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Co-Development of Information Transfer within and between Infant and Caregiver

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***Abstract*—This paper presents a computational approach to measuring information transfer in infant-caregiver interaction. It is supposed that both an infant and a caregiver mutually shape the interaction by sending various signals to each other, of which the dynamic structure changes according to the infant's age. We investigated such developmental change both in infants and caregivers by measuring transfer entropy within and between their body movements. Our analysis demonstrated that infants significantly improve their body coordination and social contingency between 6 to 13 months of age. Their gaze, for example, start responding to caregivers' gaze, which indicates the development of joint attention. The coordination between infants' two hands also drastically improves as they grow. Of particular interest is that such development in infants elicits caregivers' adaptation. Caregivers change their social responses and body coordination to a more sophisticated manner in order to further facilitate infant development. Our approach is the first study to quantitatively verify the "co-development" of infants and caregivers, which appears as increases in information transfer within and between their behaviors.**

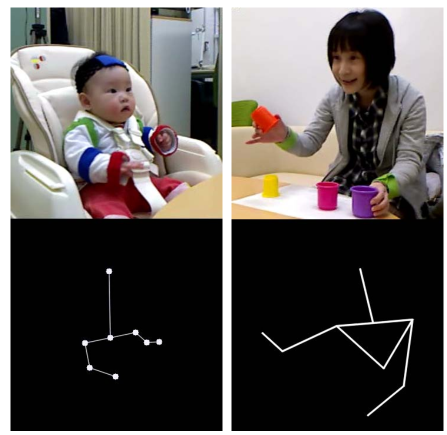

Fig. 1. 3D body movement of an infant and a caregiver detected using Kinect sensors. Measuring information flow within and between their body movements assesses their social contingency and body coordination.

I. Introduction

Interaction between an infant and a caregiver is a dynamic and bidirectional process (e.g., [1], [2]). They both send various signals to the partner, which elicit and shape the partner's reaction. For example, a caregiver's gaze indicates an interesting event in the context and therefore motivates an infant to look at and share the event with the caregiver (i.e., joint attention). Their hand movement also conveys various information to the partner. Not only communicative gestures (e.g., pointing) but also task-related movement (e.g., playing with a toy) influences the partner's reaction. Infant-directed action (IDA) (e.g., [3]–[5]) as well as infant-directed speech (IDS) (e.g., [6]), which are characterized by exaggeration and/or simplification of behaviors, is typical phenomena showing such adaptation of caregivers. An open question here is how the dynamics of infant-caregiver interaction changes according to infants' age. Understanding the link between caregivers' adaptation and infant development is necessary to better understand infant cognitive development.

Interdisciplinary approaches employing computational techniques have a great potential to reveal such dynamic and microscopic structure of interaction. Yu, Smith, and colleagues [7], [8] have investigated multimodal information transfer in infant-caregiver interaction. They examined how speech, visual attention, and body movement of participants were orchestrated while a caregiver was teaching a label of a new object to an infant. Their analysis using an information theoretic measure showed that successful learning of infants resulted from their better attentional coordination with caregivers. Ruvolo et al. [9] examined face-to-face interaction between an infant and a caregiver focusing on their smile behavior. They tried to infer the intention of participants (i.e., what infants tried to get caregivers to do and vice versa) by measuring probabilities of their behaviors. Their result showed that even 4- to 18-week-old infants had an intention to elicit caregivers' smile rather than randomly acted whereas caregivers showed a different strategy to elicit infants' smile.

Inspired by the above studies, we investigate the developmental change in information transfer between an infant and a caregiver and within each participant. Fig. 1 shows a sample scene from our experiment, where the 3D body movement of participants were analyzed. Our main question, which is different from previous studies, is twofold: how infants im-

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prove the quality and the quantity of their information transfer (e.g., social responses and body coordination) as they grow and how their development influences the information transfer by caregivers. Studies on IDA and IDS have suggested that caregivers adjust the complexity of their behavior according to the perceptual and motor ability of infants [10], [11] although the relationship has not fully been understood yet. Our study addresses the challenge of uncovering the "co-development" of infants and caregivers by introducing a common framework to measure their social capabilities. We systematically examine infant development, caregivers' adaptation, and their relationship by employing an information theoretic measure called transfer entropy [12].

