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Switching language switches mind: linguistic effects on developmental neural bases of 'Theory of Mind'

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Theory of mind (ToM)—our ability to predict behaviors of others in terms of their underlying intentions—has been examined through false-belief (FB) tasks. We studied 12 Japanese early bilingual children (8–12 years of age) and 16 late bilingual adults (18–40 years of age) with FB tasks in Japanese [first language (L1)] and English [second language (L2)], using fMRI. Children recruited more brain regions than adults for processing ToM tasks in both languages. Moreover, children showed an overlap in brain activity between the L1 and L2 ToM conditions in the medial prefrontal cortex (mPFC). Adults did not show such a convergent activity in the mPFC region, but instead, showed brain activity that varied depending on the language used in the ToM task. The developmental shift from more to less ToM specific brain activity may reflect increasing automatization of ToM processing as people age. These results also suggest that bilinguals recruit different resources to understand ToM depending on the language used in the task, and this difference is greater later in life.

Keywords: fMRI; theory of mind; cognitive development; language; bilingualism; medial prefrontal cortex

INTRODUCTION

Theory of mind (ToM)—ability to understand others' desires and intentions that can be different from one's own—is critical for human cognitive development (Frith and Frith, 2003) in every culture. Among a plethora of paradigms to test ToM, the false-belief (FB) task (Wimmer and Perner, 1983; Perner and Wimmer, 1985) is perhaps the most widely used to assess a person's understanding of others' beliefs (Baron-Cohen, 2000). The nearly universally observed results of the FB task are that many 4- and 5-year-olds answer correctly, while many 3-year-olds and older children or adolescents with autism answer incorrectly (Baron-Cohen *et al.*, 1985, 1986).

ToM neuroimaging studies using FB-style paradigms have consistently found ToM/FB-related activity in the medial prefrontal cortex (mPFC) (Goel *et al.*, 1995; Happé *et al.*, 1996; Brunet *et al.*, 2000; Gallagher *et al.*, 2000, 2002; Sabbagh and Taylor, 2000; Vogeley *et al.*, 2001; Kobayashi *et al.*, 2006) and/or temporo-parietal junction (TPJ) (Saxe and Kanwisher, 2003; Saxe and Wexler, 2005) in adults. Brain imaging studies of ToM in children are still scarce. The few studies performed with children have implicated mPFC (Ohnish *et al.*, 2004; Kobayashi *et al.*, 2007b), TPJ (Kobayashi *et al.*, 2007a), inferior parietal lobule (Ohnish *et al.*, 2004; Kobayashi *et al.*, 2007a) and ventral prefrontal cortex (Liu, 2006) for children's ToM.

Since both language and ToM undergo dramatic developmental change during the first 5 years of life, it has been debated whether language ability constrains ToM, or vice versa (de Villiers and de Villiers, 2000; Miller, 2006). However, the evidence is mixed on this issue. It has been shown that early language ability predicts later ToM performance (Astington and Jenkins, 1999). Similarly, marked improvement in 3–4-year-old children in FB task performance has been shown after language training (Lohman and Tomasello, 2003). Moreover, individuals with high functioning autism have been shown to pass a first order FB task, presumably because of their intact language (especially grammatical) ability (Tager-Flusberg, 2000). However, a series of recent experiments with infants have shown that non-verbal FB tasks can be performed by infants as young as 13 months-old (Onishi and Baillargeon, 2005; Surian *et al.*, 2007). These results call into question the theory that there are linguistic constraints on ToM development.

Neurological studies that have examined the relationship between neural correlates of ToM and language have obtained mixed results. An agrammatic aphasic patient has exhibited intact non-verbal ToM performance (Siegal and Varley, 2002), suggesting language is not required for ToM ability. However, some studies of ToM related abilities, such as the understanding of intentional movement, have found

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activation in brain areas that are normally associated with language (e.g. Broca's area) (Iacoboni *et al.*, 1999; Chaminade *et al.*, 2002). Moreover, in our previous brain imaging study of ToM in American children and adults, three-way interactions were found in language areas of the brain [left superior temporal gyrus (STG) and insula] between the age, task (verbal *vs* non-verbal) and condition (ToM *vs* non-ToM) (Kobayashi *et al.*, 2007a). Adults showed greater activity in language areas while processing non-verbal ToM, yet children had greater activity in them for a verbal ToM condition. These results are consistent with a recent behavioral ToM study in which adults performed poorly in non-verbal ToM task when they were asked to shadow the verbal narratives simultaneously (Newton and de Villiers, 2007). These results seem to support a conjecture that some aspects of language affect ToM throughout development and adults may process ToM more verbally than children.

