Neural Mechanisms of Parental Communicative Adjustments in Spoken Language

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Abstract—During cultural transmission, caregivers typically adjust their form of speech according to the presumed characteristics of an infant/child, a phenomenon known as infant/child directed speech (IDS/CDS) or “parentese.” Although ventromedial prefrontal cortex (vmPFC) damage was previously found to be associated with failure in adjusting non-verbal communicative behaviors, little is known about the neural mechanisms of verbal communicative adjustments, such as IDS/CDS. In the current study, 30 healthy mothers with preschool-age children underwent functional magnetic resonance imaging (fMRI) while performing a picture naming task which required them to name an object for either a child or an adult. In the picture naming task, mothers exhibited a longer naming duration in the toward-child condition than the toward-adult control condition. Naming an object for a child, compared with naming it for an adult, resulted in greater involvement in the vmPFC and other regions (e.g., cerebellum) in the global caregiving network. In particular, the vmPFC exhibited task-related deactivation and decreased functional connectivity with the supplementary motor, precentral, postcentral, and supramarginal regions. These findings suggest that the vmPFC, which is included in the default mode network, is involved in optimizing communicative behaviors for the inter-generational transmission of knowledge. This function of the vmPFC may be considered as a prosocial drive to lead to prosocial communicative behaviors depending on the context. This study provides a better understanding of the neural mechanisms involved in communicative adjustments for children and insight into related applied research fields such as parenting, pedagogy, and education. © 2020 The Author(s). Published by Elsevier Ltd on behalf of IBRO. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

Key words: communicative adjustments, infant/child directed speech, functional neuroimaging, ventromedial prefrontal cortex, global caregiving network.

INTRODUCTION

Humans often provide helpful information to others, even when such transmission involves no personal gain. The transmission of knowledge (i.e., informing) is said to be a human-specific behavior (Call and Tomasello, 2008). In particular, adults teach things to children spontaneously using communicative adjustments according to the presumed characteristics of the children. In order for knowledge transmission to be successful, adults adjust the form and style of speech so that their utterances are tailored to the particular knowledge of the child. Of such communicative adjustments, the most well-understood example is infant- or child-directed speech (IDS/CDS), alternatively known as “parentese” (or motherese) (Saxton, 2008; Saint-Georges et al., 2013). IDS/CDS is characterized by utterances that are higher in pitch, slower, and simpler compared with adult-directed speech (ADS) (Snow and Ferguson, 1977; Soderstrom, 2007). Although individual differences in the use of IDS/CDS do exist, this type of communication is used naturally on a daily basis in almost all linguistic and cultural communities (Ferguson, 1964; Snow and Ferguson, 1977), especially among caregivers during the period of parenting (Segal et al., 2009; Lee et al., 2010). Moreover, IDS/ CDS as a verbal form of communicative adjustment is

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thought to draw the infant/child’s attention to speech (Senju et al., 2008; Csibra and Gergely, 2009) and helps to facilitate the emotional and linguistic development of infants/children (Kuhl and Rivera-Gaxiola, 2008; Spinelli and Mesman, 2018). In spite of the significance of the role of IDS/CDS in the transmission of knowledge, little is known about the neural mechanisms that underlie IDS/CDS as a verbal form of communicative adjustment.

To date, the neural mechanisms supporting communicative adjustments have been investigated in non-verbal interactions, but not in verbal interactions. Recent brain lesion evidence has shown an association between impaired communicative adjustments and lesions in the ventromedial prefrontal cortex (vmPFC) (Stolk et al., 2015). For example, patients with vmPFC damage, unlike healthy individuals and patient controls, failed to generate communicative adjustments (e.g., longer action time) to the presumed characteristics of a child during non-verbal interactions on a digital game board. Despite these impairments, it has been shown that such patients are able to reason about the mental states of other agents when mental state reasoning does not require access to implied knowledge about those agents (Bird et al., 2004; Croft et al., 2010; Stolk et al., 2015). From a developmental perspective, 5-year-old children also adjust non-verbal communicative behaviors and spend more time interacting with a younger child than with a same-age peer (Stolk et al., 2013), as adults adjust these behaviors (Newman-Norlund et al., 2009; Stolk et al., 2015). In particular, the vmPFC plays an important role in adjusting non-verbal communicative behaviors. It is reciprocally connected with emotional systems in the hypothalamus and amygdala and integrates emotional and value-based information necessary for caregiving behaviors (Decety and Cowell, 2014; Decety et al., 2016), including the use of IDS/CDS as a verbal form of communicative adjustment. It is therefore likely that the vmPFC supports caregivers’ generation of IDS/CDS, as well as non-verbal communicative adjustments.

