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Functional connectivity changes in second language vocabulary learning

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ABSTRACT

Functional connectivity changes in the language network (Price, 2010), and in a control network involved in second language (L2) processing (Abutalebi & Green, 2007) were examined in a group of Persian (L1) speakers learning French (L2) words. Measures of network integration that characterize the global integrative state of a network (Marrelec, Bellec et al., 2008) were gathered, in the shallow and consolidation phases of L2 vocabulary learning. Functional connectivity remained unchanged across learning phases for L1, whereas total, between- and within-network integration levels decreased as proficiency for L2 increased.

The results of this study provide the first functional connectivity evidence regarding the dynamic role of the language processing and cognitive control networks in L2 learning (Abutalebi, Cappa, & Perani, 2005; Altarriba & Heredia, 2008; Leonard et al., 2011; Parker-Jones et al., 2011). Thus, increased proficiency results in a higher degree of automaticity and lower cognitive effort (Segalowitz & Hulstijn, 2005).

1. Introduction

Although some parts of the human brain (e.g., Broca's and Wernicke's areas) have long been known to be responsible for language processing, it is now believed that language production and comprehension, like many other complex behaviors, are also supported by non-specific circuits. In other words, the language system is viewed as a dynamic system (Liberman, 2000, 2003), subserved by a number of regions, which contribute differently according to processing demands. Over the last 20 years, functional neuroimaging studies have focused on determining which brain areas are involved in language production and comprehension.

In a recent review of 100 fMRI studies on speech comprehension and production, Price (2010) lists the areas that showed significant activation in a variety of language comprehension and production tasks, at the word and sentence levels. This review shows that areas involved in language comprehension include the superior temporal gyri bilaterally, the middle and the inferior temporal cortices, the left angular gyrus and pars orbitalis, the superior temporal sulci bilaterally, the inferior frontal regions, the posterior planum temporale, and the ventral supramarginal gyrus. As for language production, the left middle frontal cortex, the left anterior insula, the left putamen, the pre-SMA (Supplementary motor area), the SMA, the motor cortex, the anterior cingulate and the bilateral head of the caudate nuclei are also involved. This review neatly summarizes our understanding of the neurobiology of the language system; however, despite the behavioral, psycholinguistic and neurolinguistic evidence accumulated in recent decades, much remains to be studied about the details of language and the brain.

Specifically with regard to bilingual people, neurocognitive studies on bilingualism have frequently focused on the neural basis of second language processing, as a function of age of acquisition (e.g., Baker & Trofimovich, 2005; ; Bosch & Sebastián-Gallés, 2003; De Diego Balaguer, Sebastian-Galles, Diaz, & Rodriguez-Fornells, 2005; Doiz & Lasagabaster, 2004; Fabbro, 2001a or Fabbro, 2001b?; Paradis, 2001; Sebastián-Gallés, Echeverría, & Bosch, 2005; Silverberg & Samuel, 2004), and proficiency attained (Chee, Tan, & Thiel, 1999; Perani et al., 1998; Yetkin, Yetkin, Haughton, & Cox, 1996). The results are controversial. Thus, some authors claim that the age of L2 acquisition determines functional organization of L1 and L2 in the brain (Kim, Relkin, Lee, & Hirsch, 1997), whereas others claim that language proficiency is more important than age of acquisition (Perani et al., 1998; Yetkin et al., 1996). Specifically, according to some authors (Chee et al., 1999; Klein, Milner, Zatorre, Meyer, & Evans, 1995 or Klein, Zatorre, Milner, Meyer, & Evans, 1995?; Perani et al., 1996, 1998), first (L1) and second (L2) languages are supported by common brain areas.

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Conversely, Kim et al. (1997) argue that this only holds true of early L2 learners.

More recently, it has been argued that the puzzle might be solved by taking proficiency into account. Thus, according to Abutalebi and Green (2007), there is sufficient evidence that both L1 and L2 are represented and processed in the same network (Abutalebi & Green, 2007; Chee et al., 1999; Klein, Milner, et al., 1995 or Klein, Zatorre, et al., 1995?; Perani et al., 1996, 1998), and that different degrees of activation in the left prefrontal areas for L2 (e.g., Crinion et al., 2006; Frenck-Mestre, 2005; Rodriguez-Fornells, 2005; Raboyeau, Marcotte, Adrover-Roig, & Ansaldo, 2010) can be accounted for by different proficiency levels (Abutalebi & Green, 2007). More specifically, it has been suggested that functional integration between different areas involved in language and cognitive control should vary as proficiency increases (Abutalebi & Green, 2007). Furthermore, Abutalebi and Green point to the need for longitudinal studies to examine changes in connectivity patterns among different regions of interest (ROIs), or a better understanding of changes that may occur during the acquisition of L2.

