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Research report

Language exposure induced neuroplasticity in the bilingual brain: A follow-up fMRI study

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ABSTRACT

Although several studies have shown that language exposure crucially influence the cerebral representation of bilinguals, the effects of short-term change of language exposure in daily life upon language control areas in bilinguals are less known. To explore this issue, we employed follow-up fMRI to investigate whether differential exposure induces neuroplastic changes in the language control network in high-proficient Cantonese (L1)–Mandarin (L2) early bilinguals. The same 10 subjects underwent twice BOLD-fMRI scans while performing a silent narration task which corresponded to two different language exposure conditions, CON-1 (L1/L2 usage percentage, 50%:50%) and CON-2 (L1/L2 usage percentage, 90%:10%). We report a strong effect of language exposure in areas related to language control for the less exposed language. Interestingly, these significant effects were present after only a 30-day period of differential language exposure. In detail, we reached the following results: (1) the interaction effect of language and language exposure condition was found significantly in the left pars opercularis (BA 44) and marginally in the left MFG (BA 9); (2) in CON-2, increases of activation values in L2 were found significantly in bilateral BA 46 and BA 9, in the left BA44, and marginally in the left caudate; and (3) in CON-2, we found a significant negative correlation between language exposure to L2 and the BOLD activation value specifically in the left ACC. These findings strongly support the hypothesis

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Abbreviations: L1, first language, Cantonese; L2, second language, Mandarin; PL, language proficiency level; AoA, age-of-acquisition; BOLD, blood oxygen level dependent.

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that even short periods of differential exposure to a given language may induce significant neuroplastic changes in areas responsible for language control. The language which a bilingual is less exposed to and is also less used will be in need of increased mental control as shown by the increased activity of language control areas.

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1. Introduction

Whether L1 and L2 are represented in different brain regions, has always been an interesting issue for neuroscientists. So far, many studies have investigated brain activities of bilinguals involved in the processing of L1 and L2, and as summarized by Indefrey (2006) and Abutalebi (2008), differences between L1 and L2 are usually reflected at the brain level by more extended activation patterns of L2 within or surrounding those regions responsible for L1 processing. As to why L2 engages more widespread brain activity, several studies have also suggested that the brain activity for language processing is modulated by specific demographic, linguistic and/or behavioral variables, such as language exposure in daily life (Abutalebi, Brambati, et al., 2007; Jeong et al., 2007; Perani et al., 2003), proficiency level (PL) (Briellmann et al., 2004; Chee, Caplan, et al., 1999; Chee, Tan, & Thiel, 1999; Frenck-Mestre, Anton, Roth, Vaid, & Viallet, 2005; Gandour et al., 2007; Golestani et al., 2006; Illes et al., 1999; Kotz, 2009; Perani et al., 1996, 1998), age-of-acquisition (AoA) of L2 (Bloch et al., 2009; Dehaene et al., 1997; Hernandez, Hofmann, & Kotz, 2007; Kim, Relkin, Lee, & Hirsch, 1997; Mayberry, Chen, Witcher, & Klein, 2011; Perani et al., 2003; Wartenburger et al., 2003), cross-linguistic similarities/dissimilarities (Jeong et al., 2007; Saur et al., 2009), and syntactic complexity (Suh et al., 2007; Yokoyama et al., 2006). Following Abutalebi and Green (2007), the extra-activity of L2 would be induced by an apparent lack of automaticity such as in cases where the proficiency for L2 is low or, likewise, when L2 is learnt later in life.

However, as underlined by Perani and Abutalebi (2005), there is an apparent lack of interest to one of these variables, i.e., language exposure in daily life. This fact is even more surprising when considering that language exposure in daily life was actually the first factor to be well described in the neurological literature pertaining to bilingualism and bilingual aphasia (Pitres, 1895). Language exposure was by then hypothesized to predict language outcome in bilingual aphasia, in the sense that the language the patient used more prior to the brain insult, was the one with the highest possibilities for recovery (see for discussion in Green & Abutalebi, 2008). To the best of our knowledge, only very few functional neuroimaging studies have analyzed the effects of language exposure upon the cerebral representation of languages in bilinguals (Abutalebi, Brambati, et al., 2007; Jeong et al., 2007; Perani et al., 2003). For example, Perani et al. (2003) carried out an fMRI study in high proficient Catalan-Spanish early bilinguals performing a lexical search and retrieval task, and found additional brain activity in the left middle frontal gyrus (MFG) (BAs 10, 46) and left inferior parietal lobule (IPL) (BA 40) only for the L2 to which subjects were less used. On the contrary, Perani et al. (2003) also observed less extensive engagement of prefrontal regions for the language to which subjects used more, and they attributed this to the strengthened neocortical connections by repeated activation of the cerebral representation of a more exposed language. Abutalebi, Brambati, et al. (2007), Abutalebi, Keim, et al. (2007) performed an event-related fMRI study to detect brain activity of language switching in early highly proficient Italian-French bilinguals, and observed the engagement of the left caudate nucleus and bilateral anterior cingulate gyrus (ACC) (BA 32) when switching into the less-used language during the auditory perception of language switches. The authors suggested that the activity found in the caudate nucleus and the ACC was specifically related to cognitive control mechanism and may reflect the switching cost when switching into a less exposed language. Jeong et al. (2007) examined the brain activation of Korean trilinguals in auditory sentence comprehension tasks in Korean, Japanese, and English, and found the brain activation in the opercular portion of left inferior frontal gyrus (IFG) (BA 44) and in the right cerebellum were significantly negatively correlated with the length of stay in English-speaking country. The authors suggested that this effect might be caused by the linguistic distance between languages at the syntactical level. Interestingly, most of the additional brain activities in the above-mentioned studies, i.e., left MFG (BA 10, 46), left IPL (BA 40), left caudate nucleus and bilateral ACC (BA 32), are all related to the language control network (Abutalebi & Green, 2007, 2008), suggesting that the influence of language exposure upon the brain affects mostly language control processes. However, the effects of a relatively brief period of differential language exposure upon the brain remain largely unknown since the aforementioned studies mainly investigated lifelong differences in language exposure.

