

A Model of the Emergence of Early Imitation Development based on Predictability Preference

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Abstract—This article presents a mechanism for the early development of imitation through a simulation of infant-caregiver interaction. A model was created to acquire a body mapping (a mapping from observed body motions to motor commands), which is necessary for imitation, while discriminating self-motion from the motion of the other. The simulation results show that the development of a body mapping depends on a *predictability preference* (a function of how an agent decides regarding its options of ‘what to imitate’). The simulated infants 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, which is supported by psychological studies. 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 imitation development.

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], infant’s imitative behaviors (shown in TABLE I) are observed during the infants learn to coordinate their senses and motor skills in the first two years. Before infants come to imitate other persons in the stage 3, they show repetitive behaviors (it seems they are mainly attentive to their bodies) in the stage 2. This process (from stage 2 to 3) also has been observed in other studies [3]. It is, meanwhile, suggested that infants develop a sense of self after birth [4], that is, self-knowledge of infants is formed in the developmental process. Infants, therefore, may not distinguish self-produced motions from motions produced by others on their perception in the early developmental process. However, infants come to repeat their own motions in advance of imitating others even though they are frequently near other people (caregivers) and they may observe not only self-produced motions but also movements produced by others. In primary circular reactions, infants may not recognize ‘their body’ motions but just respond to interesting events, however, it is considered this reactions works as self-imitation for 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

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.

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.

A crucial problem in imitation is the correspondence problem, in which the imitator needs to translate a sensory representation of the observed behavior into his/her own motor representation for that behavior. [6, 7]. In order to solve this problem, it is necessary to acquire 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 [8], 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, as suggested by some other studies such as an associative sequence learning (ASL) theory [9]. 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 (hereafter 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 [10] 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 [11, 12]. Yokoya et al. [13] 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. ASL theory [9] also considers a body mapping acquisition by other’s imitation, however, the developmental process of the transition from self to mutual imitation is not considered.

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 [14]. 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, infant needs to be imitated by caregiver, and also infant needs to imitate caregiver because it is considered caregiver’s imitative behavior is elicited when he/she is imitated [15]. 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 infant and caregiver need to choose a motion from one corresponding to self motion (self-imitation) and one corresponding to the other’s motion (imitating other). This motion selection problem possibly relies on the predictability of the observation since it has been observed that infants are highly sensitive to contingency [16]. We propose a mechanism for the motion decision that uses a *predictability preference*, which is the

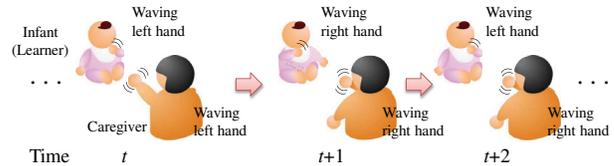


Fig. 1. Model of mutual imitation in infant-caregiver interaction.

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 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 same motion because the self motor command can be matched with equally both of the observed self-motion and 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 also reproduce disordered development when the model has some deficits in order to show the validity of the model. We also investigate imitation development when the infant has an atypical predictability preference. The paper suggests 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 EARLY IMITATION DEVELOPMENT

In order to deal with the issue of the imitation development, 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. A body motion is a gestural motion pattern such as waving a right hand from side to side and moving a left forearm up and down. A body motion is performed in one time step.
- The infant and caregiver have homologous body motions.
- The agent shows 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.

An example of infant-caregiver interaction is shown in Fig.1, in which both agents perform a body motion at the same time and observe both their own motion and that of the other. 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 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.,

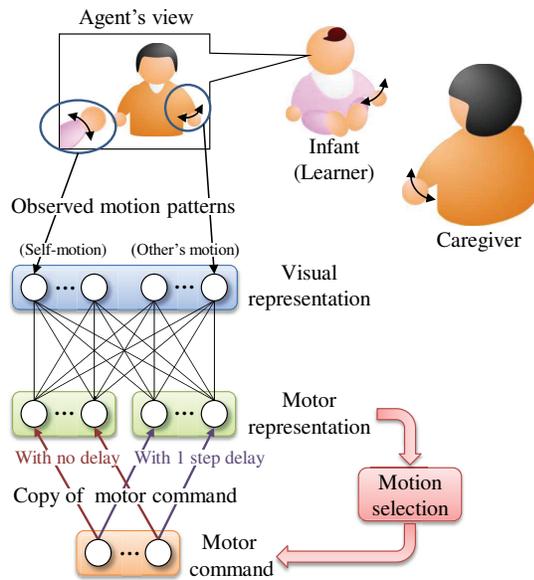


Fig. 2. Model of body mapping.

