

## Functional MRI and Structural Connectome Analysis of Language Networks in Japanese-English Bilinguals

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**Abstract**—We aimed to clarify the mechanisms of neural plasticity involved in language. We hypothesized that alterations which occur in bilinguals could reflect the mechanisms of acquisition of a second language and simulate neural plasticity related to language. We compared spatial characteristics of story listening-related hemodynamic modulations and subcortical fiber networks between monolinguals and bilinguals. Participants were Japanese monolinguals and Japanese–English bilinguals whose first language was Japanese. We divided bilinguals into early and late bilinguals depending on whether the age of acquisition was before or after 7 years of age. We applied intergroup analysis to investigate the following: (1) blood oxygen level-dependent response (BOLD) responses during story listening by block-based fMRI; (2) number of fibers (NOFs) between specific edges by DTI. Both bilingual samples showed larger BOLD responses (BRs) in the right putamen and bilateral superior temporal gyri compared to the Japanese monolinguals in fMRI. Late bilinguals demonstrated bigger BRs in the right anterior temporal lobe and left medial parietal lobe than early bilinguals. Early bilinguals showed a higher NOFs between the right putamen and precentral gyrus than monolinguals and late bilinguals in DTI. Late bilinguals showed a lower NOFs between the left superior temporal gyrus and supramarginal gyrus than monolinguals and early bilinguals. Early bilinguals reinforce the subcortical fiber network between the right putamen and precentral gyrus, and activate the right putamen to gain alternative language function. We conclude that these key cerebral regions and subcortical fiber networks could contribute to the neural plasticity of language. © 2020 The Authors. Published by Elsevier Ltd on behalf of IBRO. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

**Key words:** neural plasticity, bilingualism, functional MRI, connectome, neural efficiency hypothesis, default mode network.

### INTRODUCTION

Neural plasticity can occur as a compensatory brain function after certain types of brain damage, such as stroke, trauma, brain tumors, and even after neurosurgery. Neural plasticity can occur from primary to higher cerebral functions (Pillai, 2010; Izutsu et al.,

2017). The degree of neural plasticity differs depending on brain function and age (Feldman et al., 1992; Vargha-Khadem et al., 1997; Baciú et al., 2003). Several hypotheses for mechanism of neural plasticity have been proposed including neurogenesis (Gu et al., 2012), change in neuronal excitation (Mozzachioldi and Byrne, 2010), rearrangement of cortical activity (Pillai, 2010), and alterations in subcortical fiber networks (Almeida and Lyons, 2017). However, detailed mechanisms of neural plasticity have not yet been clarified.

Language function is a higher cerebral function which arises from cortical activity and neural networks between speech association areas. The mechanism of language plasticity is therefore complicated in comparison to those for other functions, such as motor systems. Since the complexity arises from both cortical activity and subcortical fiber networks, both must be investigated simultaneously. With understanding of the mechanisms

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**Abbreviations:** AnG, angular gyrus; AoA, age of acquisition; BOLD, blood oxygen level-dependent response; BRs, BOLD responses; CgG, cingulate gyrus; DMN, default mode network; IFG, inferior frontal gyrus; L1, first language; L2, second language; MFG, middle frontal gyrus; MTG, middle temporal gyrus; NBR, negative blood oxygen level-dependent response; NOFs, number of fibers; PBR, positive blood oxygen level-dependent response; PCu, precuneus; PrG, precentral gyrus; PUT, putamen; SFG, superior frontal gyrus; SMG, supramarginal gyrus; STG, superior temporal gyrus; TMP, temporal pole.

of language plasticity, we can overcome educational and clinical problems, such as learning a foreign language, rehabilitation after stroke and aggressive resection in neurosurgery.

We hypothesized that some changes occurring in the acquisition of a second language (L2) by bilinguals could simulate the mechanism of neural plasticity for language. A number of previous studies have attempted to clarify the brain function of bilingualism. Berken et al. reported that simultaneous and sequential bilinguals had different patterns of gray matter density in cortical and basal ganglia regions, including the left putamen and the bilateral premotor cortex, utilizing voxel-based morphometry (Berken et al., 2016). Using fMRI, they showed different patterns of activity during tasks involving the first language (L1) and L2 (Berken et al., 2015). Hamalainen et al. used diffusion tensor imaging (DTI) to focus on the subcortical connectivity and reported that early bilinguals have increased subcortical fiber network density in the arcuate fasciculus (Hämäläinen et al., 2017). Oliver et al. used fMRI to focus on cortical activity and subcortical networks and reported that late L2 learners had stronger regional recruitment in ventral and dorsal language association areas and weaker functional connectivity within the dorsal language network during an L2 task than an L1 task (Oliver et al., 2017).