II. Information Flow Measured by Transfer Entropy

A. Transfer Entropy

Transfer entropy is an information theoretic measure proposed by Schreiber [12]. Let U and V be variables that are approximated by stationary Markov processes of order k and l, respectively. Transfer entropy defines the degree of influence of V on U as follows:

$$T_{V \to U} = \sum p(u_{t+1}, u_t^{(k)}, v_t^{(l)}) \log \frac{p(u_{t+1}|u_t^{(k)}, v_t^{(l)})}{p(u_{t+1}|u_t^{(k)})}, \quad (1)$$

where u_{t+1} is the value of U at time $t+1$; $u_t^{(k)}$ and $v_t^{(l)}$ are $(u_t, \ldots u_{t-k+1})$ and $(v_t, \ldots v_{t-l+1})$, respectively; and $p(u_{t+1}|u_t^{(k)}, v_t^{(l)})$ is the transition probability between them. Usually $k = l = 1$ is used for computational reasons.

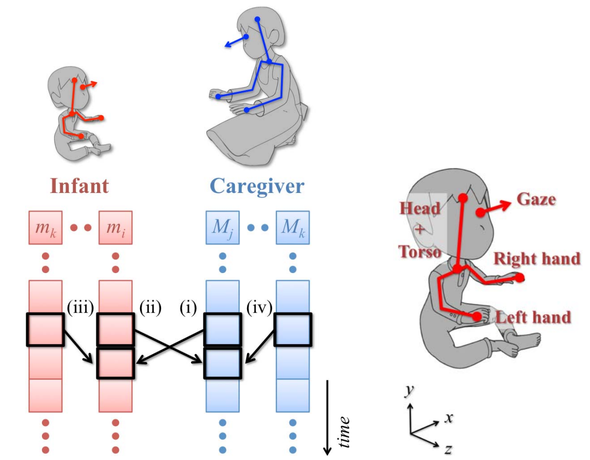
Transfer entropy shares some properties of mutual information, that is, it can quantify the dependence between two variables. In addition, this new measure takes the directional information into account and thus enables to detect asymmetric information transfer between two variables (e.g., social contingency of an infant on a caregiver vs. the other way around).

B. Four Types of Information Transfer in Infant-Caregiver Interaction

Introducing transfer entropy, we investigate what signals of an infant and a caregiver influence on each other and how the degree of influence changes according to the infant's age. Fig. 2 (a) illustrates four types of information flow (denoted by black arrows) in infant-caregiver interaction. Each column represents the time series of motion data shown in Fig. 2 (b). Let $m_{i,t}$ and $M_{j,t}$ be the motion of an infant's i-th body part and a caregiver's j-th body part at time t, respectively. The four types of information flow are defined as follows:

(i) influence of $M_{j,t}$ on $m_{i,t+1}$ (i.e., $T_{M_j \to m_i}$),
(ii) influence of $m_{i,t}$ on $M_{j,t+1}$ (i.e., $T_{m_i \to M_j}$),
(iii) influence of $m_{k,t}$ on $m_{i,t+1}$ ($i \neq k$) (i.e., $T_{m_k \to m_i}$), and
(iv) influence of $M_{k,t}$ on $M_{j,t+1}$ ($j \neq k$) (i.e., $T_{M_k \to M_j}$).

The first two values concern *social contingency* between an infant and a caregiver: (i) indicates how much an infant's motion responded to a caregiver's motion whereas (ii) the other way around. The higher $T_{M_j \to m_i}$ and/or $T_{m_i \to M_j}$ are,



(a) Four types of information transfer: (i) and (ii) represent social contingency between an infant and a caregiver, and (iii) and (iv) body coordination within each participant.