Empirically, it is well known to bilingual speakers that a period of full immersion in an almost single language context may result in less automaticity for word-finding in the non-exposed language. The possible reason is that in an immersion environment where a single language provides the dominant context, the mental control of the non-exposed language will be hampered. Recently, Abutalebi and Green (2007) proposed an explanation in terms of mental control over limited resources (such as less proficiency to a given language), which contributes to the inhibition or activation of one language or the other. Besides, Paradis' Activation Threshold Hypothesis (Paradis, 1988) proposed that this inhibition is conveyed at different thresholds of activation such that the language to which the bilingual speaker is less exposed becomes less available due to its raised activation threshold. On the other hand, the more a bilingual speaker is exposed to a given language, the lower its activation threshold will be; hence, the easier that language is available for production. As to the cognitive basis of language exposure induced neuroplastic effects, we suggest that it may act on the automaticity with which a language is processed. The less automatic a language becomes (i.e., due to less usage of that particular language), the less available it is for spontaneous production (as compared to the more exposed language). More importantly, language use in bilingual speakers yields dual language activation and so requires them to select a response in the face of competing demands from the current non-target language. If automaticity in lexical access decreases with reduced exposure, there will be increased competitive demand to select that language, i.e., more inhibition for the more-exposed language and more neural effort for the initiation of the less-exposed language. We may, thus, hypothesize that the language a bilingual uses less for a short time may be in greater need of mental control.

In the present study, our a-priori hypothesis was that the effects of differential language exposure would be manifest upon the network that governs language control, i.e., a network built by the following areas: bilateral PFC, bilateral caudate nuclei, and the ACC (Green & Abutalebi, 2013). Indeed, our main aim was to detect the fast effects of language exposure on the language control mechanism that governs L1 and L2 processing in Cantonese-Mandarin bilinguals. For the sake of clarity, we refer in this study to language exposure as the percentage of L1 and L2 usage measured as the time spent in listening, speaking, reading, writing, and thinking of the subjects in their everyday lives. This was estimated by the recordings of the subjects' daily L1 and L2 usages in minutes in a home designed table (see Table S1 in Supplementary Materials). Considering putative confounding effects, we tried to isolate language exposure from other variables of language context. When recruiting subjects, we tried to avoid the effect of AoA of L2 by selecting subjects who were exposed to two languages from birth (simultaneous bilinguals) and tried to avoid the effects of syntactic complexity by using a natural language paradigm, a silent narration task, which involves only daily oral expression and therefore minimize additional control demands of processing structurally complex sentences (Suh et al., 2007; Yokoyama et al., 2006). In order to adequately control language exposures, we recruited a group of high-proficient bilinguals living in Guangzhou, a Cantonese (L1)-Mandarin (L2) bilingual region. Each subject attended two BOLD-fMRI scans when performing language tasks in an interval of approximately 3 months. The 1st fMRI scan was carried out during the semester when the subjects had been exposed in CON-1, in which they had comparable usage of L1 and L2. Approximately, two months after the 1st scan, subjects started their summer vacation during which they had significantly more usage of L1 than of L2 for at least 30 days (i.e., CON-2). The 2nd fMRI scan was immediately performed after the summer holidays in order to provide us a condition with differential language exposure.

2. Methods and materials

2.1. *Language background of subjects*

High-proficient early bilinguals living in Guangzhou, a Cantonese-Mandarin bilingual region, were recruited for the purposes of this study. Cantonese and Mandarin can be regarded as L1 and L2 due to their large differences in the verbal communications. Cantonese is the dominant dialect spoken by over 80% of the population in Guangzhou (formerly called also Canton City) of China. Although Cantonese is considered one of the major Chinese languages, it differs significantly from Mandarin Chinese with respect to phonology, lexicon, and syntax. According to Li's statistics (Li, 1990), among all characters in the Basic Vocabulary Table of Modern Chinese Characters (Ye, 1987), only 21.5% are pronounced in a similar fashion. Of all the Cantonese words in ‘A *Dictionary of the Guangzhou Dialect*’ (Rao, 1981), only 23.1% have equivalents in Mandarin. And the same rate is amazingly as low as 1.78% when the colloquial expressions of the two are compared (Zeng, 1982). The differences in word meaning and pronunciation make Mandarin and Cantonese speakers not able to understand each other in most of their verbal communications. For example, the sentence in Mandarin: 刚认识他的时候就是这个样子的, 没有什么变化。（ kɑŋ^{55} ʐən^{51} ʂʅ^{35} t‘A^{55} dɤ^{55} ʂʅ^{35} xou^{51} tɕiou^{51} ʂ ʅ^{51} tʂɤ^{51} kɤ^{51} jɑŋ^{51} tsɿ^{214} dɤ^{55}, mei^{35} jou^{214} ʂən^{35} mɤ^{55} piɛn^{51} xuA^{51}。) (He is basically the same as when I first met him.) should be said like this in Cantonese: 之前见到区就系甘个样了, 无乜变。（ ʧi^{55} ʧhin^{21} kin^{33} tou$^{33-35}$ khœy^{13} ʧɐu^{22} hɐi^{22} kɐm^{35} kɔ^{33} jœŋ$^{22-35}$ liu^{13}, mɐu^{13} mɐt^{5} pin^{33}。) (the numeral refers to Chinese tone). Therefore, in bilingual studies, Cantonese and Mandarin are generally regarded as two distinct languages (Cai, Pickering, Yan, & Branigan, 2011).