These previous results on bilingualism support the idea that cortical and basal ganglia regions and networks related to motor and language functions contribute to language acquisition. These structures could provide clues to elucidate the mechanism of neural plasticity related to language. However, in order to clarify the mechanism of plasticity, a study is required which simultaneously assesses cortical and subcortical alternations and compares the difference between monolinguals, early, and late bilinguals during L1 and L2 tasks. L1 and L2 can be used to investigate linguistically different mechanisms. In this study, we examined cortical and basal ganglia activation by functional magnetic resonance imaging (fMRI) during a story listening task (Kansaku, 2000) and the number of subcortical fibers with DTI (Daducci et al., 2012) in a sample including Japanese monolinguals and Japanese-English bilinguals subdivided by the age of acquisition (AoA) of L2.

## EXPERIMENTAL PROCEDURES

### Participants

Participants in this study were 42 Japanese volunteers who were university students of medicine, health care, and nursing. All participants began learning Japanese as their L1 from birth, and spoke Japanese daily in their life. Participants were divided into the following three groups: Japanese monolinguals ( $n = 12$ ), early Japanese-English bilinguals ( $n = 17$ ) and late Japanese-English bilinguals ( $n = 13$ ). The Japanese monolinguals spoke only Japanese as L1 and received standard English education from 12-years-old in junior high school. Bilingual participants were defined as follows: (1) could communicate with native English

speakers in English without difficulty; (2) could speak Japanese fluently as their L1; (3) had resided in an English-speaking country continuously for at least one year; (4) depending on their age at time of residence, had received native English education in an English speaking country; (5) during their period of residence in an English speaking country, they communicated mainly in Japanese at home and English outside the home; (6) had Japanese parents; (7) received certificated English qualifications and achieved a higher level classification. English communication skills were assessed by interview with an English education specialist. The specialist was an Associate Professor at the Division of Foreign Languages, Juntendo University; an academic reputation reviewer for the Times Higher Education World University Rankings; and a member of the research committee on human speech communication for the Acoustic Society of Japan. Early bilinguals were defined as participants who had been exposed to English before the age of 7 years and late bilinguals as those who were exposed at 7 years or older (Johnson and Newport, 1989). We defined the age of acquisition as the time of exposure to L2 defined as having moved from Japan to an English-speaking country.

### Stimuli

We applied the block-based fMRI design for detecting blood oxygen level-dependent (BOLD) responses during two story listening tasks. We used the story listening tasks for the following reasons: (1) The English listening performance of the Japanese population has been reported as low (2018 Report on Test Takers Worldwide <https://www.ets.org/s/toeic/pdf/2018-report-on-test-takers-worldwide.pdf>), and thus we considered that a listening task would be suitable to distinguish between monolinguals and bilinguals; (2) reading tasks such as a verb generation task were at risk of activating the visual and motor cortex. Participants listened to both L1 (*Issunboshi*) and L2 (*Peter Rabbit*) stimuli. Both tasks targeted preschoolers, thus we considered both tasks were at the same level of difficulty of listening comprehension. Beforehand, it was explained to participants that they will hear two distinct audio stimuli which consisted of Japanese and English stories respectively, and that several questions about the story would be asked after the experiment. Each experiment consisted of nine epochs: five control epochs alternating with four narrative epochs. Only the first control epoch was 60 s in length, including a 20 s dummy scan, and all other epochs lasted 40 s. The narratives of each language were delivered during the four test epochs (epochs 2, 4, 6 and 8) and the preceding test epochs were replayed in reverse during each control epoch to exclude activation elicited by general processing of auditory signals (Kansaku, 2000). In each experiment, the participants were instructed to close their eyes and listen attentively to the tasks delivered through headphones. After all experiments, the examiner confirmed their understanding of the story by asking questions about the title and contents.

## Imaging acquisition

Participants were scanned at the Juntendo University Hospital on a PHILIPS Achieva 3.0 T TX (Philips Medical Systems, Best, The Netherlands) equipped with a 32-channel head coil. Functional images for the listening task were acquired with a T2-weighted short-tau inversion recovery, gradient echo, echo-planar imaging sequence, using 22 transverse slices collected with the following parameters: thickness = 6 mm, voxel size =  $2.5 \times 2.5 \times 6.0$  mm, in-plane resolution =  $96 \times 96$ , field of view = 240 mm, flip angle =  $90^\circ$ , echo time = 35 ms and repetition time = 4000 ms. A total of 95 brain volumes (380 s) were obtained for each language task. For morphological processing, a high-resolution three-dimensional fast field echo T1-weighted image was acquired with 180 transverse slices with the parameters: thickness = 1 mm, voxel size =  $1 \times 1 \times 1$  mm, in-plane resolution =  $256 \times 256$ , field of view = 256 mm, flip angle =  $10^\circ$ , echo time = 3.3 ms and repetition time = 15 ms.