During typical caregiving interactions, caregivers naturally use diverse social cues such as IDS/CDS, eye contact, and affectionate touch. Although human caregiving behaviors require complex higher-order psychological processes, IDS/CDS is also hypothesized to be supported partially by a global human caregiving network. As reviewed by Feldman and colleagues (Feldman, 2015, 2017; Feldman et al., 2019), the global human caregiving network includes both the subcortical network and cortical networks implicated in embodied simulation, mentalization, and emotion regulation. Of the key interconnected networks of the caregiving brain, the embodied simulation/empathy network, including the inferior frontal gyrus (IFG) and inferior parietal lobule (IPL), enables the caregiver to resonate with infant/child’s mental states (e.g., emotions) and engage in coordinated communication. The mentalizing network, including the superior temporal sulcus (STS), temporoparietal junction (TPJ) and medial PFC, enables the caregiver to understand infant/child’s intentions on the basis of coordinated communicative behaviors. The emotion regulatory network is anchored in the dorsolateral PFC (dPFC), ventrolateral PFC (vPFC), and medial PFC. By utilizing this network, the caregiver is able to regulate their own mental states and recognize the infant/child’s mental states. Regarding the subcortical network, the reward-motivation system, such as the striatum and amygdala, supports multiple attachment-related motivational behaviors (e.g., social orienting and seeking). The cortical networks, which jointly comprise the human social brain, partly overlap, serve multiple higher-order psychological functions, and provide top-down regulatory control to the subcortical-limbic circuit (Swain, 2008; Feldman, 2015, 2017; Abraham et al., 2016; Kim et al., 2016; Feldman et al., 2019). Furthermore, the cerebellum has been increasingly recognized to play a potentially important role in parent–child interactions (Noriuchi et al., 2019) among other social interactions (Van Overwalle et al., 2014). In terms of the repetitive use of IDS/CDS during natural caregiving interactions, implicit internal models for predictable patterns of learned communicative behaviors are thought to be constructed in the cerebellum to facilitate fluent social interactions (Heleven and Van Overwalle, 2018; Heleven et al., 2019).

The current study aims to advance understanding of the neural mechanisms that underlie IDS/CDS as a verbal form of communicative adjustment using functional magnetic resonance imaging (fMRI). Based on the previous studies reviewed above, we hypothesized that the vmPFC and other brain regions in the global caregiving network would be involved when caregivers generated IDS/CDS. In order to investigate this hypothesis, we adopted a picture naming task which required caregivers to name an object for a child or for an adult. In the picture naming task, caregivers named an object for a child (toward-child condition), which corresponds to the generation of IDS/CDS and served as the experimental condition. They then named an object for an adult of approximately the same age (toward-adult condition), which corresponds to the generation of ADS and served as the control condition. If our hypothesis is correct, the caregivers would exhibit a longer naming duration in the toward-child than the toward-adult condition. In addition to adjusting verbal communicative behaviors directed toward the child, their naming of the object in the toward-child relative to toward-adult condition would show greater involvement in the vmPFC and other brain regions in the global caregiving network.

**EXPERIMENTAL PROCEDURES**

**Participants**

Thirty healthy mothers (age range = 27–44 years; mean age = 34.6 years; standard deviation (SD) = 4.2 years) who were native Japanese speakers participated in this study after providing written informed consent. All participants were female caregivers who were caring for at least one preschool-age child. The minimum number of participants (n = 26) was determined based on an a priori power analysis (alpha level = 0.05; power = 0.80) using G*Power software (Faul et al., 2007) to detect behavioral communicative adjustment. This analysis
assumed an effect size \((r = 0.52)\), which is comparable to that observed in a previous study on non-verbal communicative adjustment in healthy adults (Stolk et al., 2015). The study protocol was approved by the Research Ethics Committee of the University of Fukui and was conducted in accordance with the Declaration of Helsinki and the Ethical Guidelines for Medical and Health Research Involving Human Subjects of Japan. All caregivers had received at least 12 years of education in Japan. No participant had a standard of living below the relative poverty line. Almost all (90%) were right handed according to the FLANDERS handedness inventory (Nicholls et al., 2013; Okubo et al., 2014). All had normal or corrected-to-normal vision. The participants had no history of speech, hearing, neurological, or psychiatric disorders. All participants met the safety requirements for participation in an fMRI study (exclusion of ferromagnetic implants, claustrophobia, pregnancy, and others).

The demographic and psychological characteristics of the participants are listed in Table 1. The Beck Depression Inventory-II (BDI-II) (Beck and Steer, 1996; Kojima et al., 2002) was used to measure participants’ depressive symptoms, which have been previously associated with a reduced use of IDS/CDS among caregivers (Kaplan et al., 2002). The Japanese version of the Parenting Stress Index (J-PSI) (Narama et al., 1999), an adaptation of the PSI (Abidin, 1995), was used to evaluate the participants’ parenting stress (comprising items on the Child and Parent domains). To assess empathic ability, the participants completed the four subscales (Empathic Concern, Personal Distress, Perspective Taking, Fantasy) of the Interpersonal Reactivity Index (IRI) (Davis, 1983; Sakurai, 1988).

