this result could be an extreme case because no reward is assumed.

*b) Atypical developmental process:* In the results with preferences (B), (D), (E), and (F), it was observed that the learner chooses random motions with low frequency, as can be seen in Fig.7 (3) and tends to keep same motions. The caregiver is encouraged to imitate these actions, then this results in an infant who has trouble differentiating the observed actions. This is because the learner has high preference for a wide range of the prediction error. Meanwhile, when the infant has preferences curve (A), (G), or (H), the caregiver does not often imitate (the rate of selected other-related motion is low in Fig.7 (4)) and the infant, therefore, cannot acquire the other-model. These infants could not elicit the imitation behavior from the caregiver because:

- The learner with the preference curve (A) always prefers random motions.
- The learner with the preference curve (H) prefers only

self-imitation due to the quickly acquired self-model.

- The learner with the preference curve (G) prefers using the immature other-model rather than the mature self-model.

Since the caregiver is assumed to have preference curve (C), it is up to the infant to choose behaviors that are within the limits of acceptable predictability. The infant must be able to elicit well-balanced imitation behavior from the caregiver. Otherwise, it is incapable of forming the correct mapping.

It is considered that the confused body mapping and the deletion of the other-model express mappings of developmentally disordered children; the former indicates a disorder in self-other distinction and the latter indicates a disorder in understanding other people. For example, earlier psychoanalytic theories have suggested that a developmental disorder of distinction between self and non-self is fundamental to children with autistic spectrum disorders (ASD) (ex., [26]). Recent studies have found functional brain abnormalities in children with ASD in the task of distinguishing their own face from those of others (ex., [27]). A confused body mapping could be related to these failures in self-other distinction. Furthermore, psychological studies have reported that children with ASD lack a theory of mind (ex., [28]). A body mapping without an other-model could be related to the failure in estimating other people's internal states. In the result with preference (A), the other-model is not learned in 10000 steps but is slowly learned owing to the caregiver's occasional imitation. The infant with preference (A) can learn the other-model by taking much time. It might be related to a kind of delayed-development of the infant. Additionally, the transition from self to mutual imitation is not seen in this result, which means that it is not a typical developmental process.

Concerning the preferences, it has been observed that developmentally disordered children tend to show strong interest in one object and repeat the same behavior patterns (especially children with ASD [29]), and that this tendency could be explained from the preferences (B), (D), (E), and (F). It has also been observed that developmentally disordered children tend not to initiate communication with other people (especially children with ASD [29]), and this tendency could be also explained from low preference for the wide range of the prediction error in preferences (A), (G), and (H). The preference curve (H) is for highly-predictable motions but the agents do not initiate communication because they prefer only self-imitation. The learner with preference curve (G) prefers using the immature other-model (i.e., always explores new things) and, therefore, does not communicate with other people.

Using our system, we can test disordered developmental mechanisms and processes and observe the resultant developmental disorder. For example, the infant with preference curve (H) (Familiarity greedy) tends to frequently imitate self motion and consequently fails to develop its other-model; which is typical in the developmental process of children with ASD. This result suggests that a failure in acquisition of a healthy body mapping for imitation stems from atypical preferences of individuals, though it is necessary to investigate why the atypical preferences occur in the first place.

### C. Summary

From the results shown above, it is considered that the following aspects are necessary for typical development (the transition from self to mutual imitation).

- The acquisition of the self-model by self-imitation and the subsequent inhibition of self-imitation.
- The elicitation of imitation from the caregiver through the infant's self-imitation and other-imitation.
- The experience of a wide variety of motions (the perseverance of certain motions can result in atypical development).

Removing one of these requirements results in abnormal development. These requirements depend on the predictability preference of the agents. The preference with the inverted-U shape, which is typical in a healthy person, leads to a typical developmental process while the atypical preferences leads to a disordered body mapping. We emphasize that a typical developmental process of transition from self to mutual imitation emerged from our system without any explicit mechanism of developmental order. The results suggest that the predictability preference is a very important factor in the development of an infant's body mapping, which enables it to distinguish self-motion from other's motion and gives it the ability to imitate both. It is also suggested that an abnormal body mapping structure stems from atypical predictability preferences.