A recent meta-analysis found that although the timetables of children's acquisition of FB understanding may vary, the developmental trajectory is the same across cultures (Liu *et al.*, in press; see also Wellman *et al.*, 2001, for a similar meta-analysis). Similarly, no difference was found between Canadian, Indian, Peruvian, Thainese and Samoan children in the developmental onset of passing a single FB paradigm (Callaghan *et al.*, 2005). However, these results do not necessarily rule out that there may be linguistic influence on 'how' ToM is understood. Several cross-linguistic studies on ToM have found some linguistic effects on the FB task performance. For example, Mandarin Chinese speaking children performed significantly better when *yiwei* and *dang*, which connote that the belief referred to may be false, were used then when *xiang* (the more neutral verb) was used (Lee *et al.*, 1999). Similarly, Turkish or Puerto Rican Spanish (PR Spanish) speaking children who have either a specific verb (Turkish) or a case marker (PR Spanish) available to make the FB mental state more explicit, performed better in the FB task than Brazillian Portuguese or English speaking children who do not have those lexicons (Shatz *et al.*, 2003). These qualitative differences in ToM may not easily be detected by the forced-choice style FB tasks used in the majority of the cross-cultural studies of ToM.

Our previous study was the first to find linguistic influences on ToM at the neural level in American monolingual and Japanese bilingual adults (Kobayashi *et al.*, 2006). Japanese bilingual adults performing a FB task in Japanese showed activity in the bilateral dorsolateral prefrontal cortex. These same participants, while performing the FB task in English, showed greater activity in the left precentral gyrus and caudate nucleus. Although those differences may be related to language-switching specific to bilingualism (Hernandez *et al.*, 2001), they may also be associated with different ways of understanding ToM depending on the language used in the tasks.

The present study sought to explore the linguistic effects on the developmental neural bases of ToM in Japanese-English late bilingual adults [who acquired English (L2) after 15 years of age] and early bilingual children [who acquired English (L2) and Japanese (L1) simultaneously before 5 years of age]. Our main aim was to find both language-dependent and -independent neural bases that might be important for ToM development. Hemodynamic responses were recorded using fMRI while the participants performed FB tasks in English (L2) (Figure 1A) and Japanese (L1) (Figure 1B). We reasoned that brain regions that showed more activity during the L1 task would be important for processing ToM in Japanese. Conversely, brain regions that exhibited more activity during the L2 task would be important for understanding ToM in English. In terms of the developmentally important ToM neural bases, those regions that showed greater activity in children than adults would be more important for understanding ToM during childhood, whereas those brain regions that exhibited more activity in adults would have developed later. In a few recent studies of developmental neural correlates for understanding ToM (Kobayashi *et al.*, 2007a) or irony (Wang *et al.*, 2006), negative correlation between age and ToM/irony specific brain activity has been found. This may be related to increasing automatization of ToM/irony understanding as people age (Wang *et al.*, 2006). Thus, we predicted that similar decrease in ToM related activity in the frontal regions in adults relative to children would be found.

Brain imaging studies in bilingualism using various tasks have suggested that bilinguals may employ at least some different brain regions depending on the language used in the task (Kim *et al.*, 1997; Luke *et al.*, 2002; Wartenburger *et al.*, 2003), and that these differences can be modulated by the age of acquisition (AoA) for the L2 (Kim *et al.*, 1997; Wartenburger *et al.*, 2003). Several studies have found a relationship between AoA and the degree of separation between the neural correlates of L1 and L2, with late bilinguals showing greater separation of the two languages than early bilinguals (Ullman, 2001, 2005; Hernandez and Li, 2007). Thus, we also predicted that we would find more dissociation between the L1- and L2-dependent neural correlates of ToM in adults (late bilinguals) than in children (early bilinguals).

METHODS

Twenty-eight healthy, right-handed Japanese-English bilinguals participated [16 (8 female) adults with mean age of 29 years 8 months (s.d. = 4.6, range 18 to 38) and 12 (6 female) children with mean age of 10 years and 1 month (s.d. = 1, range 8 to 11.11)]. Adult participants were late bilinguals and started to use English by an average of 19 years of age. Child participants were early bilinguals and started to use English by an average of 4 years of age. The adults and children had lived in the United States or other English speaking countries for 8.8 years and

Fig. 1 Example of English L2 (**A**) and Japanese L1 (**B**) ToM tasks. All the ToM tasks were the second-order FB tasks in the form of 'x thinks that y thinks that . . .' Japanese was an exact translation of English. All slides were presented serially, with six slides in each story. On the sixth slide, the subjects were asked to choose from two possible answers, A or B.