**Object stimuli**

The object stimuli of the task were 12 black-and-white line drawings of natural objects (animals and fruits), selected from a picture database (Snodgrass and Vanderwart, 1980; Nishimoto et al., 2005). All of the object stimuli were items of high familiarity (>4.0) on a seven-point scale (extremely unfamiliar to extremely familiar), high naming consistency (>95.0 %), and a low age of acquisition of naming (<5.0 years). These object stimuli were divided into two lists (6 objects per list) that were matched on the distribution of the morae and accent patterns of these objects’ names.

**Face stimuli**

The face stimuli of the task were two color drawings of faces: the face of a preschool girl and that of a woman who belonged to the same generation as the participants in this study. The face stimuli were selected on the basis of a preliminary rating study in which an additional 51 mothers (mean age ± SD = 36.1 ± 4.6 years) rated the faces based on gender, age, and pleasantness. The raters all judged the child face as a girl and the adult face as a woman. They estimated the age of the child face at 5.1 ± 1.8 years and that of the adult face at 33.5 ± 4.6 years. The child and adult faces were matched in terms of pleasantness (>4.2) on a 5-point scale (very unpleasant to very pleasant).

**Picture naming task**

Stimuli were presented using NBS Presentation software (https://www.neurobs.com) on a Windows computer via a 24-inch MRI-compatible LCD display (BOLDscreen; Cambridge Research System, UK) located at the head end of the scanner bore. The participants viewed the stimuli through a mirror attached to the head coil. A fiber optic microphone (Optimic1140; Optoacoustics, Israel) recorded the participants’ speech. From the recorded speech, the naming duration of the task was computed using Praat software (https://www.fon.hum.uva.nl/praat).

Participants were told that their speech recorded during the picture naming task would be played at a later time toward other real persons: i.e., a preschool girl and a woman. Like this experimental paradigm, in previous neuroimaging studies for non-verbal (visual) communication (Schippers et al., 2009, 2010), a sender made gestures to convey communicative messages during fMRI scanning, and the visually-recorded gestures would later be received by another person (receiver). Using the recorded messages, the task involved a sender (the participant) and a receiver, and their goal in the task was to transmit information (the name of an object) presented on the board from the sender to the receiver. The information of the object on the board was available only to the sender and was opaque to the receiver. This cover story emotionally engaged the participants with and prevented their detachment from the receivers.

In the picture naming task (Fig. 1), participants were instructed to name the object on the center of the board held by the child or adult on the display. The picture naming task had two conditions, i.e., toward-child and toward-adult conditions. In the toward-child condition, the participants’ naming of the object was directed toward a child (i.e., IDS/CDS). In the toward-adult

| Table 1. Participant characteristics | Mean | SD | % |
|-------------------------------------|------|----|---|
| **Demographic characteristics**     |      |    |   |
| Age (years)                         | 34.6 | 4.2|   |
| Right-handed                        | 90.0 |    |   |
| Education (≥12 years)               | 100.0|    |   |
| Married                             | 100.0|    |   |
| Number of family members            | 4.6  | 1.3|   |
| Number of children                  | 2.1  | 0.8|   |
| Time since last childbirth (months) | 37.2 | 20.3|100.0|
| Living above the relative poverty line | 100.0 |    |   |
| **Beck Depression Inventory-II**    | 9.0  | 6.1|   |
| Parenting Stress Index              |      |    |   |
| Child Domain scores                 | 84.1 | 16.3|   |
| Parent Domain scores                | 95.1 | 16.9|   |
| **Interpersonal Reactivity Index**  |      |    |   |
| Empathic concern                    | 18.1 | 2.9|   |
| Personal distress                   | 12.7 | 4.3|   |
| Perspective taking                  | 17.0 | 4.0|   |
| Fantasy                             | 13.1 | 2.4|   |
condition, which acts as a control for visual and motor processing, the naming of the object was directed toward an adult (i.e., ADS).

During each trial of the fMRI task (Fig. 1), a person’s face was presented along with a white board as though the person were holding the board. For the first 500 ms, a black fixation cross was displayed at the center of the white board and the person’s head was tilted to better engage the participant. This was followed by the presentation of an object on the white board for 4000 ms. The participants were asked to view the person’s face together with the object for the 2000-ms duration of the fMRI scanning period. The participants were asked to name the object toward the child or adult face (in the toward-child or toward-adult conditions, respectively).

The participants completed two sessions of the fMRI task. In each session (36 trials per session, total of 72 trials), participants underwent two task conditions (toward-child and toward-adult conditions) using one of two lists (List 1 or 2) of the object stimuli; the task conditions and lists were counterbalanced between sessions. This fMRI task experiment adopted a block design (CACBCACBCACBC), consisting of two task blocks of 27 s (A and B) interleaved with 27-s resting baseline blocks (C). Each session included three toward-child condition (IDS/CDS) blocks and three toward-adult condition (ADS) blocks. Each condition block consisted of 6 trials (27 s). The task condition block order was counterbalanced in each session. Before the fMRI task session, participants received instructions and underwent a short practice task with training stimuli outside the MRI scanner.