### D. Discussions on the simulation model

*a) Assumptions of the body mapping and interaction model:* In order to simplify the model, we assumed that the body motions of the agents are spatially and temporally discretized. Here, we consider the capabilities of the motion segmentation in infancy. Concerning the spatial motion segmentation, Rochat and Morgan [30] have revealed that 3–5 months old infants are sensitive to differences in the directionality of the self-produced movements of their legs. This suggests that the target infants in the simulation (1–8 months old infants) could segment the body motions at least with respect to the directional information of the motions. The capability of the temporal segmentation is discussed in a rhythm of body movement. A rhythmic body movement is considered to be a sign of the motion segmentation. McAuley et al. [31] studied the tempo of people's spontaneous rhythmic movements. They revealed that 4–5 year old children frequently showed rhythmic movements of about 300ms tempo (period) and the rhythm was shifted to a slower tempo with increasing age. Young infants (less than 12 months) also show rhythmic motions (e.g., arm banging and rattle shaking). Merker et al. [32] have shown that 6 months old infants can rhythmically show movements of 1–3 Hz to music. It is guessed, from these facts, that the target infants could have the capability to discretize body motions with the above temporal resolution. However, it is considered that the motion segmentation and the imitation capability are developed in parallel in the infant's developmental process.

In our model, the delay introduced by copying the motor commands plays an important role in the acquisition of the other-model and self-other distinction. The model assumed



that the delay is discretized and fixed to a single step because both agents are assumed to synchronously perform their body motions at fixed time intervals. This assumption of interaction is not realistic. In real-world situations, the motions of both agents are not simultaneous and the delay varies in several time-scales owing to the context of interaction. Hiraki [33] has investigated infants' sensitivity to a temporal aspect of contingency using a delayed self-image and revealed that 5 and 7 months old infants cannot distinguish between a 1 sec delayed image of the self-movement and a live image of the self-movement (they can distinguish when the delay is 2 sec). This suggests that some time delay is allowed to discriminate self from other (small time delay can be treated as there is no delay). If our model has a mechanism to distinguish between a small delay (less than about 1 sec) and a large delay (more than about 1 sec), the model can deal with an unsynchronized interaction (the agents do not need to move simultaneously). This mechanism can be realized by assuming that the activation of the copied motor command is preserved for a short term (for example, the immediate copied motor command is activated for about 1 sec). On the other hand, a large time-scale of delay is related to the development of delayed imitation (deferred imitation). In order to deal with the delayed imitation, temporal matching of motion also needs to be considered. The resultant process in our simulation does not sufficiently account for infants' developmental process of body mapping in that the process of the spatial and temporal segmentation of the body motion is not implemented. A model that includes a mechanism for motion segmentation and allows continuous and several time-scales of delay needs to be investigated in the future.

The simulation in the paper has dealt with a kind of gesture imitation; however, it is known that a goal-oriented imitation with object manipulation (e.g., imitating position change of an object but not the hand and arm's movements to move the object) is acquired before gestural imitation [34] in the infant developmental process. This suggests that the main attention in imitation shifts from the goal of the motion to the motion itself. Some studies have shown that gestural imitation is also goal-oriented [35]. In gesture imitation, we also need to consider how to reproduce the movement (i.e., in a mirroring manner or not-mirroring manner) although our simulation did not deal with this issue. This is also an attention problem. In order to obtain a deeper understanding of imitation development, we need to further investigate the mechanism of shifting the attention in imitation.

*b) Biological mechanism related to the body mapping model:* The model of the body mapping in the paper was derived with much consideration of computational requirements (e.g., the mechanism of the delayed copy of the motor command and the duplicated motor representation layer) and was not based on anatomical evidences of biological systems. Here, we describe how the body mapping model is associated with biological mechanisms of the human brain.

In the brain of macaque monkey, a mirror neuron that fires both when the animal acts and when it observes the same action [36]. This neuron contributes to a direct matching between action and perception. Many studies have revealed

that human brain also has a mirror neuron system (MNS) to directly associate an action with the corresponding observation [37,38]. Brady et al. [39] have shown that there is dissociation in face recognition processing such that the left brain is dominant for the recognition of self and the right brain is dominant for the recognition of others. Saxe et al. [40] have suggested that extrastriate body area (EBA) in the human brain, which selectively responds to visual images of human bodies or body parts [41], distinguishes between body parts presented from egocentric and allocentric perspectives. The authors also have found that the right EBA selectively responds to visual images of body parts presented from an allocentric perspective. The future works will study how the laterality of MNS in the recognition of self and others is related to the proposed model of body mapping.

The mechanism of motor command copy in the model is equivalent to an efference copy of a motor command in the human body system. No studies have found a brain mechanism which is equivalent to the delayed copy mechanism in our model, however, we think that the delayed copy can be represented by a memory mechanism, that is, the activation of the copied motor command is preserved for a short period.

It is considered that these biological evidences are related to our model; however, we need further investigation to match our model with the human system.

#### IV. FURTHER INVESTIGATION

In addition to the basic mechanism of healthy social development, we would also like to investigate the best possible interaction methods for caregivers when dealing with atypical infants. Some computer simulation studies have investigated what kind of caregiver behavior can alter an infant's development or improve their capabilities (ex., [14,42]). A greater understanding in this area would be of enormous benefit to guide care in real situations.