Functional integration between brain areas can be studied by means of functional connectivity analysis. Functional connectivity allows us to understand how brain areas involved in the processing of specific tasks operate within a system, and how different systems interact within a specific task; functional connectivity has also been related to information flow in the neural system (Anders, Heinzle, Weiskopf, Ethofer, & Haynes, 2011; Babiloni et al., 2005; Ramnani, Behrens, Penny, & Matthews, 2004; Shinkareva, Gudkov, & Wang, 2010). Functional connectivity changes are expressed in terms of functional integration, a measure that characterizes the global integrative state of a network (Marrelec et al., 2008). This approach allows one to examine the dynamic links between the language and control networks involved in L2 vocabulary learning, as proficiency in L2 picture naming increases.

Studies of functional connectivity first appeared rather recently. A few authors have examined the functional connectivity of language networks in healthy monolinguals performing language comprehension tasks (Leff et al., 2008; Van de Ven, Esposito, & Christoffels, 2009; Warren, Crinion, Lambon Ralph, & Wise, 2009) and language production tasks (Bitan et al., 2005; Just, Cherkassky, Keller, & Minshew 2004; van de Ven et al., 2009), whereas others have focused on people with aphasia (Abutalebi, Rosa, Tettamanti, Green, & Cappa, 2009; Marcotte, Perlbarg, Marrelec, Benali, & Ansaldo, 2012; Sonty et al., 2007). Studies of functional connectivity in bilinguals are scarce (Dodel et al., 2005; Majerus et al., 2008; Prat, Keller, & Just, 2007; Veroude, Norris, Shumskaya, Gullberg, & Indefrey, 2010). To date, no study has examined the functional connectivity profiles associated with L2 vocabulary learning.

Prat et al. (2007) examined functional connectivity profiles as a function of processing demands in a group of monolinguals who performed a reading task. Based on an fMRI test, subjects were divided into two groups, with either high or low working memory capacity. The results showed greater efficiency, increased adaptability and greater synchronization of the language network for the high-capacity readers, whereas low-capacity readers showed either no reliable differentiation, or a decrease in functional connectivity with increasing demands.

Studies with bilingual populations have mostly focused on the impact of cognitive load (i.e., task difficulty and cognitive capacity) on functional connectivity within the language processing network. Specifically, Dodel et al. (2005) focused on the syntactic processing level, and showed that differences in syntactic proficiency in L2 were associated with differences in the functional connectivity patterns in low- and high-proficiency L2 speakers. The authors used a condition-dependent functional interaction approach, a psychophysiological interaction technique introduced by Friston et al. (1997). This approach allows one to compare two conditions by computing a weighted correlation between the time courses of each pair of regions from a set of pre-determined ROIs. The authors reported that differences observed within these networks were correlated with TOEFL scores, reflecting low or high syntactic proficiency. Hence, this study provides evidence for links between functional connectivity and proficiency at the syntactic level of L2 processing.

In another study, Majerus et al. (2008) examined the links between short-term memory (STM) capacity and bilingual language achievement, in two groups of German–French bilinguals differing in L2 proficiency. They focused on connectivity between the left intra-parietal sulcus and bilateral superior temporal and temporo-parietal areas. Compared to the high-proficient group, the low-proficient group showed enhanced functional connectivity between the latter areas, which the authors interpreted as evidence of poorer storage and learning capacity for verbal sequences in that group.

One shortcoming of these studies is that L2 proficiency (high and low) is measured in different groups of participants, and thus a number of individual factors across groups could influence the connectivity patterns observed. Longitudinal studies with a single group of participants are better suited to measuring proficiency effects and their neurofunctional correlates (Abutalebi & Green, 2007). Moreover, by examining the functional connectivity patterns of networks that are known to contribute to L2 learning, a better understanding of the dynamic roles of the language and cognitive control systems can be achieved.

The aim of the present study is to describe the functional connectivity patterns that characterize L2 vocabulary learning in a group of Persian (L1) speakers who learnt French (L2). The language processing network described by Price (2010) and the control network described by Abutalebi and Green (2007) were identified with a ROI approach. The functional connectivity patterns of these two regions were described at two points in time during the process of learning L2 vocabulary: the shallow phase and the consolidation phase. These patterns were compared to those of the mother tongue, which was tested at both points. No changes in L1 functional connectivity patterns were expected.