(b) Motion data used for analyzing information transfer within and between participants

Fig. 2. Information flow in infant-caregiver interaction measured by transfer entropy

the more contingent the infant's and/or the caregiver's motion are. The last two values represent *body coordination* within each participant: (iii) indicates how much an infant's body part coordinated with his/her another body part whereas (iv) for a caregiver. The higher $T_{m_k \to m_i}$ and/or $T_{M_k \to M_j}$ are, the better the infant's and/or the caregiver's body are coordinated.

C. Our Hypotheses on Developmental Changes in Information Transfer

We suggest that the four types of information transfer are closely coupled and thus co-develop in infants and in caregivers. Our hypotheses are:

(i) $T_{M_j \to m_i}$ may increase as infants grow.
(ii) $T_{m_i \to M_j}$, however, may not change regardless of infants' age.
(iii) $T_{m_k \to m_i}$ may increase as infants grow.
(iv) $T_{M_k \to M_j}$ may also increase as infants grow.

Regarding (i), it is well known that infants enhance a sensitivity to social contingency in the first and second years of life [13], [14]. They show the ability to imitate others [15] and to differentiate self from other using contingency in early infancy [16]. Their social contingency further develops so as to involve an object in interaction. Gaze following and joint attention to an object are evidences of contingent reactions of infants' gaze on caregivers' gaze [17], [18].

As to (ii), on the other hand, we anticipate *no* significant change in caregivers' social contingency. It is assumed that caregivers always try to respond to infants as properly and socially as possible. Behavioral studies also suggest that caregivers treat infants as intentional agents rather than non-social entities from early infancy (e.g., mind-mindedness) [19]. We thus hypothesize that caregivers' contingency would not change regardless of infants' age.

Fig. 3. Experiment of infant-caregiver interaction. A caregiver demonstrated a cup-nesting task to an infant while the interaction was recorded by two Kinect sensors and two digital video cameras next to and behind the participants.

Regarding (iii) and (iv), we assume mutual development of body coordination in infants and caregivers. It is known that infants improve their ability of reaching (i.e., eye-hand coordination) [20], bimanual manipulation (i.e., hand-hand coordination) [21], and so on in the first few years of life. We suggest that this development encourages caregivers to adapt the complexity of their body coordination. They may act in a more sophisticated manner when interacting with older infants than with younger infants. Since *no* studies have quantitatively verified it, our analysis would provide the first evidence showing the link between infant development and caregivers' adaptation.

III. Experiment of Infant-Caregiver Interaction

We conducted an interaction experiment to investigate the developmental change in the information transfer in infant-caregiver interaction.

A. Participants

Participants were 26 pairs of an infant and his/her mother. They were divided into two age groups: a younger age group for 6- to 8-month-old infants ($M = 186.4$ days, $SD = 22.64$, $N = 16$) and an older age group for 11- to 13-month-old infants ($M = 359.5$ days, $SD = 16.72$, $N = 10$). We chose these age groups because various capabilities develop in infants at around these ages as described in Section II-C.

B. Setting and Data Recording

Fig. 3 shows a sample scene; an infant and his/her mother sat across a table, on which four colorful cups were placed. The mothers were asked to demonstrate how to nest the cups to the infants and to play with the infants using the cups if the infants demanded. In fact, many infants showed their strong interest in playing with the cups by reaching for them and/or getting fussy as well as mothers proactively motivated infants to play together. The interaction took place for about 3 minutes unless infants kept being fussy and/or crying.

The interaction was recorded using two Kinect sensors[1] and two digital video cameras. The Kinect sensors were placed diagonally in front of the participants so that their 3D body motion was clearly recorded. Fig. 1 shows a sample image, in which the skeletons of an infant and a mother are detected. We employed OpenNI [22] for tracking the mothers' skeleton while using colored markers for the infants (red, blue, and green for the hands, elbows and head, and shoulders, respectively) since OpenNI could not detect a small body. The digital video cameras were placed in front of and above the participants to record their speech and facial expressions though they have not been used in the current analysis.