2.2. *Subject selection*

The steps for selecting subjects in this study are shown in Fig. 1. In step-1, we recruited 500 Cantonese-Mandarin bilingual undergraduates to make the subject pool. In step-2, these 500 subjects were asked to fill out a questionnaire and interviewed about their language acquisition experience. 51 representative bilinguals who acquired L1 and L2 simultaneously after birth (the AoA being 0) were selected. In the next step, i.e., step-3, according to the standard scale of the Common European Framework of Reference (CEFR) for Languages (Verhelst, Van Avermaet, Takala, Figueras, & North, 2009), we assessed their oral and listening PLs. The listening PLs of L1 and L2 were assessed by self-report (10 questions) using the CEFR for Languages and by answering accurately to the just listened stories in L1 and L2 (5 probe questions). The oral PLs of L1 and L2 were assessed in two interviews, respectively, in which three language experts graded each subject's usage of L1 or L2 according to a standard scale of CEFR. The grade ranges from A1 (break-through) to C2 (mastery). A1 and A2 refer to competence level of basic users, B1 and B2 to the independent users, and C1 and C2 to the proficient users. Thus, 45 subjects who had comparable listening and oral PLs between L1 and L2 were selected. In order to evaluate the language exposure of these 45 subjects selected in step-3, we requested them to record their daily L1 and L2 usages in minutes in a home designed table (see Table S1 in Supplementary Material) and calculated the mean percentage of usage time to L1 and L2 for each of the last 30 days. We additionally asked the subjects to estimate their mean usage of L1 and L2 through whole life time in seven age intervals (0–1, 2–3, 4–5, 6–12, 13–15, 16–18, and above 18 years old

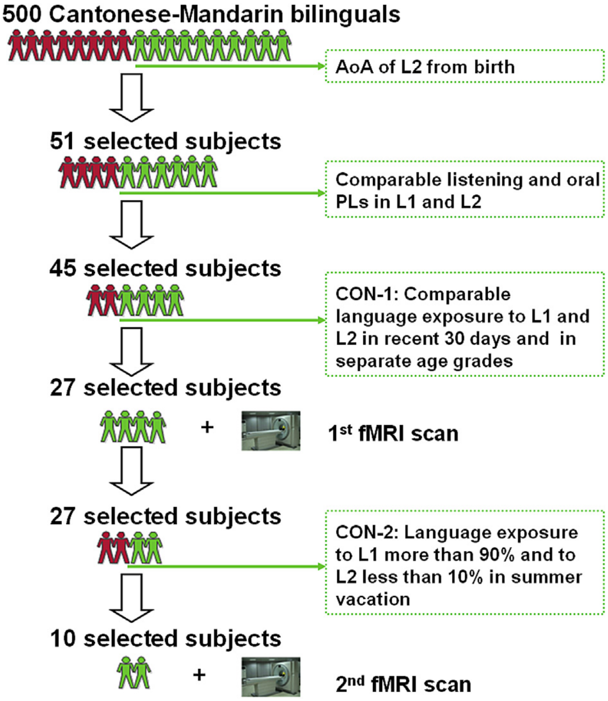

Fig. 1 – The procedures for selecting Cantonese-Mandarin bilingual subjects in this study. L1: Cantonese; L2: Mandarin (see Methods for details and Table 1 for more detailed demographic information of subjects).

until now) based on a seven-scale (‘1’ represents being exposed to L1 only, ‘7’ to L2 only, and ‘4’ to same language exposure to L1 and L2). Actually, this is just an approximate estimation for their mean usage of L1 and L2 in their past life, because there was not always equal language exposure during their language acquisition in their varying home and school language environments. Hence, in step-4, we selected 27 subjects who had comparable language exposure to L1 and L2 (about 50%:50%) during the last 30 days and had comparable mean language exposure of L1 and L2 through whole life time to attend the 1st fMRI scan (noted as CON-1, the first language exposure condition). These 27 subjects were invited to attend the 1st task-fMRI scan. Approximately, two months after the 1st task-fMRI scan, these 27 subjects had a summer vacation for more than one month, in which most of them were significantly more exposed to L1. Thus, in step-5, we chose 10 of them who were exposed to L1 more than 90% and to L2 less than 10% (noted as CON-2, the second language exposure condition). At the end of summer vacation and before returning to be exposed to L2, we invited these 10 subjects to participate in the 2nd task-fMRI scan. In summary, 27 bilinguals underwent the 1st task-fMRI scan when they were in CON-1, and 10 of them underwent the 2nd task-fMRI scan after they had changed from CON-1 to CON-2 for more than 30 days. The interval between the 1st and 2nd task-fMRI scans was more than 3 months.

We ultimately included only these 10 subjects (6 F/4 M; 19–26 years, mean ± std = 21.30 ± 2.36 years) into the further analysis. All of them satisfied the following criteria, AoA of L2 from birth, comparable listening and oral PLs between L1 and L2, and comparable language exposure to L1 and L2 (about 50%:50%) in CON-1, but language exposure to L1 more than 90% and to L2 less than 10% in CON-2. Table 1 lists the detail information of these 10 subjects and their language assessment results.

All subjects were right-handed according to the Edinburgh Handedness Inventory (Oldfield, 1971) and had no experience that their left-handedness was adjusted to right-handedness by their parents when they were toddlers. None of subjects had a current or past history of neurological or psychiatric disorders or brain injury. Written informed consent was obtained from each subject prior to the study. The protocols were approved by the Review Board of the School of Psychology, South China Normal University.

2.3. *Experimental task*

The experimental task consisted of a language production (silent free narration task) and a baseline condition in an externally triggered periodic block design (Bloch et al., 2009; Kim et al., 1997; Wattendorf et al., 2001). As shown in Fig. 2, the stimulus paradigm consisted of nine 30s-ON-30s-OFF blocks. Just immediately before each fMRI scan, each subject was instructed to use L1 or L2 according to which language was required during the experimental task. To avoid syntactic complexity effects, we employed a silent narration task, which is similar to everyday communication. A task block consisted 10 sec of graphical cues and 20 sec of blank. The graphical cues were composed of three types: midday, dusk, and night. These cues provided common non-linguistic information for the task and were presented in unpredictable and counterbalanced in order to reduce the tendency of the rehearsing mentally before the cue (each type of graphical cue appeared 3 times in a run). The baseline block consisted of 10 sec of a red crossing followed by 20 sec of blank.