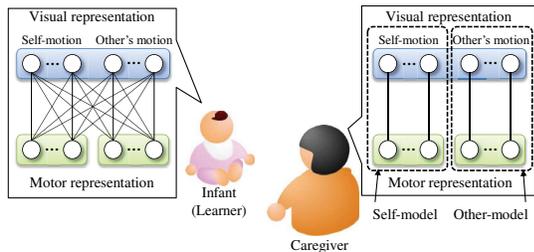


Fig. 3. Body mappings of infant and caregiver.

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).

- The caregiver has a perfect body mapping, while the infant does not know the correct correspondence and does not 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 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. 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. In the motor representation layer, 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 of the mapping are immature (i.e., connected with small random weights as shown in Fig.3). A Hebbian 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.

The self-other distinction is essentially a problem to discriminate sensory information that always synchronizes with the self-motion from the other sensory information. This problem occurs when there are some moving objects in the environment around the infant, one of which is the caregiver. Caregivers actually does not always act at the same time that infants move, however, we assume the caregiver and the infant always move at the same time as a simple setting to deal with the self-other distinction problem. 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 infant 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, 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. These are equivalent to a proprioceptive feedback of a motor command and a memory of the proprioceptive feedback. For the sake of convenience, motion commands copied without delay are called the self-related motions (left part of the motor representation layer in Fig.2), and motion commands copied with a one step delay are called the other-related motions (right part).

The simulation proceeds as follows: (a) both agents execute a motor command, (b) the infant updates the body mapping, (c) both agents select a new motion to perform, as shown in Fig.4, and this process is repeated.

- The current motor command and the previous motor command are copied to the motor representation layer (M'_s, M'_o) when the motor command is executed. The

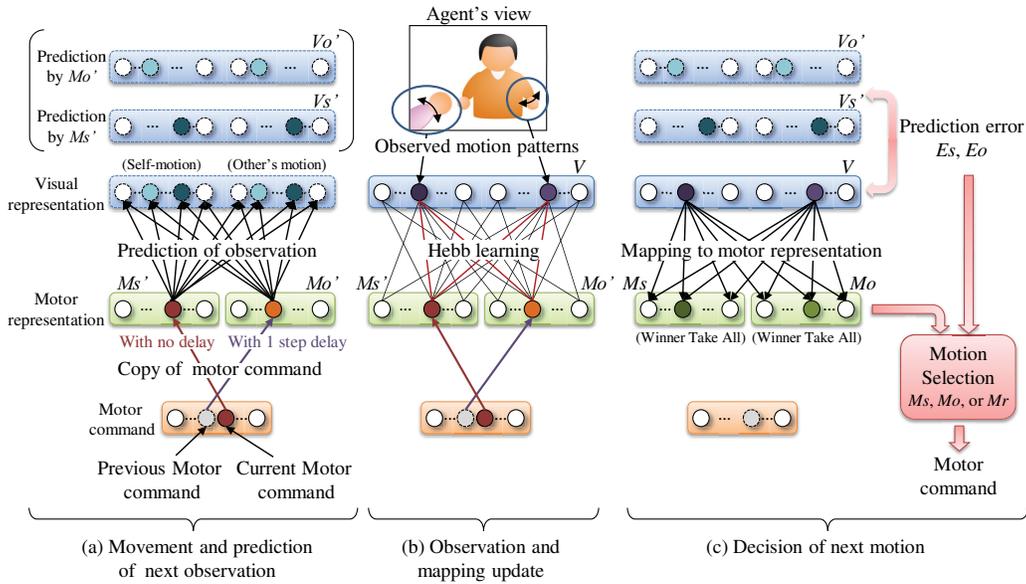


Fig. 4. Motion decision process.