**MRI data acquisition**

All participants were scanned using a 3T MRI scanner (Signa PET/MR; GE Healthcare, Milwaukee, WI) with an 8-channel head coil. For functional imaging, a sparse temporal sampling technique (Gracco et al., 2005; Shimada et al., 2015) was adopted to reduce the effects of participants’ jaw and head movements caused by the picture naming task. A T2*-weighted gradient-echo echo-planar imaging (EPI) sequence was used to produce 42 continuous transaxial slices with a thickness of 3.0 mm and a 0.5 mm gap, which covered the entire cerebrum and cerebellum (repetition time (TR) = 4500 ms; echo time (TE) = 20 ms; acquisition time (TA) = 2000 ms; flip angle (FA) = 88°; field of view (FOV) = 192 mm; 64 × 64 matrix; voxel dimension = 3.0 × 3.0 × 3.5 mm). Each volume was composed of the initial 2000-ms scanning period and the 2500-ms silent period. High-resolution structural whole-brain images were also acquired using a 3D T1-weighted fast spoiled-gradient recalled imaging sequence (TR = 8.46 ms; TE = 3.24 ms; FA = 11°; FOV = 256 mm; 256 × 256 matrix; 172 slices; voxel dimension = 1.0 × 1.0 × 1.0 mm).
fMRI data analysis

Imaging data were analyzed using the Statistical Parametric Mapping software (SPM12; https://www.fil.ion.ucl.ac.uk/spm) implemented in MATLAB (https://www.mathworks.com). To allow for stabilization of the magnetization, the first three volumes from each session were discarded. The remaining 81 volumes of two sessions for a total of 162 volumes were used for analysis. The images were realigned to correct for head motion, and then corrected for differences in slice timing within each volume. The high-resolution anatomical image was coregistered with the mean of the EPI functional images. The coregistered anatomical image was then normalized to the Montréal Neurological Institute (MNI) space, using the Tissue Probability Map (TPM) template. The same parameters were adopted for all EPI images. The normalized EPI images were spatially smoothed in three dimensions using an 8-mm full-width-at-half-maximum (FWHM) Gaussian kernel.

Statistical analysis was conducted at two levels. First, the individual task-related activation was evaluated. Second, to make inferences at a population level, the summary data for each individual were entered into a group analysis using a random effects model (Friston et al., 1999). In the individual analyses, a design matrix was prepared for each participant. The matrix had two regressors, one for the toward-child condition (IDS/CDS) and the other for the toward-adult condition (ADS). The brain activation during each condition was modelled with a general linear model using a box-car function convolved with the canonical hemodynamic response function (HRF). Blood-oxygen-level-dependent MR signals were high-pass filtered at 1/256 Hz to eliminate low-frequency artifacts. Motion-related artifacts were minimized by incorporating six parameters (three displacements and three rotations) extracted from the rigid-body realignment analysis into the design matrix. Assuming a first-order autoregressive model, serial autocorrelation was estimated from the pooled active voxels using a restricted maximum likelihood procedure. The obtained estimation was subsequently applied to whiten the data and design the matrix (Friston et al., 2002). Using the estimated parameters, contrast images were created for each participant corresponding to toward-child vs. resting, toward-adult vs. resting, and toward-child vs. toward-adult contrasts. The contrast images obtained in the individual analyses represented the normalized task-related increment or decrement in the MR signal for each participant.

For the group analysis, contrast images were generated using the weighted sum of the estimated parameters for the individual analyses. The contrast weights representing the group averages were calculated to identify brain regions showing greater activation or deactivation in the task condition vs. resting contrasts, and in the toward-child condition vs. toward-adult (control) condition contrasts. Moreover, the whole-brain regression analysis was conducted to identify brain regions in which behavioral performance of the task predicted activation (or deactivation) in the task-related contrasts. The resulting set of voxel values used for each contrast generated a statistical parametric map of the t-statistic, SPM(t), which was transformed to a unit normal distribution (SPM[Z]). The statistical threshold was set at $p < 0.05$ with family-wise error (FWE) correction for multiple comparisons at the cluster level (height threshold of $Z > 3.09$) (Flandin and Friston, 2019).