In order to confirm that subjects completed the experiment as required and to exclude the effects of repetition and language translation, all subjects were asked to perform the following steps. First, subjects were instructed to ruminatively prepare three pieces of speech about what they had done the day before at midday, dusk, and night, each of which lasted at least 2 min in L1 and L2 (each kind of cue appeared three times in a run and each cue lasted 30 sec, e.g., each cue appeared three times in a run, e.g., 1.5 min in total for each narration for midday, dusk, or night in a run). The content of L1 and L2 could be the same. Second, subjects completed a training session, which required them to perform the silent narration task according to their preparations. This training session was conducted in front of the computer prior to scanning and the task was the same as in the formal experiment. The order of the cues was randomized and each cue appeared three times in each run. Subject were invited to retell the same content in L1 and L2 in the free narration task, but not allowed to repeat the content in each language. Further, subjects were allowed to use some transition sentences such as ‘Where was I in the last description on the events occurred at noon?’ or ‘Let me think about it’, and etc., in the narration task in order to help them start the retelling in the very beginning of the 30 sec task period. Finally, subjects were asked to perform the

Table 1 – **Demographic characteristics, language proficiency level (PL) assessment, and the amount of language exposure to the first language (L1), Cantonese, and the second language (L2), Mandarin, for all subjects in this study. The listening PLs of L1 and L2 were assessed by self-report (10 questions) using the Common European Framework of Reference (CEFR) for Languages and by answering accuracy to the just listened stories in L1 and L2 (5 probe questions). The oral PLs of L1 and L2 were assessed in two interviews, respectively, in which three language experts graded each subject's usage of L1 or L2 according to a standard scale of CEFR. The grade ranges from A1 (break-through) to C2 (mastery). A1 and A2 refer to competence level of basic users, B1 and B2 to the independent user, and C1 and C2 to the proficient user. The language exposure lasting 30 days indicates the language exposure to L1 and L2 in the last 30 days of each language exposure condition immediately before the experiment. The language exposure in separate age grades indicates the language exposure to L1 and L2 from birth to now; and it was assessed by a seven-level scale, ranging from 1 (only using L1) to 7 (only using L2). Abbreviations: Ex, language expert for L1 or L2; CON-1, the language exposure to L1/L2 is about 50%:50%; CON-2, the language exposure to L1/L2 is about 90%:10%; self, self-report of listening PL; acc, answering accuracy of listening PL.**

Subject	Sex	Age	Listening PLs				Oral PLs						Language exposure lasting 30 days (%)				Language exposure in separate age grades						
			L1		L2		L1			L2			CON-1		CON-2								
			Self	acc	Self	acc	Ex1	Ex2	Ex3	Ex4	Ex5	Ex6	L1	L2	L1	L2	0–1 yrs	2–3 yrs	4–5 yrs	6–12 yrs	13–15 yrs	16–18 yrs	19 yrs
S1	F	21	10	5	9	4	C2	C2	C2	C2	C2	C1	64.1	35.9	95.1	4.6	4	4	4	4	5	5	5
S2	M	21	10	5	8	5	C2	C2	C2	C2	C1	C2	43.3	56.7	90.6	9.4	2	4	4	4	3	4	5
S3	M	19	10	5	9	5	C2	C1	C2	C2	C2	C1	57.0	43.0	95.2	4.8	4	4	4	3	3	4	3
S4	F	21	10	5	10	5	C2	C2	C2	C2	C2	C2	39.0	61.0	91.7	8.3	4	5	5	6	5	4	6
S5	F	19	9	5	9	5	C2	C2	C2	C2	C2	C1	62.0	38.0	90.3	9.7	3	3	4	4	4	4	4
S6	F	26	9	5	9	5	C2	C2	C2	C2	C2	C1	55.1	44.9	95.5	4.5	4	4	4	3	3	5	4
S7	M	23	10	5	10	5	C1	C1	C1	C1	C1	C1	35.1	64.9	90.6	9.4	4	4	4	5	4	4	4
S8	M	24	10	5	10	5	C2	C2	C2	C2	C2	C1	61.0	39.0	89.7	10.3	4	4	5	5	3	4	3
S9	F	20	8	4	9	5	C1	C2	C1	C1	C2	C2	38.4	61.6	90.9	9.1	3	4	4	4	5	4	3
S10	F	19	8	5	9	4	C2	C2	C2	C2	C2	C2	55.7	44.3	93.8	6.2	3	4	4	3	5	5	5

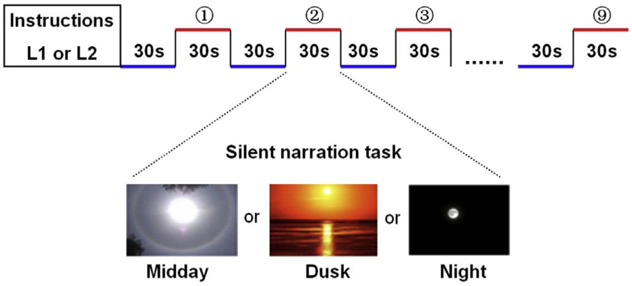

Fig. 2 – Illustration of the stimulation paradigm, nine 30s-ON-30s-OFF blocks were adopted in this study. Prior to each fMRI scanning session, subjects were instructed to use Cantonese (L1) or Mandarin (L2) according to which language they were invited to speak. The task was composed of three types of graphical cues, midday, dusk, and night, each being displayed in a counterbalanced randomized order for 10 sec. During the task period, subjects were asked to perform the silent narration task or to tell what they had done the day before at midday, dusk, and night.

experimental task during scanning. The order of L1 and L2 in silent narration was counterbalanced between the pre-test and the final experiment for each subject. For each subject, two fMRI datasets were acquired corresponding to L1 and L2 in the experiment, respectively. Half of the subjects started the experiment first in Cantonese and then in Mandarin, and vice versa for the other half in counterbalance language order.

In order to control the content of the narration task, we invited subjects to recall their narration in written words to confirm the length of the narration after scanning. Also, in order to control performance of subjects, each subject was reminded that there would be a performance check after the scanning.

To ensure that subjects took the second scan in CON-2 (L1/L2 exposure, 90%:10%), immediately after holidays, and before being immersed in a potential L2 speaking surrounding, we asked them to hand over their bus/coach tickets for refunding so that we could check whether they came directly from their homes.