If a caregiver were to assume an atypical imitation pattern, how would this affect the results of interaction? Fig.9 shows the results of varying both the infant's *and* the caregiver's preference curves. The table shows which *type* of result is acquired by the infant. The three possible types are:

- (I) *Self and Other:* Has successfully acquired both self-model and other-model. Generally results from healthy behavior from both infant and caregiver.
- (II) *Self Only:* Has successfully acquired the self-model, but the other-model is weak or absent. The infant has not successfully elicited enough imitation from the caregiver; for example, by being too unpredictable.
- (III) *Confusion:* The infant is totally confused, unable to distinguish self from other. This usually results from being too repetitive and predictable.

The first column shows that the agent successfully acquires a good body mapping in which the self-model is discriminated from the other-model most of the time. This is strange and counter-intuitive since the infant with preference curve (A) (Nothing) is almost always displaying a random behavior and rarely trying to imitate. In these developmental processes, the caregiver frequently imitates the infant motion which is

Infant Care-giver	(A)	(B)	(C)	(D)	(E)	(F)	(G)	(H)
(A)	IIa	IIb	IIa	IIb	IIb	IIc	IIc	IIb
(B)	I	IIIe	IIIa	IIIc	IIIe	IIIa	I	IIIb
(C)	IIa	IIIe	I	IIIc	IIIe	IIIh	IIa	IIb
(D)	I	IIIe	IIIb	IIIc	IIIe	IIIb	I	IIIg
(E)	I	IIIe	IIIa	IIIc	IIIe	IIIa	I	IIIg
(F)	I	IIIe	IIIb	IIIc	IIIc	IIIa	I	IIIb
(G)	I	IIIe	I	IIIb	IIIc	IIIb	I	IIIf
(H)	I	IIIe	IIIc	IIIc	IIIe	IIIc	IIIg	IIb

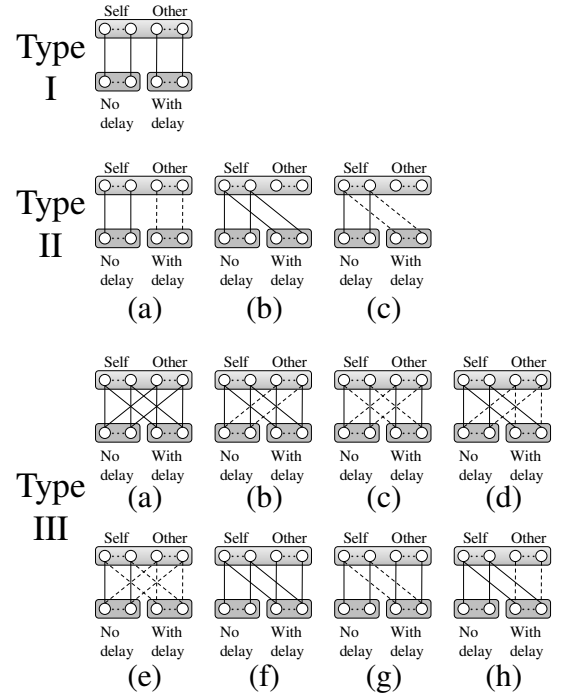


Fig. 9. Results from all possible combinations of preference curves.

randomly chosen, in other words, the caregiver voluntarily shows various imitative motions to the infant. However, the developmental process of transition from self to mutual imitation does not emerge. These results suggest that the infant can acquire a healthy body mapping if the caregiver frequently imitates various motions of the infant on his/her own initiative, even though the infant does not try to imitate self/caregiver's motion. We suggest that this is an unrealistic developmental process because a caregiver would not consistently continue to imitate the non-interactive body babbling over an extended period of time.

As another remarkable result, it appears that even when the infant has atypical preference curve (G) (novelty greedy), it can actually develop a healthy body mapping through the interaction with a caregiver that has an atypical behavior. Curiously enough, it fails when the caregiver displays behavior based on typical preference curve (C), but manages to do well most other times. The result suggests that the preference of novelty greedy usually does not properly elicit the imitation from the caregiver with typical preference, but it does from the caregiver with atypical preferences. The healthy body mapping is acquired in these cases but the developmental process of transition from self to mutual imitation does not emerge.

It is also interesting to note that row (C) (see Fig.9) shows all three types of result, more so than any other row. This suggests that this preference curve leads to a much wider repertoire of behavioral types and richer dynamics, rather than simple saturating or repetitive results. The infant must be careful to be neither too predictable nor too unpredictable, but instead aim for the caregiver's comfort zone. This way, he/she can successfully elicit just the right amount of imitation, with which the correct mappings can be learned. The typical developmental process of transition from self to mutual imita-

tion emerges only for the pair of infant and caregiver both who have typical preference curve. These results, characterized by the difference between typical and atypical preferences, lend credence to our simulation.