Furthermore, in line with the psycholinguistic literature on L2 learning, and with previous functional connectivity studies on motor learning, reading and syntactic processing tasks, it was expected that functional connectivity levels would decrease with increased proficiency. Moreover, in accordance with Abutalebi and Green (2007), it was expected that higher proficiency would result in less effortful, and thus more automatic, processing, reflected in decreased functional integration between the language and control networks.

2. Experimental design

This was a longitudinal group study, with repeated behavioral, fMRI and functional connectivity measures at two points in time: (a) the shallow phase: after one week of computerized training and a 35% success rate in naming trained items; and (b) the consolidation phase: following 30 days of training and attaining a 100% success rate in naming trained items. Participants completed a pre-experimental assessment of bilingualism and cognitive status before inclusion.

2.1. Participants

A group of 12 native Persian speakers, aged between 26 and 66 (6 females and 6 males), with no history of neurological or neuropsychological disorders, participated in our study. All participants were right-handed (Edinburgh Handedness Inventory; Oldfield, 1971), they were homogeneous in terms of their cultural and educational background, and were matched for an elementary level of French (see Table 1).

2.2. Pre-experimental assessment

Participants were recruited from the immersion courses offered by the Quebec government for immigrants. This ensured an equal amount of exposure to L2 at recruitment and an equivalent level of L2 knowledge. Baseline in L2 proficiency was determined by means of a questionnaire based on the work of Silverberg and Samuel (2004), Flege (1999) and Paradis and Libben (1987), which had been used in our previous study of L2 proficiency (Scherer et al., 2012) (see Table 2). Participants were tested on their knowledge of the experimental stimuli before they experienced any lexical learning in L2; the exclusion criterion was being able to name more than 15% of the stimuli. All participants included respected these criteria.

To control for factors that may have an influence on L2 learning, a battery of tests was administered, including the following: MOCA: The Montreal Cognitive Assessment (Nasreddine, 2003); the Memory and Learning Test (Grober & Buschke, 1987; Grober, Buschke, Crystal, Bang, & Dresner, 1988), and the Stroop test (Beauchemin, Arguin, & Desmarais, 1996). After completing the pre-experimental assessment (see Table 2), participants were enrolled in a computerized lexical-training programme in French.

2.3. Stimuli

The experimental list included 130 words divided to three types of words: Cognates ($N = 35$; e.g., *Téléphone* /telefɔn/, French, and *Telephone* /telefɔn/, Persian; both words meaning 'telephone'), French and Persian Clangs (homophones) ($N = 40$; e.g., *Table* /tabl/, French, and *Tabl* /tabl/, Persian; meaning 'table' in French and 'drum' in Persian), and Non-Cognate Non-Clangs ($N = 35$; e.g., *Champignon* /ʃɑ~piɲɔ~/, French, and *Ghaarch* /ʀʌɾtʃ/, Persian; both words meaning 'mushroom'); each word had a corresponding picture. Word frequency was controlled across experimental lists and across languages. The items were matched for visual complexity, object familiarity and word familiarity in Persian and French, as well as the length of the words, in terms of number of phonemes and syllables, within each word category and across languages. All categories of words (Cognates, Clangs, and Non-Cognate Non-Clangs in French and Persian) were controlled for category effect. An equal number of items were selected for animals, fruits and vegetables, clothes and accessories, stationery, and household objects to control for a possible category effect (Caramazza & Shelton, 1998). Finally, Clangs and Non-Cognate Non-Clangs were controlled for similarity with their English equivalents to avoid CLT (Cross-Linguistic Transfer) effects of a third language. Twenty distorted images were used as the control condition and participants were instructed to say *dido* (a pseudo-word in Persian, French and English) upon the presentation of such pictures.

2.4. Lexical training programme

The participants completed self-training with a computer and a lexical training programme developed for a previous study by our group (Raboyeau et al., 2010). They completed a daily routine for 15 min for a total of 30 days. The importance of following the instructions was thoroughly explained to the participants at the beginning of the experiment; the respect of all instructions was checked with each participant, on the phone and by e-mail every 2–3 days. Participants were fully committed to respecting the 15-min training routine.

Table 1
Information on the participants' knowledge of L2 (French) at baseline. This questionnaire is based on Silverberg and Samuel (2004), Flege (1999) and Paradis and Libben (1987).