2.4. *Image acquisition*

MRI data were acquired on a 1.5T Philips Achieva Nova Dual MRI scanner with a standard head coil at the Department of Radiology, Huangpu Clinical Medical Center, Sun Yat Sen University First Affiliated Hospital. Subjects were asked to lie in a supine position inside the MRI scanner while wearing MRI-compatible earphones. Foam pads were used to reduce head movements during MRI data acquisition. BOLD-fMRI scans were performed along the AC-PC line using the gradient-echo echo-planner imaging (GE-EPI) sequence with the following parameters: repetition time (TR) = 3000 msec, echo time (TE) = 40 msec, flip angle = 90°, field of view (FOV) = 240 mm × 240 mm, data matrix = 64 × 64, slice thickness = 4 mm without gap, 36 transverse slices in interleaved order covering the whole brain. For all subjects, functional images were obtained for L1 and L2 in separate runs. 180 volumes were acquired for each run in 9 min, including 90 volumes during the experimental task and 90 volumes for the baseline. In addition, we also acquired 3D high resolution brain structural images with T1-weighted Magnetization-Prepared Rapid Gradient Echo (MP-RAGE) sequence. The sequence parameters were TR/TE/flip angle = 9.6 msec/3.8 msec/8°, data matrix = 288 × 288, FOV = 256 mm × 256 mm, slice thickness = 1 mm, and 176 sagittal slices.

2.5. *Data processing*

The fMRI data were preprocessed using SPM8 (http://www.fil.ion.ucl.ac.uk/spm). Prior to preprocessing, dummy scans were discarded. The images were first corrected for the acquisition time delay among different slices, and subsequently realigned to the first volume for head-motion correction. The time course of head motions was obtained by estimating the translations in each direction and the rotations in each axis. All subjects included in this study met the criteria of the head motion less than 1.5 mm of displacement and 1.5° of rotation in any direction. The functional data were co-registered to the individual anatomical images and then to the MNI standard space. At last, all the images were smoothed using a spatial filter kernel of Full Width at Half Maximum (FWHM) of 8 mm.

At the first level, we analyzed individual brain activation corresponding to L1 or L2 of each language exposure condition in the framework of a random effect general linear model (GLM). Then the contrast maps were generated and were entered into the following analysis.

2.6. *Statistical analysis in language control network*

Given the aim of our study was to investigate the effects of differential language exposure upon those brain areas involved in language control network, we defined nine 6-mm-radius spheres as our regions of interest (ROIs). These were defined as seven language control ROIs and were selected from prominent neuro-cognitive models of language control in bilinguals (Abutalebi & Green, 2008; Green & Abutalebi, 2013), from experimental evidence (Abutalebi & Green, 2008; Abutalebi, Rosa, Tettamanti, Green, & Cappa, 2009) and from a recent meta-analysis on language switching in bilinguals (Luk, Green, Abutalebi, & Grady, 2011). These ROIs are the left MFG (i.e., BA 9 and BA 46 involved in response selection (Abutalebi et al., 2008), the right MFG (i.e., BA 9 and BA 46 involved in response inhibition (Videsott et al., 2010)), bilaterally the head of caudate (involved in supervising the correct choice of languages (Abutalebi, Brambati, et al., 2007)) and the left ACC (involved in monitoring and error detection (Abutalebi et al., 2012). We also included another two ROIs: the left BA 44 for word production (Demonet, Thierry, & Cardebat, 2005) as well as for controlling verbal interference (Jones et al., 2012), and BA 47 for lexical retrieval (Demonet et al., 2005). For each subject, we extract the mean contrast value of all voxels in each ROI corresponding to L1 and L2 in CON-1 and CON-2, respectively. All these ROIs and their corresponding coordinates are displayed in Table 2.

Based on our defined language control and language production network, we extracted the mean activation value of

Table 2 – The ROIs used in our study and their corresponding coordinates.

Index	Regions	Coordinates in the MNI space (mm)		
		X	Y	Z
ROI 1	Left BA46	−48	23	23
ROI 2	Right BA46	48	23	23
ROI 3	Left Caudate	−8	6	−3
ROI 4	Right Caudate	18	11	7
ROI 5	Left BA9	−44	13	29
ROI 6	Right BA9	44	13	29
ROI 7	Left ACC	−4	6	48
ROI 8	Left BA44	−53	21	1
ROI 9	Left BA47	−34	22	−15

each ROI in the network corresponding to L1 and L2 in CON-1 and CON-2, respectively. We then performed a 2-by-2 repeated measures analysis of variance (ANOVA) in each ROI's mean activation value. The first factor was the language exposure condition (CON-1 and CON-2), and the second factor was language type (L1 and L2). Once significant differences were observed, we estimate the η^2 according to Cohen's definition to detect the statistical power (Cohen, 1988). The levels of small, medium and large effect size corresponding to .01, .06, and .14, respectively.

In order to investigate the language exposure effects on the difference between L1 and L2, we also used paired *t*-test to compare each ROI's mean activation value between L1 and L2 in CON-1 and CON-2, respectively. Once significant differences were observed, we estimate the effect size (Cohen *d*) according to Cohen's definition to detect the statistical power (Cohen, 1992). The levels of small, medium and large effect size corresponding to .2, .5, and .8, respectively.

Noteworthy, we then correlated the respective activation value of each subject with their corresponding language exposure in each language in condition 2 (CON-2) in order to investigate directly the effects of differential exposure and usage upon the BOLD effect in our nine ROIs.

Finally, we also investigated if the order of language production could have potentially altered the activation profile for each language. In the calculations, we selected the large sample size of the first scan (27 subjects in the 1st scan, 14 of them in the order of L1-L2, while the other 13 in the order of L2-L1). For each language, we used a paired *t*-test to detect brain activation profiles between the two different orders, L1-L2 or L2-L1, in each of the following nine ROIs.

In order to test the reliability of our findings, we also conducted a voxel-wise analysis on our selected ROIs.

3. Results

3.1. *Behavioral comparison*

Using paired two-sample *t*-tests (nonparametric permutation test), we compared the difference in proficiency assessment between L1 and L2 on a group level. We found neither a significant difference in listening PL test (self report: $p = .12$; answering accuracy: $p = .50$) nor in oral PL test (the average score by the experts assessment, $p = .15$) between L1 and L2. The mean language exposures to L1 and L2 were determined by averaging all subjects' percentages of usage time, respectively. In CON-1, the mean percentages of language exposure of L1 and L2 were 51.07% and 48.93%. While in CON-2, the mean percentages of language exposure of L1 and L2 were 92.34% and 7.66%. Moreover, statistical analysis showed that the language exposure to L1 and L2 were comparable for each of seven age grades. The average assessment scores of each age grade were 3.5, 4, 4.2, 4.1, 4, 4.3, and 4.3, respectively, according to the above described seven scales.