- resulting observations are predicted (V'_s, V'_o) from M'_s and M'_o with the inverse mapping of the body mapping.
- (b) 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, M'_o) using a modified Hebbian learning rule which takes mutual exclusivity into consideration [17].
- (c) The motions corresponding to the observed motions are found by the body mapping (M_s, M_o), and the prediction errors (E_s, 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 agent observes 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 agent imitates the observed motions he/she 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 agent chooses the motion based on the predictability of the observation. This paper proposes a *predictability preference* for motion decision, which is a function relating predictability to action selection. The agent predicts the resulting observations from the activations in the motor representation layer by inverting the body mapping (the self-model and other-model are not discriminated). Two patterns of the observation (V'_s, 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 agent observes the motions, two prediction errors (E_s, 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

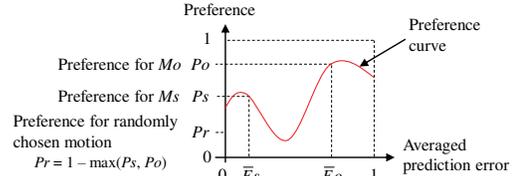


Fig. 5. Decision of imitative motion based on predictability preference.

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, the agent 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 agent probabilistically chooses 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.

III. SIMULATIONS

A. Simulation settings

In order for the infant to acquire the body mapping and imitation capability, he/she needs to elicit the right balance of imitative motions from the caregiver. Too much imitation from the caregiver might make it difficult for the infant to

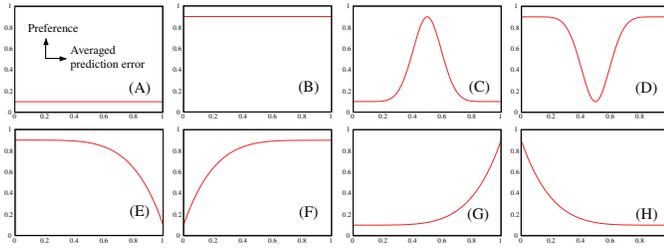


Fig. 6. Test patterns of preference curve.

discriminate their own motions from those of the caregiver, whereas too little imitation will not allow the infant to fully develop a correct mapping for self and other motions. In our simulation, the preference curve influences 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. We tested eight distinct preference curves for the infant. The profiles of the curves are qualitatively different, as shown in Fig.6. 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 prediction error essentially indicates a measure of novelty in the resultant observation. The meanings of the preference curves are:

- A *Nothing*: Mostly choose random behavior.
- B *Everything*: Mostly try to imitate.
- 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 Wundt curve where greatest pleasure comes from a moderate amount of stimulus novelty, which is considered to be a person’s intrinsic preference [18]. 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 a inverted-U relationship between novelty (opposite of familiarity) and preference. Many studies have shown that this kind of relationship appears in psychological experiments [19,20]. The caregiver was assumed to be a typical healthy person, and was therefore given this preference curve.

The simulation assumes that both agents have 30 patterns of body motion. In the simulation, a motion pattern is coded as a symbol and the agents interaction is implemented in symbol communication. The range of the connection weights of the body mapping is $[0, 1]$, and the infant’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. 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, 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, \bar{E}_o) are calculated from the errors in the last 20 steps.

B. Results

The averaged 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) 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 infant’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 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.
- (2) 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 in the last 20 steps.
- (3) Rate of selected motion in the caregiver’s action selection. The same as (2) for the caregiver.
- (4) Acquired mapping of the infant.

The network shows the qualitative features of the mapping acquired by the infant. 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.

In our simulation results, 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 (4). When the infant has 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 infant has 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 infant is unable to construct a model of the other.