Do you consider yourself fluent in French?	No: 12	Yes: 0		
Are you comfortable having an informal conversation in French with an unfamiliar person?	Never 6	Rarely 2	Sometimes	Always 0
How would you consider the presence of accent of your first language, when speaking French?	Inexistent 0	Discrete 4	Heavy 8	
Do you think people understand you, when you speak French?	No 10	Somehow 2	Yes 0	
Self-assessment				
Please rate your proficiency in French on a scale of 1–5	Speaking	Understanding Speech	Reading	Writing
5 = Poor	8	4	6	7
4 = Regular	4	7	3	5
3 = Good	0	1	3	0
2 = Very good	0	0	0	0
1 = Excellent	0	0	0	0
Exposure				
How long have you taken French courses?	0–3	6–9	9–12	
(in months)	8	1	3	
Do you speak French in daily conversations outside home?			Yes: 0	No: 12
Do you use French in daily conversations at home?			Yes: 0	No: 12
Watching TV (minute per week)			None	
Reading			None	
Listening to the radio			None	
Talikng to a native French boy/girlf firnd or husband/wife			None	
Talking to people at work			None	
Motivation				
Indicate in the list below the factor(s) that lead you to learn French			Yes	No
To understand songs in French			4	8
To integrate in the community where you live/study/work			11	1
To feel yourself as being part of a member of the community			11	1
To make friends who are French speakers			9	3
To speak without accent			7	5
To enter school/University			8	4
To have/look for a better job			12	0

Table 2
Neuropsychological test results including: MOCA Memory test (Nassredine et al., 2005); Memory and Learning Test (Grober et Bushcke; Grober et al., 1988), and the Attention and inhibition Stroop test (Beauchemin et al., 1996).

Participants	Male/ female	Age	Education	Profession	Moca	Grober and Buschke: free recall/48	Grober and Buschke: category/16	Stroop					
								Color/ time (S)	Color/ error	Words/ time (S)	Words/ errors	Word-color time (S)	Word-color errors
1	m	42	20	Student	30	28	0	11.3	0	8.3	1	28	3
2	m	31	20	Student	30	47	0	12	0	8.9	0	21.64	2
3	f	28	14	Hairdresser	29	22	9	12.9	0	9.2	0	25.4	2
4	f	54	14	Teacher	30	24	8	27.5	0	13.7	0	15.8	3
5	f	40	21	Student	29	31	4	15.9	0	11.2	0	34.2	0
6	m	36	16	Constructor	29	21	8	19.5	0	14.4	0	40.1	1
7	f	26	18	Student	30	29	4	13.8	0	10.2	0	19.8	1
8	m	46	16	Geologist	27	24	6	23.5	0	9.8	1	23.5	1
9	f	29	16	Mathematician	30	22	16	11.9	0	9.2	1	24.3	0
10	f	42	16	Biologist	30	22	9	11.7	0	11.7	0	19.8	0
11	m	66	17	Physician	26	21	6	18.12	0	11.3	0	46.8	2
12	m	40	20	Student	30	26	8	11.5	0	10.5	0	22.7	2
M	6m	40	17.3	NA	29.2	26.4	6.5	15.8	0	10.7	0.2	26.	1.4
SD	6f	21.2	2.2	NA	1.2	6.6	3.9	4.9	0	1.7	0.4	8.3	0.9

The training programme included the experimental stimuli in French and the corresponding pictures. With the computer software, the target picture is displayed on the screen, followed by a series of phonological cues, displayed under the target picture when an icon is pressed. The first cue is the first sound of the target word, followed by the first and second sounds, and finally the whole target word. Participants were instructed to look at the picture, and listen to the first cue, then to the second cue, and then to the whole word. They were allowed to repeat this procedure as many times as necessary to learn the word. In their subsequent practice sessions, participants would first try to name the object when they saw the target picture; if unsuccessful, they would press on the icon and listen to the first cue; if they failed to recall the name of the object, they would listen to the second cue, and if necessary to the whole word. Participants were asked to make an effort to pronounce the word as similarly to the native pronunciation as possible.

2.5. Experimental task and procedure

At each measurement point (i.e., shallow and consolidation phases) participants were tested on an overt picture-naming task during fMRI scanning. The task was performed both in L2 and in L1 (Persian). The task in L1 served as a control condition, as no changes were expected in the mother tongue, either at the behavioral or at the functional connectivity level. The procedure and task were practised in the fMRI simulator for optimal data acquisition conditions in the fMRI scanner.

Stimuli were displayed by means of a computer equipped with Presentation software v.11.2 (http://www.neurobs.com). Participants lay on their back with their head fixed by cushions and belts, and an fMRI-compatible microphone was placed close to the participant's mouth to record responses. No bite-bars were used considering that the evidence does not support the use of this device, as it may add extra inconveniences for the participants and thus affect their attention and performance (Heim, Amunts, Mohlberg, Wilms, & Friederici, 2006). Rigid-body head movements were corrected with online movement correction.