Furthermore, our observation of the deactivation of the vmPFC when naming the object toward the child was followed by an exploration of the brain regions showing increased or decreased connectivity with the vmPFC as a seed region. Therefore, a psychophysical interaction (PPI) was performed with the vmPFC seed that was determined as a cluster from the toward-child vs. toward-adult contrast. The PPI analysis allows for the examination of whether connectivity between brain regions differs in different psychological contexts (Friston et al., 1997; Gitelman et al., 2003). The time series from a 4-mm radius sphere around the peak coordinates in the seed were extracted. The PPI was calculated as the element-by-element product of the time series of the seed region and the psychological vector of interest (toward-child > toward-adult contrast). This product was subsequently re-convolved with the HRF. The interaction term was then entered as a regressor in a first-level model, together with the time series of the seed region and the psychological vector of interest. The model was estimated, and contrasts generated to test the effect of PPI were used for the second-level analysis. In the second-level random-effects analysis, we explored brain regions of the vmPFC which showed increased or decreased connectivity during the toward-child > toward-adult contrast.

**RESULTS**

**Behavioral data**

Naming accuracy and duration of the picture naming task for the toward-child (IDS/CDS) condition and toward-adult (ADS) control condition are presented in Table 2. All participants showed 100% naming accuracy for both conditions. On the other hand, they exhibited a longer naming duration in the toward-child than in the toward-adult condition (difference = 189.43 [95% CI, 144.73–234.13], paired $t(29) = 8.67$, $p < 0.001$, $r = 0.85$). To further explore the relationship between behavioral performance and psychological measures (i.e., BDI-II scores, J-PSI domain scores, and IRI subscale scores), we carried out correlation analyses with a Bonferroni correction for multiple tests. No measures were significantly correlated with the naming duration differences between the toward-child condition and the toward-adult control condition (all $ps > 0.25$).

**Neuroimaging data**

**Task activation and deactivation.** Group-level whole-brain analyses were conducted to examine the brain regions that showed greater activation and deactivation during the toward-child (IDS/CDS) condition compared with the toward-adult (ADS) control condition. In the
task-related activation analysis (toward-child > toward-adult), as shown in Table 3 and Fig. 2, we observed significant activation in the left caudate, left superior frontal gyrus (SFG)/precentral gyrus, and cerebellum regions (e.g., crus II). On the other hand, in the task-related deactivation analysis (toward-child < toward-adult), significant deactivation was observed in the right insula, right middle/inferior frontal gyrus (MFG/IFG), and subgenual anterior cingulate cortex (sgACC)/vmPFC (Table 3 and Fig. 2).

Furthermore, whole-brain regression analyses were conducted by using the naming duration differences between the toward-child condition and the toward-adult control condition as an independent variable. The analysis showed that the naming duration differences were positively associated with task activation in the supplementary motor area (SMA) (MNI coordinates, $x = -6$, $y = -12$, $z = 72$; cluster size = 276 voxels). In contrast, no significant association was found between the naming duration differences and task deactivation.

**Psycho-physiological interaction (PPI).** In the PPI analysis, the vmPFC identified by the whole-brain task-related deactivation analysis was used as a seed region. As shown in Table 4 and Fig. 3, significantly decreased, but not increased, connectivity of the vmPFC seed during the toward-child condition compared with toward-adult control condition was found in the SMA, left precentral gyrus, postcentral gyrus, and right supramarginal gyrus (SMG).

**DISCUSSION**

This fMRI study investigated the neural mechanisms underlying IDS/CDS as a verbal form of communicative adjustment. As predicted, in the picture naming task, the caregivers exhibited a longer naming duration in the toward-child (IDS/CDS) condition than in the toward-adult (ADS) control condition. Their naming of the object directed toward the child relative to the adult also showed greater involvement (activation and deactivation) in the vmPFC and in a widely distributed neural network of the caregiving brain. In particular, the vmPFC had greater task-related deactivation and decreased connectivity (anti-correlation) with the SMA, precentral, postcentral, and SMG.

In line with a previous brain lesion study for non-verbal communicative adjustments (Stolk et al., 2015), our findings indicate that the vmPFC plays an important role in generating IDS/CDS as a verbal form of communicative adjustment. As in previous studies, participants in the current investigation had to adjust communicative behaviors according to the presumed characteristics of a child in non-verbal or verbal communications. Further, vmPFC damage was previously reported to associate with failures in non-verbal communicative adjustments (Stolk et al., 2015).

**Table 2.** Naming accuracy and duration of the picture naming task

|                     | Naming accuracy (%) | Naming duration (ms) |
|---------------------|---------------------|----------------------|
|                     | Mean    | SD     | Mean    | SD     |
| Toward-child condition | 100.0  | 0.0    | 665.8   | 242.2  |
| Toward-adult control condition | 100.0  | 0.0    | 476.3   | 251.2  |

SD, standard deviation.