3.2. *Functional neuroimaging analysis*

For each ROI's mean activation value, we performed a 2-by-2 repeated measures ANOVA with language exposure conditions (CON-1 and CON-2) and language type (L1 and L2) as factors. Individual activation value in each ROI for L1 and L2 within two language exposure conditions are displayed in Supplementary Material Table S2 to S10. Statistical results revealed that the main effect of language was significant in the left BA 46 ($p = .036$, $\eta^2 = .403$) and in the right BA 46 ($p = .036$, $\eta^2 = .404$) areas. The interaction effect of language and language exposure condition was significant in left BA 44 ($p = .004$, $\eta^2 = .624$) (see Fig. 3). Besides, the interaction effect was marginally significant in left BA 9 ($p = .076$).

For the paired *t*-test in each ROI's mean activation values between L1 and L2 in each language exposure condition, statistical results revealed that, in CON-1, there was no significant difference in any ROI. However, in CON-2, L2 had significant higher contrast value than L1 in five regions, including the left BA 46 ($p = .0061$, $d = 1.0605$), right BA 46 ($p = .0078$, $d = .9658$), left BA 9 ($p = .0462$, $d = .6391$), right BA 9 ($p = .0200$, $d = .7574$) and left BA 44 ($p = .0023$, $d = .1737$), as well as a marginally significant effect in the left Caudate ($p = .0822$) (see Fig. 3).

As to the correlation analysis between the activation value in each language and language exposure in CON-2, the average activation values in four ROIs, left BA 44, left ACC, right Caudate, and right BA 9, all showed significantly negative correlation with the language exposure to L2 ($p < .05$). But after performing the Bonferroni correction, we detected that only in the left ACC,[2] the correlation was survived ($p = .004$). In addition, we found the activations in all of the nine ROIs were negatively correlated with the language exposure to L2 (Fig. 4).

Finally, no significant order effect on activation profile was found in each of the nine ROIs for L1 or L2 ($p < .05$) (see Table S11 in the Supplementary Materials).

3.3. *Validation analysis*

A 2-by-2 repeated measures ANOVA in the activation of the ROIs was performed using SPM 8. We found that, in the left IFG (BA 44), the interaction effects of language exposure conditions and languages were significant ($p < .05$, AphaSim

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[2] In a previous analysis, a different ACC coordinate (−4, 2, 56) from Abutalebi et al., (2013) was used that did not survive the correction. We hence, decided to use the ACC coordinate from Abutalebi et al., (2012).

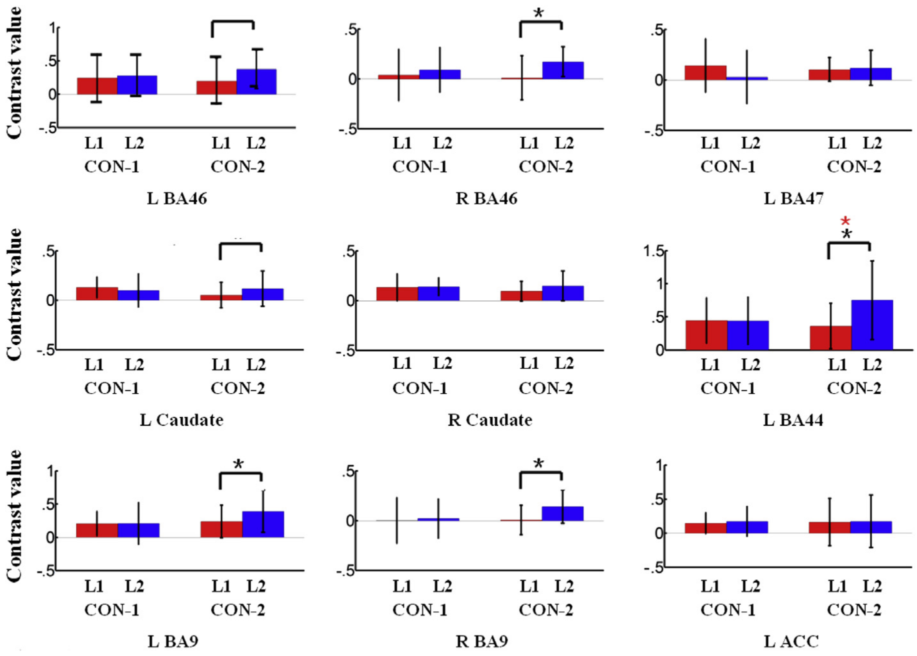

Fig. 3 — Statistical results in the language control network based on ROI's mean activation value (BOLD contrast value). Repeated measures ANOVA with a 2 (Languages: L1 and L2) by 2 (Conditions: CON-1 and CON-2) approach revealed that the effect of interaction between language and language exposure condition was significant in the left BA 44 ($p = .004$, $\eta^2 = .624$) and was marginally significant in the left BA 9 areas ($p = .076$). In addition, the main effect of language was significant in both the left BA 46 ($p = .036$, $\eta^2 = .403$) and right BA 46 ($p = .036$, $\eta^2 = .404$). Paired *t*-test between L1 and L2 revealed that, in CON-2, L2 showed significantly high activation value compared to L1 in six ROIs, the left BA 46 ($p = .0061$, $d = 1.0605$), right BA 46 ($p = .0078$, $d = .9658$), left BA 9 ($p = .0462$, $d = .6391$), right BA 9 ($p = .0200$, $d = .7574$), and left BA 44 ($p = .0023$, $d = 1.1737$). This effect was also marginally significant in the left Caudate ($p = .0822$). The red '*' indicates the significant interaction effect in ANOVA, and the black '*' indicates the significant effect in paired *t*-test ($p < .05$).