Before the naming task, and as practised in the simulator, participants were once again instructed to look at the computer screen and name aloud each of the pictures presented to them, as accurately and as quickly as possible. These pictures were the same as those used in the training phase ($N = 130$ stimuli) presented randomly by means of Presentation v11.2. Each picture was presented for 4 s, after which there would be a blank page for a randomized interval of 4600–8600 ms, then the next picture would be presented. As in our previous study (Raboyeau et al., 2010), we used a variable inter-stimulus interval (ISI) to assure a better sampling of the haemodynamic response and prevent attentional bias (Huettel, Song, & McCarthy, 2004).

Participants were instructed to name the pictures they saw. The total duration of the task was 47 min: 21 min in each language and 5 min for anatomical acquisition.

Acquisition parameters were the same as in a previous study by our group (Raboyeau et al., 2010). Sequential slices were used, to avoid the stripping that might happen because of certain types of head motion (Siemens 3T Scanner User Training: Supporting Information and FAQ). The stimulus presentation time was 4500 ms, with a variable ISI (between 4325 ms and 8375 ms), TR = 3 s, TE = 40 ms, matrix = 64×64 voxels, FOV = 24 cm, and slice thickness = 5 mm. Acquisition included 28 slides in the axial plan, so as to scan the whole brain, including the cerebellum.

A high-resolution structural scan was obtained during the two functional runs (naming in L1 and naming in L2), using a 3D T1-weighted pulse sequence (TR = 13 ms, TE = 4.92 ms, flip angle = 25°, 76 slices, matrix = 256×256 mm, voxel size = $1 \times 1 \times 1$ mm, FOV = 28 cm).

2.6. Data analysis

2.6.1. Behavioral data analysis

Oral responses were acquired with the fMRI-compatible microphone, and Sound Forge software (Sonic Foundry Madison, Wisconsin, USA). Response times (RTs) and accuracy rates (ARs) were calculated. Non-responses, Persian words, and phonological errors (e.g., /pi/ instead of /pie/) were considered to be wrong answers. The event-related design allowed us to discriminate between correct and incorrect responses. Statistical analysis included ARs and RTs for each word category and the pseudo-word; significant differences between ARs and RTs across word categories were captured with SPSS, version 17.0.

2.6.2. Functional connectivity analysis

2.6.2.1. Selection of regions of interest. Pre-processing of the fMRI data was performed with SPM5 (http://www.fil.ion.ucl.ac.uk/spm) software. The images were corrected for delay in slice acquisition and rigid-body head movements; they were then realigned and smoothed. For each subject, the rp∗.txt outputs of the SPM5 realignment function was checked for translation (parallel to the *x*-, *y*-, and *z*-axes), and rotation around these axes (pitch, roll, and yaw), to discard the data from participants with more than 4 mm of head motion (Marcotte & Ansaldo, 2010; Marcotte, Perlbarg, Marrelec, Benali, & Ansaldo, 2012; Raboyeau et al., 2010). The identification of ROIs and the calculation of the functional interactions between these ROIs was completed with NetBrainWork software (http://sites.google.com/site/netbrainwork/) (Perlbarg et al., 2009).

ROIs selected for the language network were chosen according to the model proposed by Price (2010), based on an extensive review of the fMRI-based literature on language processing. Only the areas reported to be significantly activated in tasks involving isolated word processing were included. Twenty-one brain areas involved in prelexical speech perception, meaningful speech, semantic retrieval, word retrieval, articulatory planning, and initiation and execution of speech were selected. These areas covered the mid to anterior superior temporal and left angular gyri bilaterally; the left inferior frontal gyrus, including the left pars orbitalis/pars triangularis and the left posterior superior temporal gyrus; the left pars orbitalis (BA 47); the bilateral hippocampus; the left inferior and middle frontal gyri, including the pars opercularis (BA 44), the pars triangularis (BA 45), and the inferior frontal sulcus; the left dorsal pars opercularis; the precentral gyrus; part of the rolandic operculum; the pre-SMA and the left putamen; the insula; the bilateral temporal pole; the left angular gyrus; and the left ventral pars opercularis (Price, 2010).

ROIs selected for the control network areas were chosen according to Abutalebi and Green's (2007) work, and included the left fusiform gyrus, the left and right postcentral gyri the right superior parietal lobule, the left and right cingulate gyri, the left anterior cingulate, the left and right inferior frontal gyri, the right limbic lobe, the parahippocampal gyrus, the left frontal lobe and the superior frontal gyrus. (See Table 3 and Fig. 1.)

Table 3
Selection of regions of interest for (a) the classic language specific network according to Price (2010) and (b) the control network according to Abutalebi and Green (2007) involved in L2 vocabulary naming.