7.4 years on average, respectively. They had spoken English for 11 years (adults) and 7.5 years (children) on average. All participants were balanced bilinguals (i.e. they had comparable proficiencies in the two languages according to a questionnaire). Ten children had two Japanese parents, and two children had a Japanese parent and an American parent. All participants lived in the New York Metropolitan area and had similar socio-economic backgrounds (all adult participants were students or employees of companies, and all child participants were sons/daughters of middle-to-high income families according to a questionnaire). IQ was assessed [Wechsler *Abbreviated* Scale of Intelligence™ (WASI™, The Psychological Corporation®, Harcourt Assessment Inc., San Antonio, TX)] and all were above the standard norm for verbal IQ (Adults: $M = 123.3$, s.d. $= 10.4$; Children: $M = 132.9$, s.d. $= 15.5$) and performance IQ (Adults: $M = 114$, s.d. $= 9.6$; Children: $M = 143.09$, s.d. $= 10.05$) with no significant difference between the groups in the full IQ. Children's English syntax ability was assessed ['sentence combining' subtest in Test of Language Development, Intermediate–3rd Edition (TOLD-I:3; Hammill and Newcommer, 1999)], showing an average of the 99 percentile. Children were also tested for proficiency in Japanese with an in-house test, similar to the TOLD-I:3. Their average score for the Japanese test was 99.17%. We confirmed that all participants could read and comprehend all the Japanese *kanji* characters, which appeared in the task. All participants signed written consent forms approved by Weill Medical College of Cornell University Institutional Review Board.

Participants completed three conditions for each language (Japanese or English) (see Supplementary data 'Examples of story stimuli'): an experimental ToM, a non-ToM control and scrambled sentence or baseline, in a standard block design (Posner *et al.*, 1988) (Figure 1). The ToM condition consisted of second-order FB stories (in the form of 'x thinks that y thinks that . . .') (Perner and Wimmer, 1985; Astington *et al.*, 2002) in order to test the participants with a paradigm, which was difficult enough to keep them engaged. The non-ToM condition described physical causal situations (as in Fletcher *et al.*, 1995). The non-ToM stories were matched in terms of syntax with the ToM stories, however they contained perceptual verbs (e.g. 'sees' and 'hears') instead of mental verbs. The baseline conditions consisted of unlinked sentences, which as a whole did not tell a coherent story. The Japanese conditions were an exact translation of the English, except characters were given Japanese names. The Japanese translation was back-translated by another translator to confirm accuracy of the initial translation. Length and semantics of each Japanese

sentence were checked by a linguist to ensure that they matched with the corresponding English sentences. Each story was preceded by 2 s prompt showing either 'What are they thinking?' (for ToM), 'What is happening?' (for non-ToM), or 'Scrambled sentences' (for baseline).

There were five stories for each condition, each consisting of five slides (4 s each) followed by a sixth outcome slide (10 s). The participants' task was to choose the correct outcome by pressing one of two keys for either possible outcome. For the baseline condition participants chose which of two sentences had appeared in the preceding five slides. Each functional run (L1 or L2 task) consisted of five episodes of each of the three conditions (counter-balanced across participants), and therefore, contained 15 episodes (5 episodes × 3 conditions) (Figure 2). Before each run, there was an 8 s fixation for a total time of 32 s per episode and 8 m 8 s for an entire run. Paper-based examples, which were similar but not identical to the actual tasks, were shown to the participants before scanning. All child participants were acclimated to the MRI scanner environment with a simulator before the experiment. Participants were scanned during both English and Japanese versions of the task, with order of language counter-balanced across participants. All participants were tested in the Weill Medical College of Cornell University in New York City.

Brain image slices were acquired on a 3-T GE Signa scanner (General Electric Medical Systems, Milwaukee, WI). A 3D SPGR scan (TR = 23 ms, TE = Minimum Full, Flip angle 20°, 124 slices, 1.4 mm slice thickness, FOV = 240 mm, in-plane resolution of 0.9 mm by 1.3 mm) was acquired. T2-weighted 2D axial anatomical images with a Fast spin-echo sequence (TR = 6000 ms, TE = 68, Flip angle = 90°, 29 slices, 5 mm slice thickness, FOV = 200 mm) were acquired and used as a prescription for the functional images, which were acquired using Spiral-in/out sequence (Glover and Law, 2001) (TR = 2000 ms, TE = 30 ms, FOV = 200 mm, Flip angle = 90° and 64 mm × 64 mm matrix). The center of the 29 axial 5 mm thick slices was positioned along the AC-PC to cover the whole brain.