## Data analysis

Data processing was carried out using Statistical Parametric Mapping version 12 (SPM12) (Wellcome Department of Imaging Neuroscience, London, UK) and MATLAB version 2014a (The MathWorks Inc., Natick, MA, USA). Imaging data were realigned, slice timing corrected, normalized to the Montreal Neurological Institute (MNI) template (resampled voxel size =  $2 \times 2 \times 2$  mm), and smoothed with an 8 mm full-width at half-maximum isotropic Gaussian kernel to increase the signal-to-noise ratio. A voxel-wise analysis of the BOLD signal was computed by applying a general linear model. After model estimation, both positive and negative T-contrasts were assessed to detect positive blood oxygen level-dependent response (PBR) and negative blood oxygen level-dependent response (NBR).

## Group analysis

We analyzed PBR and NBR of the whole brain in three groups. The Japanese monolinguals were played the L1 task. The early and late bilinguals were played the L2 task. In each group, uncorrected one-sample *t*-tests were conducted to identify statistical significance at the level of  $p < 0.01$ , with a 10 voxel minimum activation threshold. Statistically significant areas were rendered on 3D brain models in SPM12.

## Intergroup analysis

We analyzed intergroup differences in BOLD responses (BRs) of the whole brain. The BRs of the Japanese monolinguals during the L1 task were used as a control. We made three intergroup comparisons, similar to Cao et al.: (1) BRs of the late bilinguals during the L2 task compared to BRs of the Japanese monolinguals during the L1 task; (2) BRs of the early bilinguals during the L2 task compared to BRs of the Japanese monolinguals

during the L1 task; and (3) BRs of the late bilinguals during the L2 task compared to BRs of the early bilinguals during the L2 task (Cao et al., 2013).

Two-sample *t*-tests were conducted to scrutinize the differences using an uncorrected threshold value of  $p < 0.01$  and containing at least 10 contiguous voxels (Cao et al., 2013). Thresholded SPM clusters were superimposed on a T1 template in multiple axial planes within MNI coordinates. The peaks of clusters were labeled using Neuromorphometrics atlas ([www.neuromorphometrics.com](http://www.neuromorphometrics.com)).

## Connectome analysis

DTI data were acquired with a single-shot spin-echo echo-planar imaging sequence using 55 transverse slices with the following parameters: thickness = 2.5 mm, voxel size =  $1.88 \times 1.88 \times 2.5$  mm, in-plane resolution =  $128 \times 128$ , field of view = 240 mm, flip angle =  $90^\circ$ , echo time = 70 ms, repetition time = 5485 ms, and echo-planar imaging factor = 51, including 15 gradient directions with  $b = 800$  s/mm<sup>2</sup> and one without diffusion sensitization (*b*<sub>0</sub> image).

DTI and high-resolution T1-weighted gradient echo data were processed using the Connectome Mapping Toolkit (Daducci et al., 2012). Segmentation of gray and white matter was based on high-resolution T1-weighted gradient echo volumes. Gray and white matter were parcellated into 83 regions of interest (ROIs) based on two anatomical atlases (Fischl et al., 2002; Desikan et al., 2006) followed by whole-brain streamline tractography. Edges were defined as connections between each ROIs according to graph theory and were quantitatively analyzed as the number of fibers (NOFs).

We conducted statistical analysis to evaluate the different of NOFs in each edge between both bilingual groups and the Japanese monolinguals. The Japanese monolinguals were used as a control. One-way ANOVA (threshold  $p < 0.01$ ) was conducted for all edges using SciPy statistical functions on Python. We used IBM SPSS Statistics version 22 for Windows (IBM Corp., Armonk, NY, USA) to conduct a normality test with the Kolmogorov–Smirnov test (threshold  $p < 0.05$ ) for all edges significant in one-way ANOVA. Following this, Dunnett's T3 test was performed for post-hoc analysis to examine unequal variance.