Area	Talairac coordinates
a	
Left and right superior temporal gyri	[−59, −6, −5]
Left posterior superior temporal	[62, −5, −10]
	[−54, −37, −1]
Left inferior frontal gyrus	[−56, 28, 6]
	[−48, 28, 21]
Left pars orbitalis,BA47	[−51, 24, −9]
Left dorsal pars opercularis	[−40, 17, 25]
Left ventral pars opercularis	[−53, 7, 15]
Left middle frontal gyrus	[−51, 25, 25]
Left and right hippocampus	[−30, −3, −30]
	[33, −6, −33]
Left angular gyrus	[−47, −59, 25]
Left and right temporal pole	[−53, 18, −30]
	[54, 20, −32]
Precentral gyrus	[−57, 9, 9]
Part of the rolandic operculum	[−50, −9, 23]
	[59, −5, 17]
Pre-SMA	[2, 6, 60]
	[−6, 13, 50]
Left putamen	[−24, −6, 6]
Insula	[−54, −36, 15]
b	
Right postcentral gyrus	[45, −19, 61]
Left postcentral gyrus	[−20, −32, 55]
Right superior parietal lobule	[8, −66, 62]
Right cingulate gyrus	[−10, −16, 36]
Left cingulate gyrus	[−10, −16, 36]
Left anterior cingulate	[−10, −16, 36]
Right inferior frontal gyrus	[22, 14, −14]
Left superior frontal gyrus	[55, 8, 16]
	[−16, 62, 8]
Right parahippocampal gyrus	[20, −44, 2]

Coordinates include 10 voxels around the peak.

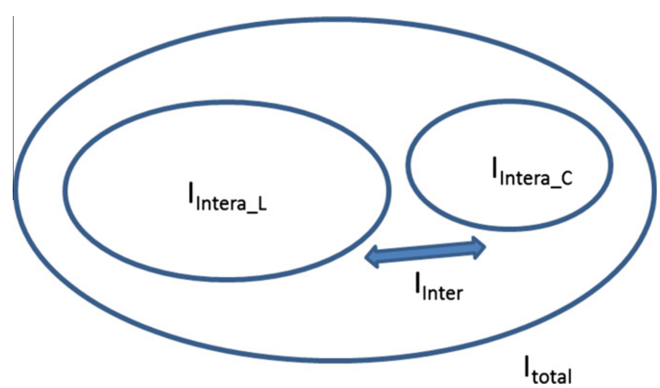

Fig. 1. A schematic diagram of the total Integration (I_{total}), integration between networks (I_{inter}), within the language processing network (I_{Intra_L}) and within the control network ($I_{Intra\text{-}C}$).

2.6.2.2. Measurement of integration value. Functional networks that were reproducible across subjects and conditions were extracted from BOLD data and represented as t-maps. The 21 ROI peaks (10 voxels around the peak) within the language network and the 11 ROIs peaks (10 voxels around the peak) in the control network were defined in the MNI standard space. (see Table 3 for the corresponding Talairach coordinates.) For each peak, a statistical map with the highest t-score was selected. Then, the extension of the corresponding ROI was achieved by using a region-growing algorithm that recursively added to the region the adjacent voxel with the highest *t*-score. The algorithm stopped when the region size was 10 voxels.

The fMRI data were corrected for physiological noise using CORSICA (, Anton, & Doyon, 2007). Averaged fMRI time-series from each of the 32 ROIs in the two networks of interest (NOIs, i.e., the language and control networks) were extracted. Then, the functional interactions between NOIs were evaluated with a measure referred to as integration, which quantifies the total amount of interaction within a network or between networks (Marrelec et al., 2008). To infer these integration measures by taking the intra- and inter-subject variability into account, we used a hierarchical model in a Bayesian framework with a numerical sampling scheme (Marrelec et al., 2006). The samples were then used to provide approximations of probabilities (e.g., probability of an increase in integration between the shallow and consolidation phases, based on the frequency of integration increase observed in the sample). Inferences on differences in integration were conducted at a probability of difference higher than 0.90.

The total integration I_{total} of the network involved in second language production can be decomposed as $I_{total} = I_{Intra\_L} + I_{Intra–C} + -I_{inter,}$ where I_{Intra_L} stands for the integration within the language network areas, I_{Intra_C} for the integration within the control network areas, and I_{inter} for the integration between the two networks (Marrelec et al., 2008) (Fig. 1).