Statistical parametric mapping software (SPM2) (http://www.fil.ion.ucl.ac.uk/spm) implemented in MATLAB 6.1 (Mathworks, Inc, Sherborn, MA) was used for preprocessing and analyzing the acquired images. The first four acquisitions of each series were discarded to avoid intensity variation due to magnetization non-equilibrium effects in the Spiral-in/out pulse sequence. The functional images were normalized to a Montreal Neurological Institute (MNI) template image and smoothed using an isotropic Gaussian filter kernel having a full-width half-maximum of twice the normalized voxel size of 3.125 mm × 3.125 mm × 5 mm.

Individual analyses were performed using a fixed-effect model where data were best fitted at every voxel, using the General Linear Model (Friston *et al.*, 1999) to describe the variability in the data in terms of the effects of interest.

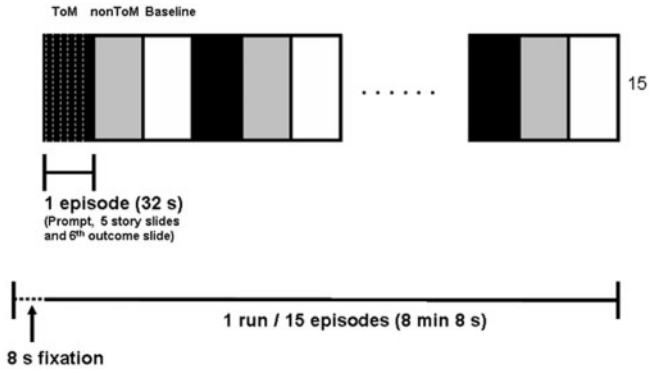

Fig. 2 Experimental design. Each task (L1 or L2) run had three conditions, each of which had five episodes. Each episode was shown for 32 s (including the 2 s prompt at the beginning), for a total of 15 episodes in each task run lasting 8 min 8 s. Eight second fixation was shown at the beginning of each run, which was removed from the data analyses to avoid intensity variation due to magnetization non-equilibrium effects in the Spiral-in/out pulse sequence.

At the single subject level, there were six contrasts of interest: 'ToM minus baseline,' 'non-ToM minus baseline,' 'ToM minus non-ToM,' and three other contrasts of the opposite subtractions. A group-level analysis was performed using a random-effect model that enables statistical inferences at the population level (Friston *et al.*, 1999). Contrast images were made for each participant for the six contrasts listed above. At a group level, we performed two-sample *t*-tests to compare adults and children in their ToM specific activity using the 'ToM minus baseline' images. A set of paired *t*-tests was performed to compare between the 'ToM minus baseline' and 'non-ToM minus baseline' images within each age group. Another set of paired *t*-tests was performed to compare between the L1 and L2 'ToM minus baseline' images within each age group. In addition, a conjunction analysis (for each age group) was performed to find brain regions that were activated during the ToM (minus baseline) conditions in both languages. A height threshold of $P \leq 0.005$ without correction for multiple comparisons was used, with 10 or more contiguous voxels unless otherwise noted. However, for those comparisons, in which we could not find any brain regions that were significantly different at $P < 0.005$ (uncorrected), we used more lenient height threshold of $P < 0.025$ (uncorrected) to recognize the significant differences (actual *P*-values for these cases are shown in each table). We also used this more lenient height threshold of $P < 0.025$ (uncorrected) to find activity in a few brain regions (e.g. mPFC and TPJ) in which we had a priori hypotheses. The stereotactic coordinates of the voxels that showed significant activations were matched with the anatomical localizations of the local maxima on the standard brain atlas (Talairach and Tournoux, 1988). Before the matching, the MNI coordinates of the normalized functional images were converted to the Talairach coordinates using 'mni2tal' matlab function (Mathew Brett; http://www.mrc-cbu.cam.ac.uk/Imaging/Common/mnispace.shtml).

RESULTS

Behavioral data

Mean proportion correct of each adult and child group was above chance-level for the ToM and non-ToM conditions [Adult-L1: 79.5%, $t(15) = 11.79$, $P < 0.001$; Adult-L2: 86.25%, $t(15) = 9.97$, $P < 0.001$; Child-L1: 73.3%, $t(15) = 4.20$, $P < 0.01$; Child-L2: 81.6%, $t(11) = 6.68$, $P < 0.001$] and the scrambled stories [Adult-L1: 89.3%, $t(15) = 12.69$, $P < 0.0005$; Adult-L2: 86.3%, $t(15) = 6.72$, $P < 0.0005$; Child-L1: 88.3%, $t(11) = 7.37$, $P < 0.0005$; Child-L2: 88.3%, $t(11) = 6.66$, $P < 0.0005$]. Average reaction times (RT) (during the sixth slide) for the ToM condition did not differ significantly from the non-ToM condition within each age group for either task. There was no difference between adults and children in the RT for each condition (ToM or non-ToM) in each task (L1 or L2). In addition, there was no correlation between the task performance and each of the indices to assess language ability (i.e. verbal IQ, number of years of speaking English, time spent in the United States and other English-speaking countries) in either age group.