## Statistical analysis of the demographic characteristics

We conducted a normality test with the Kolmogorov–Smirnov test. For the nonparametric data, we used Kruskal–Wallis test (age) and Mann–Whitney *U* test (length of residence in English speaking countries). The chi-square test was used for gender and handedness. Statistics were performed by using IBM SPSS Statistics version 22 for Windows (IBM Corp., Armonk, NY, USA), and the significance level established for all analyses was 95%.

### MRI measurement reliability

The MRI measurements were performed in accordance with the standard protocol of our institution and previously reported method (Kansaku, 2000).

### Ethical statement

The study was approved by the Research Ethics Committee of Juntendo University, Tokyo, Japan (approval No. 2013125). All experiments were conducted in accordance with the Declaration of Helsinki and all relevant guidelines and regulations. All participants were 18 years or older, and written informed consent was obtained from all participants, and could be provided on request.

### Data availability

The original and processed MRI data related to this study will be available to share upon request to corresponding author.

## RESULTS

### Participant characteristics

Demographic characteristics of each group are presented in Table 1. AoA of L2 was  $3.0 \pm 2.3$  years (mean  $\pm$  standard deviation) in early bilinguals and  $13.2 \pm 5.0$  years in late bilinguals. Length of residence in English speaking countries was  $6.0 \pm 4.3$  years in early bilinguals and  $3.2 \pm 2.0$  years in late bilinguals. We evaluated handedness using the Edinburgh Handedness Inventory (Oldfield, 1971) and found that five participants were left handed (two Japanese monolinguals, two early bilinguals and one late bilingual). There was no significant difference between the Japanese monolinguals, early bilinguals and late bilinguals in chronological age, gender and handedness. The length of residence in English speaking countries of the early bilinguals was significantly higher than that of the late bilinguals ( $U = 62$ ,  $P < 0.05$ ,  $Z = -2.043$ ). AoA was one of the definitions of the early and late bilinguals and was excluded from the statistical analysis. In the confirmation questions following experiments, all Japanese monolinguals could correctly answer questions related to the contents of the L1 task. All bilinguals could correctly answer questions related to the contents of both the L1 and L2 tasks.

$P$  values correspond to the chi-square test (gender, handedness), Kruskal–Wallis test (age) and Mann–

Whitney  $U$  test (length of residence in English speaking countries) between groups. *Abbreviations:* AoA, age of acquisition; SD, standard deviation.

### Cortical PBRs/NBRs across groups

In the Japanese monolinguals during the L1 task, a PBR was detected in the left middle temporal gyrus (MTG). NBRs were detected in the bilateral precuneus (PCu), left cingulate gyrus (CgG), bilateral angular gyri (AnG), left superior frontal gyrus (SFG), left SFG medial segment, left inferior frontal gyrus (IFG), and right middle frontal gyrus (MFG) (Fig. 1A). In the late bilinguals during the L2 task, PBRs were detected in the bilateral MTG, left superior temporal gyrus (STG), bilateral temporal poles (TMP), bilateral precentral gyri (PrG), and left IFG. NBRs were detected in the right PCu, left CgG, right AnG, bilateral superior parietal lobules, right parietal operculum, bilateral MFGs, and bilateral SFG (Fig. 1B). In the early bilinguals during the L2 task, PRBs were detected in the bilateral STG, right MTG, left planum temporale, and left PrG. NBRs were detected in the bilateral CgGs, bilateral PCus, right AnG, and left supramarginal gyrus (SMG) (Fig. 1C).

### Intergroup analysis of BRs

The early bilinguals showed few differences in BRs between the L1 and L2 tasks. The late bilinguals showed numerous differences in BRs between the L1 and L2 tasks. The late bilinguals during the L2 task showed larger BRs at the right putamen (PUT), left pallidum, bilateral STGs, bilateral TMPs, bilateral CgGs, bilateral PCus and bilateral PrGs compared to the Japanese monolinguals during the L1 task (Fig. 2A). The early bilinguals during the L2 task showed larger BRs at bilateral PUTs, bilateral STGs, right CgG, and left PrG compared to the Japanese monolinguals during the L1 task (Fig. 2B). The late bilinguals during the L2 task showed larger BRs at the right hippocampus, right planum polare, left TMP, left CgG, and left PCu compared to the early bilinguals during the L2 task (Fig. 2C).