In this section, we have investigated the multiple combinations of preference curves, however, our model is too simple to simulate various interaction patterns. Further investigation is needed to improve the simulation model (by removing the larger assumptions).

## V. CONCLUSION

In order to study the mechanisms of imitation development involving the acquisition of self-other distinction and imitation capabilities, a model was made that was able to develop a healthy body mapping, which is a prerequisite for imitation, during the interaction between infant and caregiver in an imitation game, while discriminating self-motion from the other's motion. Although the model is not based on anatomical evidence of biological systems, we assume that humans have something equivalent to our system, with mechanisms to utilize the difference in observational delay and to choose self-imitation and other-imitation in order to solve problems of self-other distinction and body mapping acquisition from mutual imitation.

It has been shown that the order of body mapping acquisition (first the self-model followed by the other-model) can emerge from our system without any explicit mechanism of developmental sequence or specific tasks. We also have shown the inverted-U preference curve is indeed a viable proposal for healthy development. However, the proposed model does not sufficiently account for infants' developmental process of body mapping in that the process of the spatial and temporal segmentation of the body motion is not considered.

The analysis of the simulation results is still speculative but suggest that the predictability preference is one of the factors which govern the development of an infant's body mapping, enabling it to distinguish and imitate self-motions and the motions of others. Future work will need to justify the model and the resultant developmental process by comparing them with human infants' natural developmental processes. It would be interesting to see if the model allows a particular caregiver's support policy to transform an abnormal development to a typical one, and then to compare that to real data regarding infant development. Furthermore, if an atypical preference leads to developmental disorder, a mechanism to produce atypical preferences should be investigated. Our assumption that the capability of motion segmentation is already acquired needs to be investigated and if possible, a mechanism for its acquisition should be added to the system. Finally, it is also important to realize the developmental process with real robots to find issues that were not modeled in our computer simulation. The motion segmentation issues need to be investigated also for the real world implementation.

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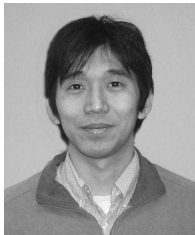
## ABOUT THE AUTHORS



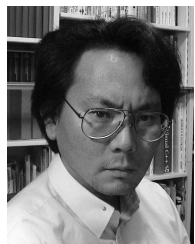
**Takashi Minato** was a researcher of CREST, JST since December 2001 and obtained his PhD degree in Engineering from Osaka University in 2004. He was an assistant professor of the Department of Adaptive Machine Systems, Osaka University since September 2002. He worked as a researcher for ERATO, JST since June 2006. He has currently been working as a researcher in ATR Hiroshi Ishiguro Laboratory since January 2011.



**Dale Thomas** received a BSc in Cybernetics and Control Engineering from Reading University, UK, in 2000. From then until 2003 he worked as a researcher in Zürich, Switzerland, and in 2004 he received an MSc in Evolutionary and Adaptive Systems from Sussex University, UK. After that he spent several years as a programmer in the computer games industry in Japan, before moving to Osaka University, in 2008, to work as a researcher for the Asada Project, ERATO, Japan Science and Technology Agency. His main research interests include: computer graphics, artificial intelligence and artificial life, with particular emphasis on embodiment, physical simulation and morphogenesis.



**Yuichiro Yoshikawa** received the Ph.D. degree in Engineering from Osaka University, Japan in 2005. From April 2003 to March 2005, he was a Research Fellow of the Japan Society for the Promotion of Science. Since April 2005, he was a researcher of ATR Intelligent Robotics and Communication Laboratories. He worked as a researcher for ERATO, JST since April 2006. He has been an associate professor of the Department of Systems Innovation, Osaka University since August 2010.



**Hiroshi Ishiguro** received the D.Eng. degree from Osaka University, Osaka, Japan, in 1991. After that he began working as a research assistant in the Department of Electrical Engineering and Computer Science, Yamanashi University, Yamanashi, Japan. Then, in 1992, he moved to the Department of Systems Engineering, Osaka University, as a research assistant. In 1994, he was made an associate professor in the Department of Information Science, Kyoto University, Kyoto, Japan, and started research on distributed vision using omnidirectional cameras.

From 1998 to 1999, he worked in the Department of Electrical and Computer Engineering, University of California, San Diego, as a visiting scholar and in 2000, he moved to the Department of Computer and Communication Sciences, University, Wakayama, Japan, as an associate professor, before becoming professor in 2001. He moved to the Department of Adaptive Machine Systems, Osaka University in 2002. He is now a professor of the Department of Systems Innovation, Osaka University, and a leader at ATR Hiroshi Ishiguro Laboratory, Kyoto.