To examine main effects and interactions between age (child *vs* adult), condition (ToM *vs* non-ToM) and language (L1 *vs* L2), a 2 × 2 × 2 repeated-measures analysis of variance was performed. There were no main effects or interactions between any combinations of the factors.

Brain imaging results

Effects of ToM (vs non-ToM). Each age group recruited similar brain regions for ToM relative to the non-ToM condition in each language condition. Moreover, each age group employed the brain regions that have been implicated previously in the ToM brain imaging studies in the ToM relative to the non-ToM condition for each language condition. These prefrontal regions include the anterior cingulate cortex (ACC), and mPFC (Figure 3). Adults employed other regions such as insula and anterior STG (aSTG), for the non-ToM relative to the ToM condition. There was no brain region that was employed more for the non-ToM relative to the ToM condition in children (Supplementary Table 1).

Effects of language (L1 vs L2) on ToM. To examine the brain network specific to processing ToM in each language in each group, we compared the activity during the L1 (Japanese) ToM condition with that during the L2 (English) ToM condition within each age group. In adults, the L1 ToM condition elicited more brain activity in the ventral ACC and bilateral mPFC than the L2 task. In contrast, the L2 task demonstrated greater activity than the L1 task in other brain regions such as the left precuneus and right temporal pole (TP) that have been suggested to be involved in ToM related processing but have not been considered to be core ToM processing regions (Frith and Frith, 2003) (Table 1).

During the L1 ToM condition relative to L2 ToM condition children showed greater activity in the right TP and right mPFC. They showed greater activity in the left inferior frontal gyrus and right inferior parietal lobule (IPL) during the L2 ToM relative to L1 ToM condition (Table 1).

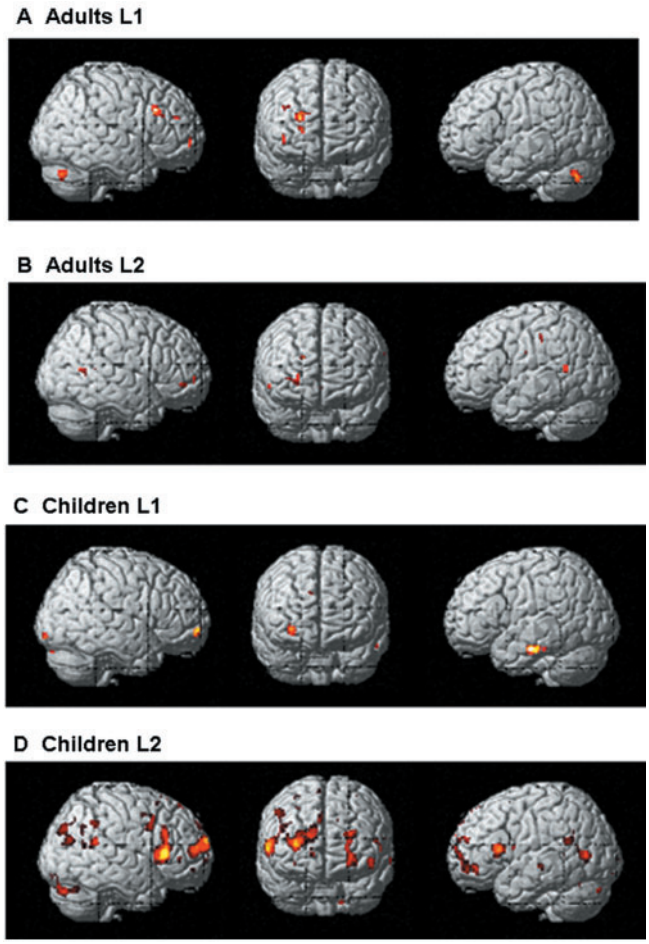

Fig. 3 Effects of ToM: Brain activity during ToM relative to non-ToM condition. Adults [during L1 (**A**) and L2 (**B**) tasks] and children [during L1(**C**) and L2 (**D**) tasks] recruited similar brain regions for ToM relative to the non-ToM condition. Moreover, each age group recruited the brain regions that have been implicated previously in the ToM brain imaging studies. These regions include the ACC and mPFC.