**Table 3.** Brain regions activated or deactivated by the picture naming task

| Brain Region              | L/R | Cluster Size | Z-score | MNI coordinates |
|---------------------------|-----|--------------|---------|----------------|
|                           |     |              |         | $x$  | $y$  | $z$  |
| Activation (toward-child > toward-adult control) | | | |         |
| Caudate nucleus           | L   | 314          | 5.00    | -16  | 6   | 24   |
| Cerebellum crus II        | R   | 782          | 4.60    | 20   | -78 | -46  |
| SFG                       | L   | 824          | 4.44    | -22  | 56  | 36   |
| Precentral gyrus          | L   |              | 4.36    | -52  | 10  | 48   |
| Cerebellum vermis IV/V    | L   | 1223         | 4.37    | 2    | -48 | -22  |
| Cerebellum IV/V           | R   | 525          | 4.00    | 30   | -68 | -28  |
| Cerebellum crus I         | R   | 3.87         | 42      | -58  | -36 |       |
| Cerebellum VIII           | L   | 342          | 3.67    | -26  | -64 | -56  |
| Cerebellum vermis VIII    |     | 3.51         | 0       | -64  | -40 |       |

Deactivation (toward-child < toward-adult control)

| Insula                    | R   | 553          | 5.70    | 34   | 8   | -10  |
| MFG                       | R   | 419          | 4.43    | 40   | 32  | 28   |
| IFG                       | R   | 3.65         | 42      | 18   | 30  |      |
| sgACC/vmPFC               | L   | 364          | 4.25    | -6   | 30  | 0    |
| sgACC/vmPFC               | R   | 4.02         | 8       | 30   | 2   |      |

IFG, inferior frontal gyrus; MFG, middle frontal gyrus; MNI, Montreal Neurological Institute.
SFG, superior frontal gyrus; sgACC, subgenual anterior cingulate cortex; vmPFC, ventromedial prefrontal cortex.
whereas the current fMRI study showed greater deactivation in the vmPFC during verbal communicative adjustments. The deactivation of the vmPFC has also been found while caregivers perform social behaviors (Seifritz et al., 2003; De Pisapia et al., 2013; Abraham et al., 2014; Rigo et al., 2017, 2019a, 2019b). For example, the caregivers exhibited greater deactivation in the vmPFC when watching themselves interact with their child than when watching an interaction between an unfamiliar caregiver and a child (Abraham et al., 2014). To date, the vmPFC, which is included in the default mode network (DMN), has shown to be deactivated (negative blood oxygen level dependent [BOLD] signal) relative to baseline during demanding task-related paradigms.

**Fig. 2.** Brain regions activated (red) or deactivated (blue) during the picture naming task. Violin plots represent the distributions of parameter estimates for the toward-child and toward-adult conditions in each brain region. White dots represent the median values; the black rectangles, the inter-quartile ranges; and the black lines, the 95% confidence intervals. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

**Table 4.** Brain regions showing increased or decreased connectivity (PPI) with the vmPFC seed during the picture naming task

| Brain Region       | L/R | Cluster Size | Z-score | MNI coordinates |
|--------------------|-----|--------------|---------|-----------------|
|                    |     | Size         |         | x   y   z          |
| Increased connectivity | No suprathreshold regions |
| Decreased connectivity |
| SMA                | R   | 379          | 4.82    | 2   2   58         |
| Precentral gyrus   | L   | 240          | 4.17    | −56 −4 46        |
| Postcentral gyrus  | L   | 507          | 4.15    | −54 −12 26       |
| SMG                | R   | 231          | 4.11    | 54 −28 24        |
McKiernan et al., 2003; Singh and Fawcett, 2008; Mayer et al., 2010); this is caused partially by neuronal inhibitory activity with a concomitant decrease in oxygen levels (Sten et al., 2017). As suggested previously, task-related deactivation in the DMN regions appears to be a mechanism through which the brain optimizes externally-oriented goal-directed processing by suppressing certain internal self-relevant thoughts (Gusnard et al., 2001; Anticevic et al., 2012; Buckner and DiNicola, 2019). According to a psychological framework of social cognitive processes (Horton and Keysar, 1996; Keysar and Horton, 1998), egocentric perspectives are inhibited for successful communication, and other-specific adjustments are enacted only when necessary. In line with these previous studies, the vmPFC deactivation when generating IDS/CDS may be involved in optimizing communicative behaviors for the inter-generational transmission of knowledge by suppressing the self-oriented (egocentric) perspective. The function of the vmPFC deactivation may also be considered as a prosocial drive, which can lead to prosocial behavior depending on the context (Decety et al., 2016).