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

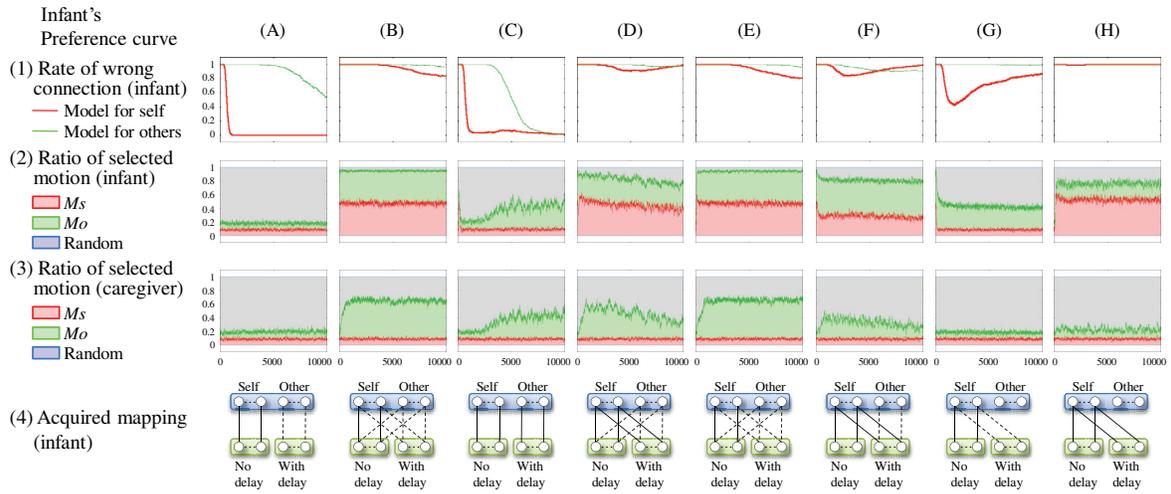


Fig. 7. Simulation results (caregiver uses preference curve (C)).

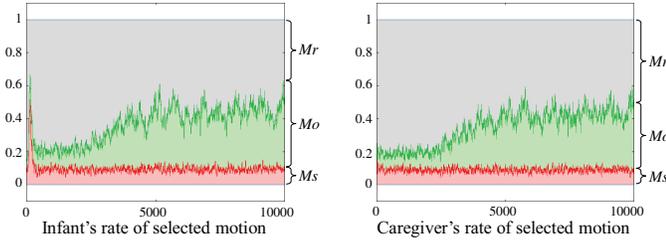


Fig. 8. The rates of selected motion when both agents have preference C (same as those in Fig.7).

seen in the left of Fig.8. Then, the frequency of the other-related motions increases relative to the self-related motions, and the infant 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 early developmental process of imitation.

The self-imitation in the results is quickly inhibited. It is inferred that the infant 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, which work as switching 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.

b) Atypical developmental process: In the results with preferences (B), (D), (E), and (F), it was observed that the infant chooses random motions with low frequency, as can be seen in Fig.7 (2) 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 infant 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 (3)) and the infant, therefore, cannot acquire the other-model. These infants could not elicit the imitation behavior from the caregiver because:

- The infant (A) always prefers random motions.
- The infant (H) prefers only self-imitation due to the quickly acquired self-model.
- The infant (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 developmental disorders; 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) [21]. 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 [22]. A body mapping without an other-model could be related to the failure in estimating other people's internal states.

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 [23]), and that this tendency could be related to 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 [23]), and this tendency could be also related to 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 infant with preference curve (G) prefers using the immature other-model (i.e., always explores new things) and, therefore, does not communicate with other people.

These results suggest 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 typical development (the shift from self to mutual imitation) requires the preference to neither too much familiarity nor too much novelty in order to avoid the perseverance of certain motions and to elicit various imitation from the caregiver. 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.

IV. CONCLUSION

In order to study the mechanisms of early imitation development, a model was made that was able to develop a healthy body mapping, which can discriminate self-motion from the other's motion, during the interaction between infant and caregiver in an imitation game. 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 typical developmental process of transition from self to mutual imitation can emerge from our system without any explicit mechanism of developmental sequence. We also have shown the inverted-U preference curve is indeed a viable proposal for healthy development. The analysis of the simulation results is still speculative but suggests that the predictability preference is one of the factors which govern the early developmental process of imitation capabilities. Future work will need to justify the model and the resultant developmental process by comparing them with human infants' natural developmental processes.

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