Conjunction between L1 and L2. To examine brain regions that are important regardless of language, we performed conjunction analyses between the L1 ToM and L2 ToM conditions in each age group separately. In children, the ToM related activity for the both languages converged in the mPFC (Figure 4B). In contrast, in adults, no such convergent activity in the mPFC regions was detected. Instead, convergent activity was seen in the posterior STG (pSTG) and TPJ, but only at a more lenient threshold ($P = 0.014$, uncorrected) (Figure 4A; see also Table 1).

Effects of age. To examine developmental differences in the neural bases involved in ToM processing, we compared adults and children using two sample *t*-tests. Overall, children showed more ToM condition specific brain activity than adults for both language conditions. For the L1 ToM condition, children recruited many more regions including the bilateral mPFC, aSTG, right precunues and

Table 1 Paired *t*-tests comparisons and conjunction analyses between L1 and L2 ToM condition relative to baseline

Region (Brodmann area)	Coordinates			*Z*	*P*-value	Direction
	x	*y*	*z*			
Paired *t*-tests comparison						
Adults: L1 ToM vs L2 ToM						
Left precuneus (7)	−10	−56	36	3.19	0.001	L2 > L1
Left precentral gyrus (6)	−28	5	61	2.18	0.001	L2 > L1
Right TP (21/38)	36	1	−25	2.86	0.002	L2 > L1
Right IPL (40)	52	−28	28	2.79	0.003	L2 > L1
Left vmPFC (10)	−6	60	−6	2.69	0.004	L2 > L1
vACC (24)*	2	36	−20	2.16	0.015	L1 > L2
Right mPFC (8)*	10	49	44	2.00	0.023	L1 > L2
Left mPFC (9)*	−10	62	28	1.99	0.023	L1 > L2
Children: L1 ToM vs. L2 ToM						
Right TP/aSTS (21/38)	44	7	−17	2.82	0.002	L1 > L2
Left IFG (47)*	−36	17	−9	2.38	0.009	L2 > L1
Right mPFC (9)*	10	62	28	2.14	0.016	L1 > L2
Right IPL (40)*	59	−47	39	2.19	0.014	L2 > L1
Conjunction						
Adults: Conjunction between L1 ToM and L2 ToM						
Right pSTG/TPJ (22/40)*	52	−44	20	2.21	0.014	
Children: Conjunction between L1 ToM and L2 ToM						
mPFC (10)	2	51	7	3	0.001	
Right SFG/mPFC (10)	10	65	19	2.94	0.002	

Abbreviations: aSTS, anterior superior temporal sulcus; IFG, inferior frontal gyrus; IPL, inferior parietal lobule; mPFC, medial prefrontal cortex; MOG, middle occipital gyrus; SFG, superior frontal gyrus; pSTG, posterior superior temporal gyrus; TP, temporal pole; vACC, ventral anterior cingulate cortex; vmPFC, ventro-medial prefrontal cortex. *A height threshold of $P \leq 0.025$ (uncorrected) was used to find significant differences in these regions because we had a priori hypotheses in them and/or because there was no significant difference in these contrasts at $P \leq 0.005$ (uncorrected), for the comparison purpose.

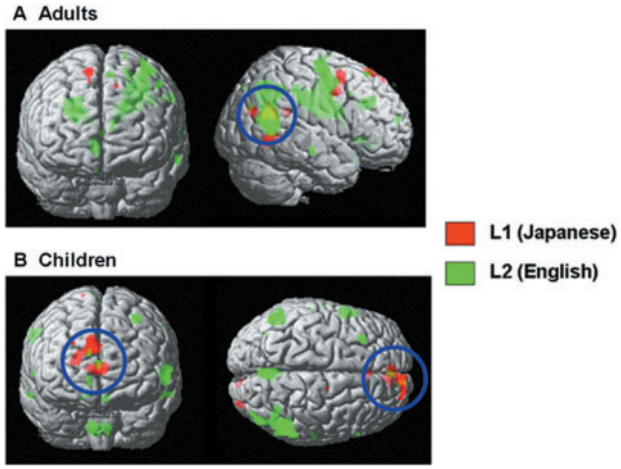

Fig. 4 Effects of Language: Convergence and divergence between L1 ToM- and L2 ToM-specific brain activity. In adults, the divergence of activity was found in several brain regions including the left precuneus, left precentral gyrus, and right IPL. The convergence of the L1 ToM and L2 ToM specific activity was found in the right pSTG/TPJ (**A**). In children, the divergence of activity was found in several regions including the right mPFC, left IFG and right IPL. The convergence of the L1 ToM and L2 ToM related activity was seen in the mPFC region (**B**).