Regarding the task-related functional connectivity of the vmPFC as a seed region, decreased connectivity (anti-correlation) was shown in the SMA, precentral gyrus, postcentral gyrus, and SMG. In particular, the SMA exhibited not only decreased task-related connectivity but also task-related activation modified by the naming duration of the IDS/CDS. When generating IDS/CDS, SMA activation may be involved in speech modification (e.g., longer naming duration) as a communicative behavior for the inter-generational transmission of knowledge. Concerning the involvement of the SMA in speech production, previous fMRI studies reported that the activation of a posterior part of the SMA (the SMA-proper) was related to motor output control (Alario et al., 2006). As recently reported in a review, the SMA-proper has also been suggested to be primarily involved in speech motor control as an initiation and timing interface (Hierrich et al., 2016). In addition to speech production, the SMA-proper seems to be involved in affective vocalization, which conveys a speaker’s emotional state through modulation in various vocal parameters (Brown et al., 2009; Belyk and Brown, 2016). According to a dual-pathway model of human vocal control, sensorimotor cortical systems, including the SMA, precentral gyrus, and postcentral gyrus, support the production of learned and affective vocalizations (e.g., speech and song), whereas the limbic system supports innate vocalizations (e.g., laughter) (Pisanski et al., 2016). In terms of the control of affective vocalization, the sensorimotor cortical systems (specifically the SMA), in cooperation with the vmPFC, may be associated with conveying communicative ostensive signals through the modulation of vocal parameters (e.g., duration) during IDS/CDS generation.

Regarding the right SMG, there was no significant task-related activation (toward-child vs. toward-adult contrast), but there was significantly decreased connectivity with the vmPFC, suggesting involvement in optimizing externally-oriented goal-directed processing. In the current study, both conditions required participants to construct a triadic context which included an object and a child (toward-child condition) or an adult (toward-adult condition); IDS/CDS in a teaching (informing) context is partially used as a prosocial behavior to manipulate a child’s attention toward relevant stimuli (Kline, 2015). When teaching a child an object’s name, the participants may have entailed a bit more reorientation of attention than when they were teaching a same generation adult. Thus, a possibility is raised that the cooperation of the right SMG with the vmPFC during the generation of IDS/CDS may be involved in constructing a triadic teaching context, including the reorientation of attention toward a child and an object on the basis of communicative adjustments. To date, right SMG (anterior TPJ) activation during social interaction has been interpreted as reorienting (shifting) of attention to an external source (Carter and Huettel, 2013). The right SMG has also been suggested to be associated with the reorientation of attention from an internal, bodily, or self-perspective toward external stimuli or another’s viewpoint (Corbetta et al., 2008). The attentional reorienting function of the right SMG has been found to be related to self-other distinction (Newman-Norlund et al., 2008), which may be fundamental to the
construction of a triadic teaching context. Furthermore, regarding task-related functional connectivity, the decreased connectivity (anti-correlation) between the SMG and the DMN (including the vmPFC) was found during externally-oriented goal-directed processing tasks (Anticevic et al., 2012; Spreng, 2012). Given these previous findings, it is likely that the task-related decreased connectivity between the SMG and the vmPFC may be related to the attentional reorienting function in the construction of a triadic teaching context.

To the best of our knowledge, this study is the first to investigate the neural mechanisms of IDS/CDS generation as a verbal form of communicative adjustment. So far, only two fMRI studies have focused on IDS/CDS comprehension by adults (Matsuda et al., 2011, 2014). In these previous fMRI studies, caregivers – specifically mothers with preverbal infants – showed enhanced cortical activation of Broca’s and Wernicke’s areas included in a dorsal pathway for language during IDS/CDS comprehension. However, in the current study, which included mothers with preschool-age children, these areas did not exhibit any task-related differences in activation between the generation of IDS/CDS and ADS (toward-child vs. toward-adult contrast). Based on these findings, Broca’s and Wernicke’s areas as core regions of perisylvian language networks are unlikely to be IDS/CDS-specific brain regions. Moreover, regarding subcortical regions, in a previous fMRI study (Matsuda, et al., 2014), activation of the right caudate nucleus during IDS/CDS comprehension was associated with the caregivers’ ongoing use of IDS/CDS components in daily life. On the other hand, in the current study, the left caudate nucleus also exhibited task-related activation during generating IDS/CDS in caregivers with preschool-age children. The caudate nucleus seems to be important for both comprehending and generating IDS/CDS. According to the global caregiving network of the human brain (Feldman, 2015, 2017; Feldman et al., 2019), the caudate nucleus is included in the reward-motivation system supporting multiple attachment-related motivational behaviors. A growing body of evidence (Pauli et al., 2016) suggests that the anterior caudate supports multiple motivational behaviors, whereas the posterior part is involved in executive functions, such as inhibition, switching (set-shifting), and multi-tasking. In particular, the posterior caudate has been shown to have stronger coactivation with the left dlPFC (including the left SFG) and involvement in executive functions.