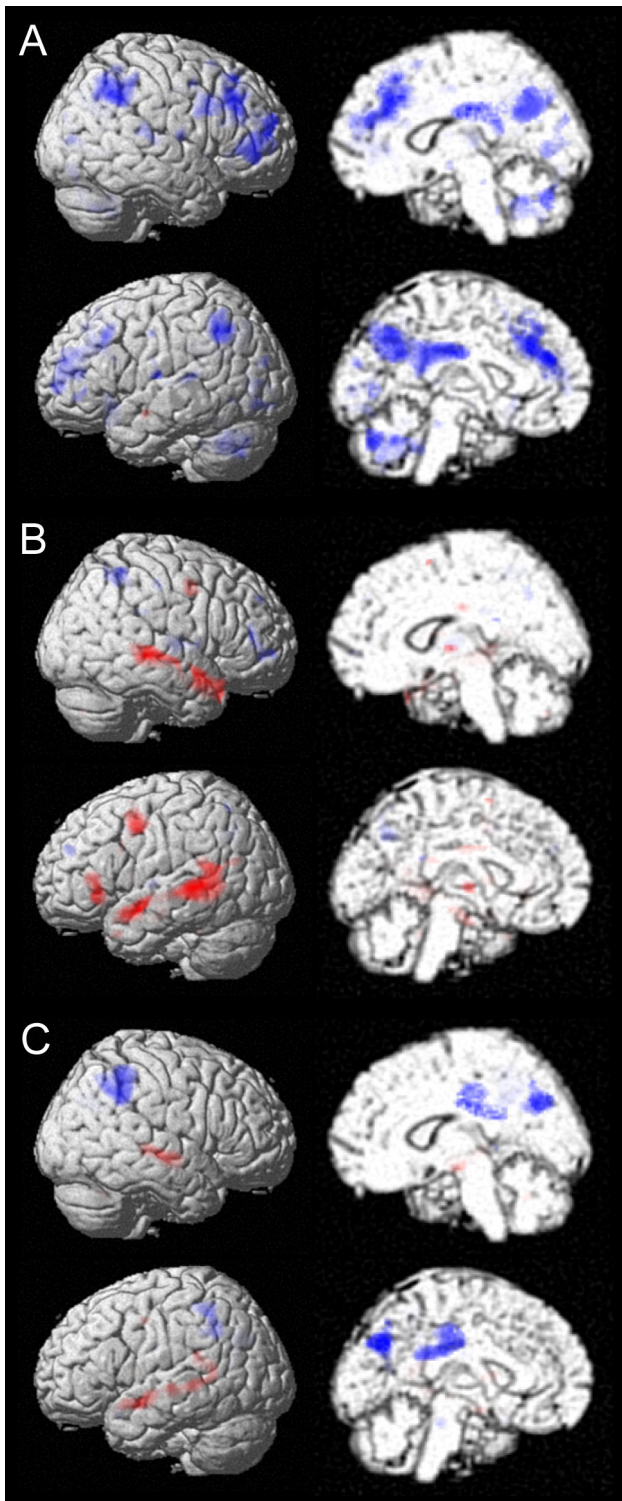
### Connectome analysis

The NOFs between the right PUT and right PrG in the early bilinguals (mean  $\pm$  standard error:  $3187.8 \pm 469.9$ ) was significantly higher than in the Japanese monolinguals and late bilinguals ( $1373.4 \pm 149.3$  and  $1773.2 \pm 247.9$ , respectively) (Fig. 3). The NOFs

**Table 1.** Participant characteristics

	Japanese monolinguals ( $n = 12$ )	Early bilinguals ( $n = 17$ )	Late bilinguals ( $n = 13$ )	$P$ values
Gender (Male/Female)	9/3	11/6	6/7	0.32
Age (years) (mean $\pm$ SD)	$23.8 \pm 3.8$	$21.6 \pm 2.6$	$23.2 \pm 2.1$	0.13
AoA (years)	–	$3.0 \pm 2.3$	$13.2 \pm 5.0$	–
Length of residence in English speaking countries (years)	–	$6.0 \pm 4.3$	$3.2 \pm 2.0$	$<0.05$
Handedness (Right/Left)	10/2	15/2	12/1	0.79

$P$  values correspond to the chi-square test (gender, handedness), Kruskal–Wallis test (age), and Mann–Whitney  $U$  test (length of residence in English speaking countries) between groups. *Abbreviations:* AoA, age of acquisition; SD, standard deviation.



**Fig. 1.** Positive and negative cortical BOLD responses in each of the three groups. Red clusters indicate positive BOLD responses and blue clusters indicate negative BOLD responses. **(A)** Japanese monolinguals during the L1 task. **(B)** Late bilinguals during the L2 task. **(C)** Early bilinguals during the L2 task. These results are rendered on 3D models in SPM12.  $p < 0.01$  uncorrected, minimum cluster size: 10 voxels. *Abbreviations:* BOLD, blood oxygen level dependent; SPM12, Statistical Parametric Mapping version 12; 3D, three-dimensional.

between the left STG and left SMG in the late bilinguals ( $213.7 \pm 44.4$ ) was significantly lower than in the early bilinguals and Japanese monolinguals ( $509.7 \pm 62.4$  and  $515.9 \pm 70.7$ , respectively).