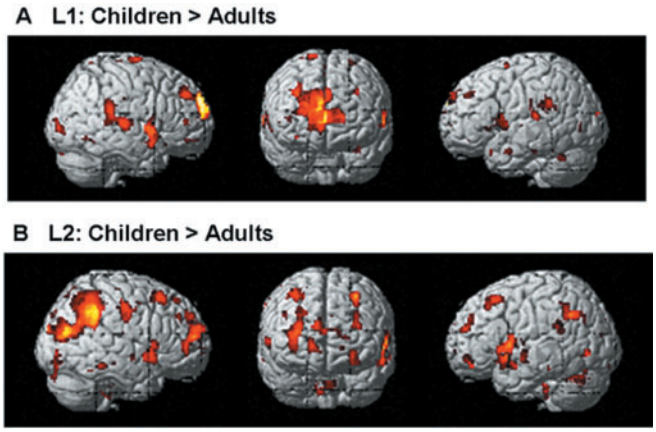

Fig. 5 Effects of Age: Two-sample *t*-test comparing adults and children in the ToM condition specific brain activity. Children showed more ToM condition specific brain activity than adults for both language conditions. During the L1 ToM condition, children activated many more regions including the mPFC, aSTG, right precunues and left TPJ than adults (**A**). During the L2 ToM condition, children activated several regions including the right IPL, bilateral aSTG, vmPFC, right TPJ and putamen more than adults (**B**).

left TPJ than adults (Figure 5A; see also Table 2). For the L2 ToM condition, children employed several regions including the right IPL, bilateral aSTG, ventral mPFC, right TPJ and putamen more than adults (Figure 5B; see also Table 2). There was no brain region where adults had more activity than children for either language condition.

DISCUSSION

This study, which is the first to explore language-specific development of neural correlates for ToM in Japanese bilingual children and adults, showed both language-dependent and -independent brain activities associated with ToM. Based on previous results from neuroimaging research of ToM, we expected to find greater activity in medial frontal regions during ToM relative to non-ToM and baseline conditions. Both children and adults showed reliable ToM specific activity in the mPFC. This finding is consistent with the previous results of ToM neuroimaging studies in adults (Goel *et al.*, 1995; Happé *et al.*, 1996; Brunet *et al.*, 2000; Sabbagh and Taylor, 2000; Vogeley *et al.*, 2001; Gallagher *et al.*, 2000, 2002; Kobayashi *et al.*, 2006) and children (Ohnish *et al.*, 2004; Kobayashi *et al.*, 2007b).

However, both children and adults showed different patterns of ToM specific activity depending on the language used in the task. Adults activated seemingly more dorsal mPFC area during the L1 ToM condition but more ventral mPFC area during the L2 ToM condition (Figure 4A), yet children activated more overlapping mPFC regions for both conditions (Figure 4B). Overall, more overlap between the two languages in the mPFC region was seen in children. In adults the convergence of the two language conditions

Table 2 Brain activity associated with ToM (L1 or L2) relative to baseline Two sample *t*-tests Adults vs Children*

Region (Brodmann area)	Coordinates			*Z*	*P*-value
	x	*y*	*z*		
L1: Children > Adults					
Right mPFC (10)	8	49	9	3.36	<0.0005
Left aSTG (22)	−59	4	5	3.14	0.001
Right aSTG (22)	46	8	−4	3.13	0.001
Right precentral gyrus	18	−8	69	3.12	0.001
Left TPJ (39/40)	−63	−41	28	2.95	0.002
Right IOG (18)	14	−93	−4	2.72	0.003
Right lateral sulcus	61	−36	20	2.71	0.003
Left cerebellum	−44	−59	−22	2.69	0.004
Left mPFC (10)	−16	54	3	2.68	0.004
Right DLPFC (9)	32	44	31	2.64	0.004
Right vMFG (11)	34	42	−12	2.61	0.005
L2: Children > Adults					
Right IPL (40)	59	−41	37	3.82	<0.0005
Left aSTG (22)	−59	6	5	3.71	<0.0005
vmPFC (11)	−4	34	−17	3.39	<0.0005
Right TPJ (39)	34	−55	23	3.38	<0.0005
Right aSTG (22)	50	13	−6	3.24	0.001
Precuneus (7)	4	−61	58	3.20	0.001
Right putamen	16	3	−10	3.19	0.001

Abbreviations: aSTG, anterior superior temporal gyrus; DLPFC, dorsolateral prefrontal cortex; IOG, inferior occipital gyrus; IPL, inferior parietal lobule; mPFC, medial prefrontal cortex; TPJ, temporo-parietal junction; vMFG, ventral middle frontal gyrus; vmPFC, ventro-medial prefrontal cortex.