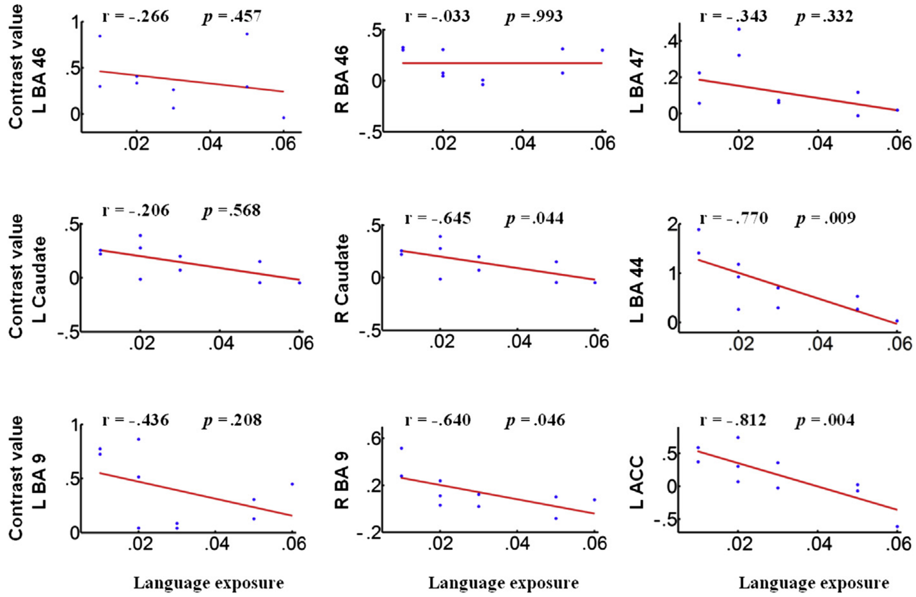

Fig. 4 — Correlations between the language exposure and each ROI's mean activation value (BOLD contrast value). When subjects performed in L2 in CON-2, the activation value in each of four ROIs, left BA 44, left ACC, right Caudate and the right BA 9, showed significantly negative correlation with the language exposure of L2. After the Bonferroni correction, only the significant correlation of the left ACC ($p = .004$) was survived. In addition, the activation values for all the nine ROIs showed negative correlations with the language exposure to L2. L1, Cantonese; L2, Mandarin.

correction) (see Fig. S1a in the Supplementary Materials). That is, in left BA 44, there was no significant difference between L1 and L2 in CON-1, while significant larger activation in L2 than L1 in CON-2.

As to the paired *t*-test in the activation of our network, we found in CON-2, that L2 was associated to greater activation in the left IFG (BA 44) and bilateral MFG (BA 46 and BA 9) ($p < .05$) (see Fig. S1b in the Supplementary Materials). While in CON-1, there was no significant difference between L1 and L2.

Finally, for both L1 and L2, no significant order effects were found for our ROIs in the voxel-wise analysis ($p < .05$). In summary, the results of the present voxel-wise analysis were relatively similar to the results based on each ROI's mean activation value.

4. Discussion

In this study, we explored the effects of a relatively brief period of differential language exposure upon the language control network in a group of early and high proficient bilinguals. Subjects were scanned twice, before (i.e., when exposed to the same degree in both languages, CON-1) and after a 30-day period (i.e., when the usage of L2 was less than 10%, CON-2). We found the interaction effect of language and language exposure condition in the left pars opercularis (BA 44) and marginally in the left MFG (BA9), and the main effect of language in bilateral BA 46. These findings in areas related to language control might indicate that a functional effect of a brief 30-day differential language exposure is indeed exerted upon the brain. Additionally, in Con-2 increases of the BOLD signal in L2 were found bilaterally in BA 46, BA 9, the left BA 44 and marginally in the left caudate, suggesting an increased engagement for L2 as compared to L1. A significant negative correlation, which survived the Bonferroni correction, was found between language exposure to L2 and the left ACC in Con-2, indicating that the less exposure and usage of L2 may result in increased engagement of specifically this region involved in monitoring and controlling languages. Our results indicate that even a short period of time, such as a 30-day period, with less usage of L2, may affect the cognitive mechanism responsible for controlling L1 and L2. These findings, i.e., the neuroplastic effects of differential language usage, will be discussed in detail.

The most striking finding is the sensitivity of the left pars opercularis (BA 44). Although the left BA44 has been traditionally emphasized for its critical role in language production, it has been recently reported that the left pars opercularis (BA 44) may be also involved in language control (Jones et al., 2012). In detail, Jones et al. (2012) found that activation in BA 44 is higher in bilinguals compared with monolinguals and they attributed this to the additional need for controlling verbal interference. Similarly, in this study, the 30-day period of less L2 exposure may result in the necessity to drive more the pars opercularis of BA44 for word production. One possibility is that L2 words have become less available due to raised activation threshold because of the decrease in exposure (see Paradis' activation threshold hypothesis, 1998), resulting in an increased difficulty (i.e., less automaticity) to access L2 words. Our findings is also consistent with the hypothesis that the left IFC plays a functionally important role in the initiation of a verbal response (Xue, Aron, & Poldrack, 2008).

Our findings in the left ACC, bilateral BA 46, BA 9, and caudate are consistent with the general framework of the language control network (Abutalebi, 2008; Abutalebi & Green, 2007) of bilingual language processing. Abutalebi and Green (2007, 2008) and Green and Abutalebi (2013) schematically summarized these specific brain regions, circuits, their distinct functions, and connections within the neurocognitive framework of the inhibitory control model (Green, 1998). In brief, these authors identified the ACC and the pre-supplementary motor area (pre-SMA) with conflict monitoring between different languages and acknowledged a role for the pre-SMA in speech initiation for language switching. Subcortical structures, such as the left caudate, are associated to the supervision of languages (Abutalebi et al., 2013) and are considered involving in the control of verbal interference (Abutalebi & Green, 2008; Ali, Green, Kherif, Devlin, & Price, 2010). The prefrontal cortex is associated with control of interference. Specifically, the left MFG (BA 46 and 9) is involved in response selection (Abutalebi et al., 2008) while the right MFG is more involved in response inhibition (Green & Abutalebi, 2013; Videsott et al., 2010). In the present study, we report that less usage of a given language results in an increased engagement of language control regions that may be necessary to regulate the particular language system in bilinguals.