## DISCUSSION

### Intergroup analysis of BRs between bilinguals and Japanese monolinguals.

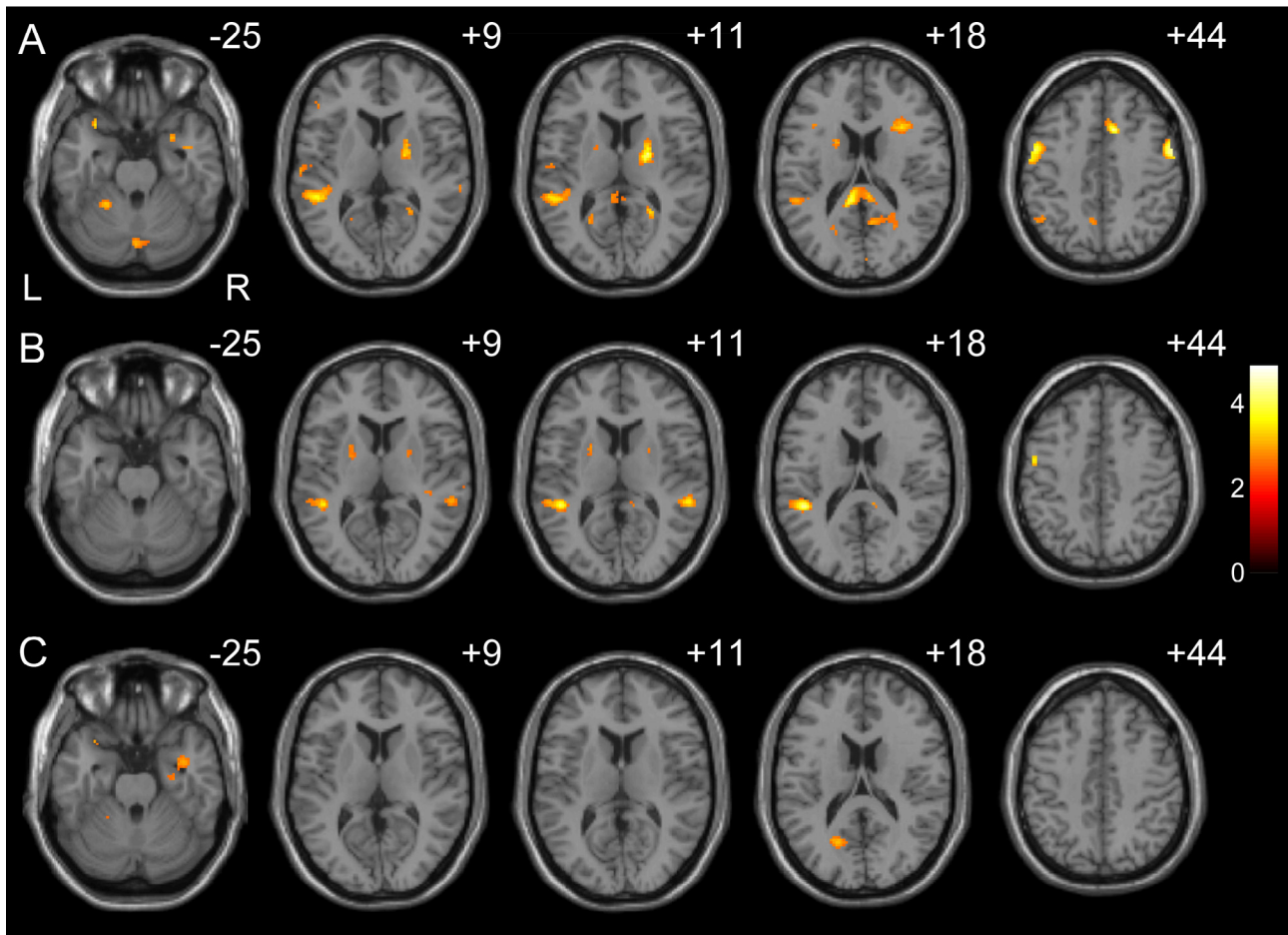
Late bilinguals and early bilinguals showed larger BRs in the right PUT and bilateral STG than the Japanese monolinguals. These results could suggest that both bilingual groups utilize the right hemisphere to understand L2. The importance of the right hemisphere for the neural plasticity of language has been reported previously (Pillai, 2010).