C. Analysis

We analyzed the data through the following three steps. The same process went for the caregivers as well as for the infants although the variables only for the infants are indicated here (lower-case letters for infants, e.g., $x_{\text{rhand},t}$, and upper-case letters for caregivers, e.g., $X_{\text{rhand},t}$).

1) Extraction of motion data: First, the 3D positions of the right hand, left hand, torso, and head were extracted from the skeletons. Additionally, the orientation of the torso was calculated using the shoulder position:

- right hand: $(x_{\text{rhand},t},\ y_{\text{rhand},t},\ z_{\text{rhand},t})$
- left hand: $(x_{\text{lhand}},\ y_{\text{lhand},t},\ z_{\text{lhand},t})$
- torso and head: $(z_{\text{torso},t},\ \theta_{\text{torso},t},\ z_{\text{head},t})$, where $\theta_{\text{torso},t} = \arctan((z_{\text{rshld},t} - z_{\text{lshld},t})/(x_{\text{rshld},t} - x_{\text{lshld},t}))$

We used $\theta_{\text{torso},t}$ instead of $(x_{\text{torso},t},\ y_{\text{torso},t})$ because the orientation of the body is more important in assessing social interaction. Only the gaze was hand-coded by an experimenter due to the low resolution of the camera image. The gaze of the participants were segmented into three regions:

- gaze: $g_t \in G = \{\text{partner, objects, others}\}$

2) Segmentation and symbolization of motion data: Next, we segmented the motion data to symbolize them in terms of motion direction. Robust singular spectrum transform [23] was applied to detect appropriate segment points t' for each data. The motion direction for each segment was then coded using three digit numbers, which allowed us to assess behavioral contingency regardless of their 3D positions:

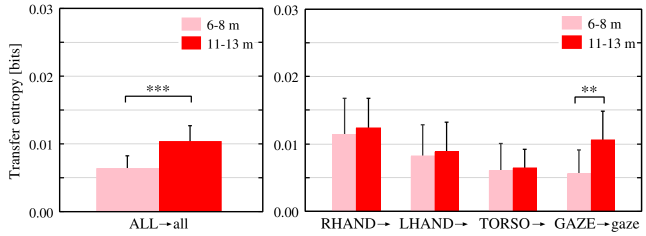
- $m_{\text{rhand},t} \in D = \{000,\ 001,\ 002,\ \cdots,\ 222\}$, where

$$\text{1st-digit} = \begin{cases} 0 & \text{if } \Delta x = x_{\text{rhand},t'+1} - x_{\text{rhand},t'} > 0 \\ 1 & \text{else if } \Delta x = 0 \\ 2 & \text{else} \end{cases}$$

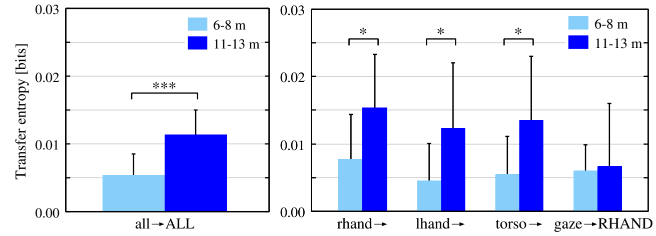
  2nd- and 3rd-digit for Δy and Δz
- $m_{\text{lhand},t} \in D$ for $(\Delta x_{\text{lhand}}, \Delta y_{\text{lhand}}, \Delta z_{\text{lhand}})$
- $m_{\text{torso},t} \in D$ for $(\Delta z_{\text{torso}}, \Delta \theta_{\text{torso}}, \Delta z_{\text{head}})$
- $m_{\text{gaze},t} = g_t \in \{0,\ 1,\ 2\}$

3) Calculation of transfer entropy: We then calculated transfer entropy within and between $m_{i,t}$ and $M_{j,t}$ with respect to the four directions explained in Section II-B. In our current experiment, i and j were rhand, lhand, torso, and gaze. Thus, we had 16 kinds of $T_{M_j \to m_i}$ and of $T_{m_i \to M_j}$, and 12 kinds of $T_{m_k \to m_i}$ and of $T_{M_k \to M_j}$, i.e., 56 kinds of transfer entropy in total. The results were evaluated separately in task-demonstration phase, in which the caregivers were