Interestingly, a significant negative correlation between language exposure to L2 and our ROIs was found only in the left ACC (Fig. 4). The ACC has been defined as the monitoring system for language control in bilinguals (Abutalebi et al., 2012) since it potentially signals errors in language selection to the prefrontal cortices. The authors have also found increased grey matter density in the ACC in bilinguals as compared to monolinguals and bilinguals use this more efficiently. Indeed, Abutalebi et al. (2012) reported that bilinguals activate this area less while outperforming monolinguals on an attentional control task. This advantage derives from the fact that during everyday life bilinguals usually use the ACC more as compared to monolinguals since they need to control use of their two languages. Here we report a similar scenario, i.e., when bilinguals do not use anymore the ACC for monitoring language conflicts (because of the non-usage of one of the two languages), the ACC may adapt to the new situation and is less used. Once put back into a context where both languages are again used, it will be in need of extra activity for controlling that language that was not anymore used such as the L2 in our group of high proficient Cantonese-Mandarin bilinguals. Green and Abutalebi (2013) refer to this phenomenon as ‘adaptive control’ in the bilingual brain.

In our correlation analysis between the activation values in each language and language exposure in CON-2, i.e., when subjects were less exposed to their L2, we found that among language control areas the activation values of the left BA 44, right BA 9, right caudate, negatively correlated with exposure to L2. These correlations did not survive the Bonferroni correction but nevertheless these data may further support our suggestion that, the effects of differential exposure and usage of an L2 are most prominent in the inhibitory component of the bilingual control network (right BA 9 and caudate) and in area dedicated to both, word production and control (BA 44). It follows that, having been less exposed to L2, activity is increased in these areas in order to properly monitor and eventually inhibit interfering responses from the now prepotent and dominant L1.

In general, our findings are consistent with the hypothesis that a short-term less usage and exposure of one language may result in greater mental control for that particular language. Interestingly, Abutalebi, Brambati, et al. (2007) reported similar findings in a cross-sectional fMRI study on early Italian-French bilinguals who had the same degree of proficiency for both languages. However, Abutalebi, Brambati, et al. (2007) only studied the effect of lifelong differential language usage on language representation and did not report the 'fast-effects' of a relatively brief period on brain representation as in their study. Abutalebi, Brambati, et al. (2007) suggested that the mental control for L1 was greater than that of L2 since their bilinguals had been exposed for more than 90% to L2 during their life. Their suggestion was based upon the observation that switching into the less exposed language (L1) was specifically associated with the bilateral ACC and left caudate activation.

Similarly, Perani et al. (2003) investigated two groups of early bilinguals with the same degrees of language proficiency, in which one group was lifelong less exposed to L2 while the other group was equally exposed to L2 and L1. They found that only the group less exposed to their L2 engaged more activation in the lateral prefrontal cortex (BA 10) for L2 word production. On the basis of these findings and our present findings, we may conclude that language usage is a crucial variable affecting the neural basis of language organization and language control in the bilingual brains. As reported here and thus extending previous research, the neuroplastic effects of less usage manifest themselves already over a 30-days period.

An explanation for why language exposure can predict the cerebral processing demands of L1 and L2 in bilinguals may be related to representational neural plasticity processes in the human brain. A substantial body of information has demonstrated that a brief period of practice alone induces plasticity of brain regions such as the left frontal cortex following the practice of verb generation, and the PFC, ACC and posterior parietal regions following the practice of free recall (Petersson, Elfgren, & Ingvar, 1999). Among similar lines, Abutalebi, Keim, et al. (2007) found the repeated usage of written dialect words (that subjects had never seen before) may result in its neural substrate converging to that of the language in which these subjects were already proficient readers. Since practice may modulate neuroplasticity, we suggest that short-term differential exposure to a given language may similarly affect plastic changes in the bilingual brain.

On the basis of our imaging findings, we propose that apart from the well-known effects of language proficiency (Abutalebi & Green, 2007), the amount of language exposure may also affect the neural processes involved in the mental control of languages. Noteworthy, we strongly rule our that our findings may be due to differences in language proficiency since it is highly unlikely that subjects may loose in a 30 day period syntactical, lexical and phonological knowledge of a language they learned over their life. Further, previous studies have clearly reported that these two variables behave differently in the brain. In the study of Abutalebi, Brambati, et al. (2007), the authors reported crucial effects of exposure upon language control areas despite subjects having the same high degree of language proficiency. A similar finding was reported also by Perani et al. (2003) with Spanish-Catalan bilinguals: when proficiency and age of L2 acquisition are kept constant, the amount of exposure to languages can make the difference upon patterns of brain activity.

In summary, our study explored the neural underpinnings of the effects of differential usage of L1 and L2 in a group of early and high proficient bilinguals. After a 30-day period of full immersion into their L1 environment, resulting in a significantly less usage of L2, we detected significant neuroplastic effects for L2 processing. Increased activation values as well as significant negative correlations between language exposure and areas involved in language control areas were observed. These findings underline the crucial role of language exposure as one of the main determinants of bilingual language processing.

As to the limitations of our study, of course, the small sample size may be a prominent one. However, in order to reduce the inherent dangers of drawing strong conclusions from small sample sizes, we performed a ROI-wise analysis based on our strong a-priori hypothesis. According to Zandbelt et al. (2008), the sample size of a ROI-wise analysis can be reduced to get the same statistical power than that of the whole-brain voxel-wise statistical analysis. The reason is that the significant level for whole-brain voxel-wise analysis is much more stringent because of the multiple comparison problem (Zandbelt et al., 2008). Second, for the ROIs showing significant statistical difference in the ROI's mean activation value, we calculated the η^2 when conducting ANOVA and the Cohen d when conducting paired t-test to estimate the statistical power. We found that all the η^2 were more than .14 and most of the Cohen d more than .8, which indicated high statistical power (Cohen, 1988, 1992). Third, in addition to the mean activation value-based analysis, we also conducted a voxel-wise analysis in our ROIs to validate our result. The results of two methods were relatively similar, hence, replicating the effects of interest of the present study.

Competing interest's statement

The authors declare no competing financial interests.

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Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.cortex.2014.09.019.

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