The involvement of the PUT in language functions has been the subject of previous study. Burgaleta et al. has reported that bilinguals have an expanded bilateral PUT compared to monolinguals (Burgaleta et al., 2016). Bilateral PUT volume has also been shown to differ according to articulatory control needs (Ramanujan, 2019). The right PUT was co-activated with the left PUT and affects certain aspects of semantic, orthographic and phonological processing (Viñas-Guasch and Wu, 2017). Crosson et al. suggested that the right basal ganglia suppress activity in the right frontal lobe, preventing right frontal structures from interfering with language production (Crosson et al., 2003). These previous findings support the idea that PUT bilaterality is a critical part of the language network and that both sides work together in bilinguals. In our study, the intergroup fMRI analysis between the Japanese monolinguals and late bilingual group did not show left PUT activation whilst listening to the L2 audio. Clusters were found at the left PUT in late bilingual group, however these clusters were not indicated as positive due to small cluster size.

Bilateral language association areas including STG-associated language function has been studied in bilinguals. English-French bilinguals showed greater neural activation in classical language areas in the left hemisphere and right hemisphere homologues during a sentence judgement task (Jasinska and Petitto, 2013). It has been argued that Spanish-English bilinguals recruit the right STG to engage a more complex network in semantic processing (Palomar-García et al., 2015). Moreover, the right STG was included as one of the crucial regions for language switching and associated with the attention demand required in language processing (Luk et al., 2011). These previous findings indicate that bilinguals may recruit both dominant and non-dominant side language association areas to develop proficiency in two languages. The results of our intergroup analysis of the STG was consistent with them.

### Intergroup analysis of BRs between late and early bilinguals

Late bilinguals demonstrated larger BRs in the following two areas: (1) the right anterior temporal lobe,



**Fig. 2.** Intergroup differences of BOLD responses: **(A)** Late bilinguals compared to Japanese monolinguals **(B)** Early bilinguals compared to Japanese monolinguals. Both groups of bilinguals showed BR differences at the right putamen and bilateral superior temporal gyri **(C)** Late bilinguals compared to early bilingual. The late bilinguals showed BR differences at the right hippocampus, right planum polare, left cingulate gyrus and left precuneus. Slice Montreal Neurological Institute (MNI) coordinates are  $z = -25, +9, +11, +18, +44$ . The color scale represents the  $T$ -value of the pixels.

consisting of the planum polare and hippocampus; and (2) the left medial parietal lobe, consisting of the CgG and PCu (Fig. 2C).

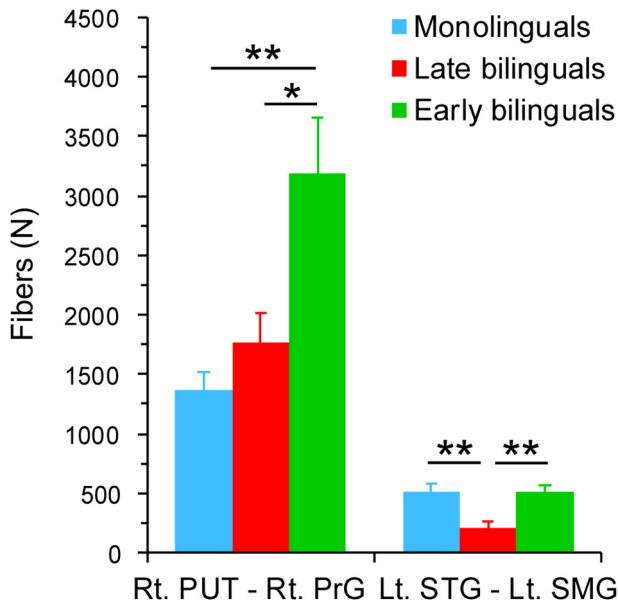
According to the results of our group analysis (Fig. 1), the PBR in the right anterior temporal lobe was stronger in late bilinguals than early bilinguals. Differences in BRs in the right anterior temporal lobe would reflect this stronger activation in late bilinguals. Our results are in concordance with previous studies which showed that early bilinguals with high proficiency in L2 displayed lower brain activation (Perani et al., 2003; Wartenburger et al., 2003; Briellmann et al., 2004; Grady, 2008). These BRs of bilinguals in L2 can be conceptualized within the neural efficiency hypothesis (Dunst et al., 2014).