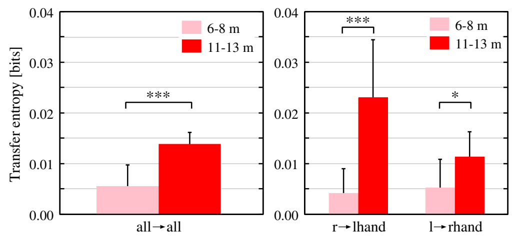
[1] Kinect sensors feature an RGB camera and a depth sensor, which provides a capability of 3D motion tracking.



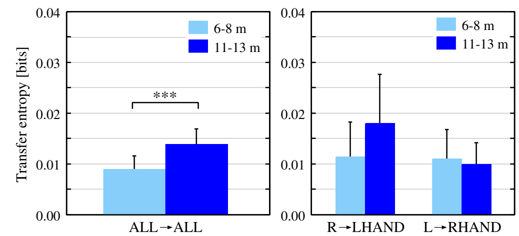
(a) Development of infants' social contingency detected as increases in $T_{M_j \to m_i}$ (left: mean value, right: infants' gaze)



(b) Adaptation of caregivers' social contingency detected as increases in $T_{m_i \to M_j}$ (left: mean value, right: caregivers' right hand)



(c) Development of infants' body coordination detected as increases in $T_{m_k \to m_i}$ (left: mean value, right: two hands)



(d) Adaptation of caregivers' body coordination detected as increases in $T_{M_k \to M_j}$ (left: mean value, right: two hands)

Fig. 4. Transfer entropy obtained during task-demonstration phase: (a) and (b) represent social contingency, and (c) and (d) body coordination. The lighter bars and the darker ones show the results for the younger age group and the older age group, respectively. Significant differences observed in the all four types of information transfer indicate "co-development" of infants and caregivers.

demonstrating the task to the infants, and in task-sharing phase, in which the caregivers were playing together with and assisting the infants manipulating the cups.

IV. Results for Information Transfer

Fig. 4 shows the results for transfer entropy: (a) $T_{M_j \to m_i}$ and (b) $T_{m_i \to M_j}$ represent social contingency, and (c) $T_{m_k \to m_i}$ and (d) $T_{M_k \to M_j}$ body coordination, all of which were obtained during the task-demonstration phase. The bars with a lighter color (pink or light blue) and with a darker color (red or blue) show the results for the younger age group and for the older age group, respectively. The error bars are standard deviation, and significant differences between the age groups are denoted by "$*$" if $p < 0.05$, "$**$" if $p < 0.01$, and "$***$" if $p < 0.001$. The labels under the bars denote the motion data to be focused on: "ALL→all", for example, indicates the mean transfer entropy from the caregivers to the infants (i.e., $\bar{T}_{M_j \to m_i}$), and "RHAND→gaze" indicates the transfer entropy from the caregivers' right hand to the infants' gaze (i.e., $T_{M_{\text{rhand}} \to m_{\text{gaze}}}$). Due to the limited space, we selected only several results to discuss in the following sections.

A. Development of Infants' Social Contingency

We first assessed social contingency of infants. The results shown in Fig. 4 (a) demonstrate significant increases in $T_{M_j \to m_i}$. The mean value for the older age group is significantly higher than that for the younger age group (ALL→all: $t(24) = 4.38$, $p < 0.001$), suggesting that responses of older infants were more socially contingent on caregivers. Our closer analysis revealed an interesting transition in infants' gaze responses. When determining where to attend, older infants relied more strongly on caregivers' gaze than younger infants did (GAZE→gaze: $t(24) = 3.12$, $p < 0.01$).

It is known that infants acquire the ability for gaze following and joint attention between 6 and 18 months of age [18]. Their gaze shift gradually becomes more contingent on caregivers' gaze. Moreover, it has been suggested that visual attention of younger infants relies more on bottom-up salience (e.g., motion and color) than on social signals (e.g., face and gaze) [24], [25]. Higher transfer entropy for RHAND→gaze of younger infants indicates their preference for salient movement because caregivers' right hand was always moving to demonstrate the task. These results are consistent with psychological evidences and thus prove the ability of our analysis to quantify infant development.