*Only the results of Children > Adults comparisons are listed because there was no significant difference in the Adults > Children comparisons at $P < 0.025$ (uncorrected).

occurred only at a low height threshold in the right pSTG or TPJ. The TPJ area has been implicated in more recent ToM brain imaging studies (Saxe and Kanwisher, 2003; Saxe and Wexler, 2005; Kobayashi *et al.*, 2007a). In our previous study with American adults and children convergent ToM-specific activity was seen in the TPJ (Kobayashi *et al.*, 2007a). Thus, these results together may indicate that adults' neural correlates of ToM are more language dependent than children's.

The children in this study were early bilinguals whereas the adults were late bilinguals. It has been hypothesized that AoA modulates linguistic and cognitive processes because procedural learning declines as age progresses while declarative leaning increases (Hernandez and Li, 2007). It has been proposed that procedural memory relies on frontal-basal ganglia circuitry, while declarative memory relies on a medial temporal circuit (Ullman, 2001, 2005; Hernandez and Li, 2007). We found more L2 ToM specific activity in the vmPFC and putamen (among other regions) in children than adults (Table 2). Thus, alternatively, the age difference in ToM processing involving the L2 may be associated with a greater reliance of adults on the declarative memory involving the temporal regions, and children's greater reliance on the procedural memory involving the frontal-basal ganglia region.

By comparing ToM related brain activity in children with that in adults, we also sought to find developmentally important neural bases of ToM. Greater ToM related activity was found in children compared with adults for both language conditions. This finding is consistent with our previous results with American adults and children (Kobayashi *et al.*, 2007a). Wang *et al.* (2006) also found more robust activity in the mPFC regions in children than in adults for processing irony. These results support the hypothesis that as people age, their ToM understanding becomes increasingly more automatic (Wang *et al.*, 2006) and may bypass the mPFC region. While there was no brain region in which adults activated more than children during the ToM condition, the convergence in pSTG between the L1 and L2 ToM conditions was found at more lenient threshold level. This pSTG region together with the adjacent angular gyrus has been implicated in hearing-based semantic analysis (see Price, 2000, for a review) and speech or heard word comprehension (Patel *et al.*, 2006; Pekkola *et al.*, 2006; Rimol *et al.*, 2006). Thus, these results may support the recent findings from both behavioral (Newton and de Villiers, 2007) and neuroimaging study (Kobayashi *et al.*, 2007a) of ToM development, that adults process ToM more verbally than children.

There are limitations in the present study. One limitation involves the effect of culture. Although throughout this article the results have been interpreted in terms of linguistic effects on neural bases of ToM, these results could equally be attributed to cultural effects since our participants were bicultural as well as bilingual. Behavioral experiments on biculturalism have found consistently significant difference between Americans/Westerns and Japanese/Asians in how the different cultural groups interpret everyday events and phenomena. Westerners have been shown to view the world more analytically, while Easterners tend to view the world more holistically (Nisbett, 2003). These differences in the world view seem to affect one's self construal (Markus and Kitayama, 1991) and other social cognition and perception including ToM and perspective-taking (Lehman *et al.*, 2004; Wu and Keysar, 2007). According to a cultural explanation, the results presented here in age differences in ToM specific activity could be attributed to early biculturalism in children (therefore, a greater overlap of the L1 and L2 ToM in the mPFC region) and late biculturalism in adults (therefore, a greater separation of the L1 and L2 ToM). However, since no measure of the participants' cultural identity or experience [e.g. cultural priming (as in Hong *et al.*, 2001)] was included, this study was unable to differentiate between cultural and linguistic effects. Future work, which includes measures of participants' cultural identity, would help address these questions.

Another limitation in the present study is that different relative height thresholds were used to detect significant brain differences. Potentially, significant differences detected through the height threshold of $P < 0.025$ (uncorrected) may

be regarded as weak results. Clearly these results will need to be replicated; however, given this is the first study to examine ToM associated brain function in bilingual adults and children, we wanted to avoid possible Type II error if significant differences are in fact present.

In conclusion, the present study has, for the first time, explored linguistic influence on developmental neural bases of ToM in Japanese bilingual children and adults. Language and age-dependent and -independent neural bases of ToM were found. Bilingual children showed an overlap in the mPFC area for the L1 and L2 ToM conditions. In adults, we found more divergence between the two conditions and some convergence in the pSTG/TPJ area. Since these areas have been implicated in ToM in American/European adults and children, it may be that these areas are important for ToM development universally. In addition, early bilinguals may utilize more similar brain regions for processing ToM in different languages than late bilinguals. Lastly, in the present study, adults, more than children, recruited different brain regions depending on the language used in the ToM task. These results may indicate that people recruit different linguistic and cognitive resources depending upon the language used to process ToM, and that this difference may become greater as people age.

SUPPLEMENTARY DATA

Supplementary data are available at *SCAN* online.

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