On the other hand, NBRs of the left medial parietal lobe was stronger in early bilinguals than late bilinguals (Fig. 1). Difference of BRs in the left medial parietal lobe would reflect stronger deactivation in early bilinguals. Mullinger et al. described how NBRs can be considered to reflect neural deactivation that reduces cerebral blood flow coupled with the cerebral metabolic ratio of oxygen (Mullinger et al., 2014). NBRs in the group analysis (Fig. 1) likely reflect the key regions of the default mode

network (DMN) (Buckner et al., 2008). The DMN is defined as the interconnected set of activated brain regions in the resting state, which can be suppressed during attention-demanding tasks (Shulman et al., 1997). The finding that the medial parietal lobe showed larger BRs in our intergroup analysis (Fig. 2C) is reflective of part of the DMN (Buckner et al., 2008). Our result could demonstrate that early bilinguals prepare for understanding the L2 by deactivating the DMN.

#### Connectome analysis of early and late bilinguals and Japanese monolinguals

Early bilinguals showed dense connectivity between the right PUT and ipsilateral PrG compared to Japanese monolinguals and late bilinguals. These results could suggest that early bilinguals modulated the right cortico-basal ganglia network. In previous studies on brain networks of bilingual participants, early second language learning is suggested to be preferentially reliant upon sensorimotor processes and frontal–basal ganglia circuits (Hernandez et al., 2005). Waldron et al. reported that early bilinguals recruit bilateral sensorimotor regions



**Fig. 3.** Connectome analysis. Mean NOFs in the edges between the right putamen and right precentral gyrus, and left superior temporal gyrus and left supramarginal gyrus in each group. The early bilinguals showed significantly higher NOFs between the right putamen and precentral gyrus than the Japanese monolinguals and the late bilinguals. The late bilinguals showed significantly lower NOFs between the superior temporal gyrus and supramarginal gyrus than the Japanese monolinguals and the early bilinguals. Blue bars, NOFs of the Japanese monolinguals; red bars, NOFs of the late bilinguals; green bars, NOFs of the early bilinguals. \* $p < 0.05$ , \*\* $p < 0.01$ . Abbreviations: NOFs, number of fibers; PUT, putamen; PrG, precentral gyrus; STG, superior temporal gyrus; SMG, supramarginal gyrus.

including the right PrG (Waldron and Hernandez, 2013). The right PrG has been reported to be one of the crucial regions for bilingual language switching (Luk et al., 2011). In terms of PUT, Gullifer et al. showed the correlation between the social diversity of language use and the development of connectivity with the PUT using resting state fMRI (Gullifer et al., 2018). The current results were consistent with these previous studies. To the best of our knowledge, our study is the first to report alterations in the subcortical fiber network between the PUT and PrG using DTI. The cortico-basal ganglia networks might be concerned with the acquisition of a new language.

On the other hand, late bilinguals showed sparse connectivity between the left STG and ipsilateral SMG compared to Japanese monolinguals and early bilinguals. These results could suggest that late bilinguals alternately utilize the left temporo-parietal network. Oliver et al. reported that late bilinguals showed stronger connectivity during an L1 task than an L2 task according to fMRI results (Oliver et al., 2017). We showed comparable results using DTI in this study. Subcortical fiber networks in areas associated with language would be different according to the AoA.

This study had several limitations. First, whilst bilingual participants could communicate with native English speakers in English without difficulty, differences in the proficiency of English skills such as reading and

comprehension may have affected the results. Second, we used several kinds of obtained qualifications to assess English skills in bilinguals. The effect of the difference between the scores of these qualifications may have also affected our results. Finally, this study included several left-handed participants. The influence of handedness on language dominance has been shown in a previous report (Pujol et al., 1999); therefore the effect of handedness on our results must also be considered.

Our study showed that AoA of language is an important factor for neural plasticity and that can be explored by cortical activation network analysis. We also showed that there are novel white matter networks which require exploration as well as known cortical activation. Early-acquisition bilingual humans reinforce the subcortical fiber network between the right PUT and PrG, and activate the right PUT to gain alternative language function. We conclude that these key cerebral regions and subcortical fiber networks could contribute to the neural plasticity of language. Future studies should focus on elucidating distinctions in the function of cortical and subcortical networks according to acquisition of language.

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**Declarations of interest:** None.

**Author contributions:** Hid. S. and H.O. planned the experiments. T.M. collected and analyzed the data and prepared figures. T.N. and T.T. supervised connectome data analysis. T.M. and Hid. S. wrote the main manuscript text. K.A., M.N., Y.I., Hir. S., Y.T., S.A. and H.A. provided scientific support and supervision. All authors interpreted the results and contributed to the manuscript.

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