B. Adaptation of Caregivers' Social Contingency

We next examined caregivers' responses to infants. Fig. 4 (b) shows $T_{m_i \to M_j}$ (i.e., social contingency of caregivers). Surprisingly, we found significant differences between the age groups unlike our hypothesis. The mean value is significantly higher for the older age group than for the younger age group (all→ALL: $t(24) = 4.12$, $p < 0.001$). Our closer analysis focusing on caregivers' right hand shows stronger influences of infants' hands and torso (rhand→RHAND: $t(24) = 2.53$, $p < 0.05$; lhand→RHAND: $t(24) = 2.47$, $p < 0.05$; torso→RHAND: $t(24) = 2.56$, $p < 0.05$) than their gaze.

Our hypothesis was that social contingency of caregivers would not change regardless of infants' age. We anticipated that caregivers would try to always establish socially contingent interaction with infants. However, our results indicate this is not the case. We suggest from these results that caregivers may have difficulties in understanding the intention of younger infants in dynamic interaction, which prevents them from contingently responding to infants.

C. Development of Infants' Body Coordination

Our next analysis focused on body coordination of infants. Fig. 4 (c) shows developmental change in $T_{m_k \to m_i}$. As we hypothesized, older infants show higher transfer entropy than younger infants (all→all: $t(24) = 5.44$, $p < 0.001$). Especially, they significantly improve the coordination between the two hands (rhand→lhand: $t(24) = 5.60$, $p < 0.001$; lhand→rhand: $t(24) = 2.64$, $p < 0.05$). A greater improvement in rhand→lhand than in lhand→rhand further suggests the right handedness of infants because the dominant hand usually initiates bimanual manipulation.

This result is again consistent with psychological evidences. Infants are known to develop bimanual manipulation between 7 to 13 months of age [21]. Regarding eye-hand coordination, we found a significant difference in gaze→lhand ($t(24) = 3.51, p < 0.01$) but not in gaze→rhand ($t(24) = 0.98, p = 0.34$), indicating that younger infants as well as older infants may already have an inverse model for the right hand but develop later for the left hand.

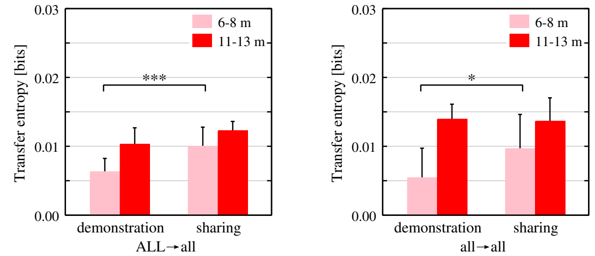
D. Adaptation of Caregivers' Body Coordination

In response to infant development, caregivers adapted their body coordination as we hypothesized. Fig. 4 (d) shows a significant difference between two age groups (ALL→ALL: $t(24) = 4.02$, $p < 0.001$). They increased the complexity of body coordination in response to infant development. Although no significant difference was found in hand-hand coordination (RHAND→LHAND: $t(24) = 1.93$, $p = 0.06$; LHAND→RHAND: $t(24) = 0.51$, $p = 0.61$), greater changes in other body parts (e.g., TORSO→RHAND) contributed to the adaptation.

Studies on IDA and IDS have suggested such adaptation in caregivers. Caregivers tend to modify their infant-directed behavior according to the infants' age [10], [11]. Our result quantitatively supports it and further suggests the great impact of infants' responses (i.e., not only their age) on caregivers' adaptation. Taken together, our results described in these sections demonstrate the link between infant development and caregivers' adaptation, which we call "co-development."