Probable integration values were inferred from the data using a fixed-effects group approach (Marrelec et al., 2008), and a Bayesian group analysis with numerical sampling scheme (1000 samples per estimate for these analyses). During the sampling procedure, we estimated the group covariance matrix for each group (the group of subjects at the two levels of proficiency), resulting in 1000 estimates of each measure (total integration, between integration, and within integration) for each group. The samples were then used to provide approximations of either statistics (e.g., mean and SD approximated as their sample counterparts) or probabilities (e.g., probability of an increase between low and high levels of proficiency), approximated as the frequency of that increase observed in the sample. This procedure had previously been used by Boly et al. (2012), Coynel et al. (2009) and Schrouff et al. (2011).

The mean and standard deviation of integration reported in the manuscript thus correspond to the mean and standard deviation of the integration sample distributions. The probability of an assertion such as [integration_T2 > integration_T1] is given between 0 and 1.

A probability greater than 0.9 is considered significant whereas a probability lower than 0.1 shows that the complementary assertion ([integration_T2 < integration_T1]) is true.

2.7. Ethical issues

This study was approved by the ethics committee of Réseau de Neuroimagerie du Québec (RNQ). All participants signed a consent form. The procedure was explained clearly to the participants. All data were recorded in the Unité neuroimagerie fonctionnelle (UNF) at the Institut de Gériatrie de Montréal (IUGM).

3. Results

Behavioral data analysis was completed with SPSS 17.0. ARs and RTs for picture naming were calculated at each measure point. A paired-sample *t*-test was conducted to compare ARs and RTs at the shallow and consolidation phases. The results show that L2 words were named faster (M_{RT} = 1.7, SD = 0.23) and more accurately (M_{AR} = 89.74%, SD = 5.3%) at the consolidation phase (M_{RT} = 2.1, SD_{RT} = 0.32), (M_{AR} = 69.9%, SD_{AR} = 22.85%). The paired-sample *t*-test showed that there was a significant difference between the two phases, both for RTs, $t(12) = 4.52$, $p = .001$, and for ARs, $t(12) = -3.02$, $p = .012$. (Refer to Fig. 2.)

L1 words were named faster at T2 (MRT = 2.21, SD = 0.61) but the difference in RT was not statistically significant [$t(12) = 3.45$, $p = .006$. Also, there was no significant difference between T1 and T2 accuracy rates ([$t(12) = -1.77$, $p = .107$]. (Refer to Fig. 2c and d.)

3.1. Functional connectivity results

The total integration values for the L2 language network and the control network were calculated at the shallow phase (T1) as I_{total} = (*M* = 4.8203, SD = 0.1158), and at the consolidation phase (T2), as I_{total} = (*M* = 4.1983, SD = 0.1165), and the probability of differences was T2 > T1 = 0.00001.

The total within-system integration value for the language network and the control network at the shallow phase (T1) was measured as I_{Intra_total} = (*M* = 3.6108, SD = 0.097782), and at the consolidation phase (T2) as I_{Intra_total} = (*M* = 3.1369, SD = 0.097472), and the probability of differences was T2 > T1 = 0.00001. The within-system integration value for the language network at the shallow phase (T1) was I_{Intra_L} = (*M* = 3.3798, SD = 0.0934); at the consolidation phase (T2), it was I_{Intra_L} = (-*M* = 2.9289, SD = 0.0936), and the probability of differences was T2 > T1 = 0.0000. The value for the within-system integration for the control network at the shallow phase (T1) was measured as $I_{Intra-C}$ = (*M* = 0.2310, SD = 0.0213), and at the consolidation phase (T2) it was (*M* = 0.2080, SD = 0.0215); the probability of differences was T2 > T1 = 0.2310.

The total between-systems integration value for the language network and the control network was measured at the shallow phase (T1) as I_{inter} = (*M* = 1.2095, SD = 0.0442), and at the consolidation phase (T2) as (*M* = 1.0614, SD = 0.0459); the probability of