Based on evidence from various studies, the cerebellum is engaged not only in motor control, but also in cognitive and affective functions (Schmahmann, 1996; Stoodley and Schmahmann, 2009; Stoodley, 2012). Within the functional topography of the cerebellum, sensorimotor function is related to primary sensorimotor (anterior I–V and adjacent VI) and secondary regions (VIII), while cognitive/affective functions are associated with posterior regions (e.g., VI, crus I/II, VIb, and IX). More recently, it has been increasingly recognized that the cerebellum plays an important role in social functions (Van Overwalle et al., 2014, 2015; Guell et al., 2018a, 2018b). A meta-analysis of fMRI studies (Van Overwalle et al., 2014) found robust activation of the cerebellum (specifically the posterior cerebellum) during social functions, including inferences about other persons’ mental states (mentalizing). In a previous fMRI study on caregivers (Noriuchi et al., 2019), cerebellar activation was found to be involved in the representation of the infant/child’s mental states and critical for mother–child interactions and human parental care. As addressed in a process model for prosocial behavior (Decety et al., 2016), communicative behavior like IDS/CDS can be promoted based on mentalizing. Furthermore, the cerebellum is suggested to act as a forward controller that not only predicts motor sequencing, but also social action sequencing to facilitate fluent social interactions (Heleven and Van Overwalle, 2018; Heleven et al., 2019). The cerebellum detects repetitive patterns of temporally or spatially structured events and constructs internal models that can be used to make predictions (Leggio and Molinari, 2015). During repetitive IDS/CDS generation (e.g., in daily life), the cerebellum may be involved in constructing the internal models of communicative behavioral sequences supporting the inter-generational transmission (sharing) of knowledge.

Finally, we discuss future directions (or limitations) for research that will likely lead to a better understanding of the underlying mechanisms involved in communicative adjustments like IDS/CDS. First, in order to generalize the current findings to everyday communication, it may be necessary to adopt more ecologically valid experimental paradigms. As recently suggested (Schilbach et al., 2013; Redcay and Schilbach, 2019), second-person (i.e., truly interactive) neuroscience approaches have been defined as studies in which at least one of two criteria – i.e., emotional engagement (“experience”) and social interaction (“participation”) – is met. For the “experience” criterion, the participants in the picture naming task implemented in the current study were thought to emotionally engage with and not be detached from social partners (i.e., a preschool girl and a woman); this was achieved through the cover story that real social partners would receive, at later time, the communicative message conveyed by the participants during the task. For the “participation” criterion, however, the current experimental paradigms are thought to involve structured, but not dynamically unfolding social interactions. Hence, the current paradigms involved different roles (sender and receiver) but neglected to establish mutual influences between interactors in real time. Further studies using dynamically unfolding social interactions in real time would help to advance understanding of communicative adjustments such as IDS/CDS within everyday communication. Second, the neural involvement in IDS/CDS identified herein may provide insight into the specific impairments in parental depression, which lead to a reduction in the use of IDS/CDS by parents (Bettes, 1988; Kaplan et al., 2001). This phenomenon may be conceived as a problem in the teaching process (Kim et al., 2015). Previously, depressed patients were found to lack DMN suppression during cognitively demanding tasks (Anticevic et al., 2012). Given the evidence, maternal depression may affect the neural mech-
anisms (e.g., vmPFC function) of IDS/CDS generation, as subclinically depressed mothers have altered prefrontal activation when interpreting facial expressions (Shimada et al., 2018). Thus, the discussed findings indicate that fMRI could be a clinically meaningful measure for the early detection of maternal depression. Third, future studies may be needed to elucidate neural similarities and differences across a suite of communicative adjustments for children, including not only IDS/CDS ("parentese") but also infant- or child-directed action ("motionese"). The behavioral characteristics of communicative adjustments are a product that evolved as a historical extension of motionese during the evolution of non-human primates; these characteristics are intended to enhance social learning (Csibra and Gergely, 2009; Masataka, 2020). Exploring the neural mechanisms of infant/child directed speech (IDS/CDS) and action (motionese) may provide some clues as to the evolutionary origins of the primitive form of teaching behavior that occurs in adult-child interactions in non-human primates, as well as in humans, by which the inter-generational transmission of knowledge is made possible (Senju et al., 2008; Csibra and Gergely, 2009; Masataka, 2020).

To summarize, the current study found that the vmPFC and other brain regions in the global caregiving network were involved when caregivers generated IDS/CDS as a verbal form of communicative adjustment. These results are in line with a previous study on non-verbal communicative adjustments (Stolk et al., 2015). Deactivation in the vmPFC and its decreased connectivity during IDS/CDS generation are suggested to be involved in optimizing prosocial communicative behaviors for the inter-generational transmission of knowledge by suppressing the egocentric perspective. This function of the vmPFC is considered as a prosocial drive, which – depending on the context – can lead to prosocial communicative behavior (Decety et al., 2016). This study improves the current understanding of the neural mechanisms involved in prosocial communicative adjustments and provides insight into the teaching behavior and related fields of research (e.g., parenting, pedagogy, and education).

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Ryoko Kasaba: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization, Funding acquisition. Koji Shimada: Conceptualization, Methodology, Formal analysis, Investigation, Writing - original draft, Writing - review & editing, Funding acquisition. Akemi Tomoda: Writing - review & editing, Funding acquisition.

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DECLARATIONS OF INTEREST

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