E. Temporal Improvement in infants' Social Contingency and Body Coordination Caused by Caregivers' Active Teaching

In addition to the above analyses focusing on the task-demonstration phase, we examined the effect of caregivers' active teaching during the task-sharing phase. Figs. 5 (a) and (b) show the transfer entropy regarding the infants' social contingency (i.e., $T_{M_j \to m_i}$) and body coordination (i.e., $T_{m_k \to m_i}$), respectively. Comparing the results between the two phases reveals significant increases in younger infants for the task-sharing phase (ALL→all: $t(24) = 3.78$, $p < 0.001$; all→all: $t(24) = 2.19$, $p < 0.05$).



(a) Temporal increase in social contingency $T_{M_j \to m_i}$ of younger infants

(b) Temporal increase in body coordination $T_{m_k \to m_i}$ of younger infants

Fig. 5. Transfer entropy obtained during task-sharing phase against task-demonstration: (a) represents social contingency and (b) body coordination. Information transfer of younger infants significantly increases owing to caregivers' active teaching.

Fig. 6. Caregivers' scaffolding during task-sharing phase. Caregivers directly taught how to nest cups to infants, which enabled infants to achieve the goal while increasing social contingency and body coordination.

When playing with the cups instead of watching caregivers' demonstration, infants often received assistance from caregivers. Since infants, especially younger infants, did not understand what the goal of their action or how to achieve the goal, they could not appropriately manipulate the cups. Then caregivers directly taught infants by handling cups together and/or giving another cup to be nested closer to infants (see Fig. 6), which enabled infants to achieve the goal while temporally improving social contingency and body coordination. There has been a study reporting such active teaching by caregivers in daily interaction (e.g., [26]). Caregivers play a role to guide infants' attention and shape their body movement, which is called scaffolding. Our analysis quantitatively demonstrates the effect of caregivers' scaffolding to improve infants' bodily and social coordination.

V. Conclusion and Discussion

Our computational analysis on infant-caregiver interaction demonstrated co-development of infants and caregivers. Information transfer calculated within participants revealed mutual development of their body coordination. Infants improve, for example, bimanual manipulation and eye-hand coordination as they grow, which motivates caregivers to increase the complexity of their body coordination. Consequently, social contingency between the participants is also enhanced. The development of infants' social behavior such as joint attention as well as their body coordination enables caregivers to better understand infants' intention and thus respond more contingently on them.

Our results are consistent with evidences from developmental psychology. Moreover, we quantitatively verified co-development of infants and caregivers in dynamic interaction. Examining dynamic interaction has a potential to reveal the roles of caregivers' scaffolding in infant development. Active teaching by caregivers shown in Section IV-E is a striking example to demonstrate the importance of caregivers' assistance in facilitating infant learning. Such finer-grained analysis also contributes to earlier detection of bodily and social abilities of infants and their disorders. For example, autistic children are known to have difficulties in coordinating their two hands as well as establishing social relationship with others (e.g., [27]). Our approach can detect even a small change in their bodily and social coordination. We thus intend to apply our approach to measuring individual differences in development.

Further analyses integrating other modalities and a longer history of information are also our great interest. Infants and caregivers exchange more varieties of information using speech, facial expression, and so on. Our current analysis focusing on their body movement is the first step to obtain insight into the dynamic structure of interaction. Integrating more modalities would reveal richer information exchange between infants and caregivers. Transfer entropy can take different length of information history (i.e., k and l in Eq. (1)) as well as more modalities into account, which allow us to assess the development of infants' working memory. It is hypothesized that older infants show higher transfer entropy with a longer history length whereas younger infants maximize it with a shorter history. We will investigate the development of infants' working memory by comparing transfer entropy with different history length.

We also intend to improve our measure to better examine several aspects of behavioral development. Transfer entropy, which we used in our current analysis, may reflect not only the degree of influence between body movements but also the amount of movements. Older infants usually produce more body movement than younger infants. It is, on one hand, an interesting aspect of development. On the other hand, it causes unnecessary higher transfer entropy for older infants even if there is no contingency in it. We need to separately examine the two aspects of development (i.e., an increase in the quantity of body movement and an improvement in the quality of body coordination).

Acknowledgment

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