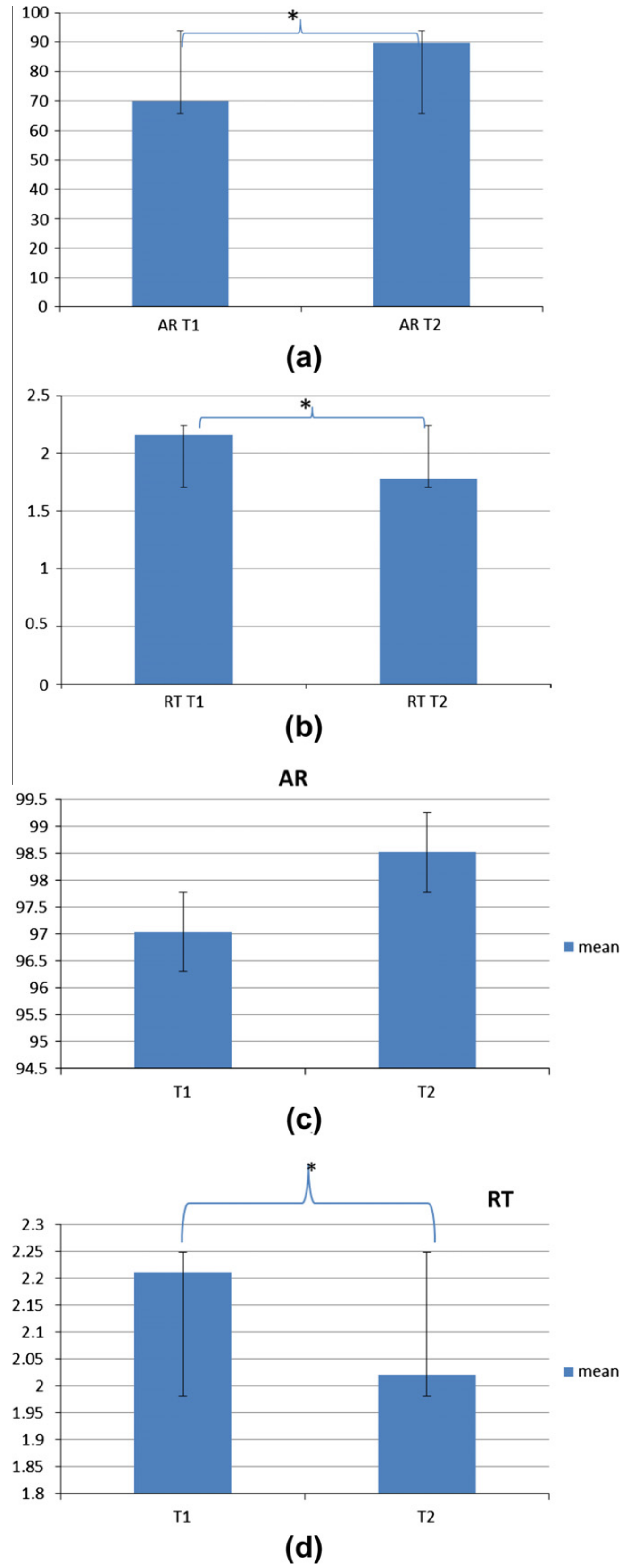

Fig. 2. (a) Accuracy rates (AR) and (b) response time (RT) for naming French (L2) words at shallow and consolidation learning phases, (c) accuracy rates (AR) and (d) response time (RT) for naming Persian (L1) words at shallow and consolidation learning phases. Asterisk show statistical significance.

Table 4
The significant probability of differences of the total integration value for classic language network as well a supplementary network at the low level of proficiency (T1) and at the high level of proficiency (T2). I_{total}: The total integration value for classic language network as well a supplementary network; I_{Intra_total}: The total within-system integration value for the classic language network and the supplementary network; I_{Intra_L}: The within-system integration value for the classic language network; I_{inter_total}: The total between-systems integration value for the classic language network and the supplementary network.

French (L2)	Low proficiency (T1)		High proficiency (T2)		(T2 > T1)
Integration value	Mean	SD	Mean	SD	*P* value
I_{total}	4.8203	0.1158	4.1983	0.1165	0.00001
I_{Intra_total}	3.6108	0.0978	3.1369	0.0975	0.00001
I_{Intra_L}	3.3798	0.0934	2.9289	0.0936	0.00001
I_{inter_total}	1.2095	0.0442	1.0614	0.0459	0.01

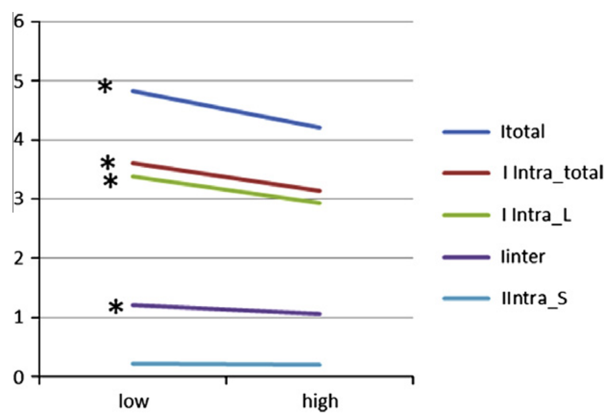

Fig. 3. The integration value of the total, between networks (I_{inter}), within the language network (I_{Intra_L}) and within the supplementary network ($I_{Intra\text{-}C}$) for L2 decrease, as the level of proficiency improves. The asterisks correspond to significant effects.

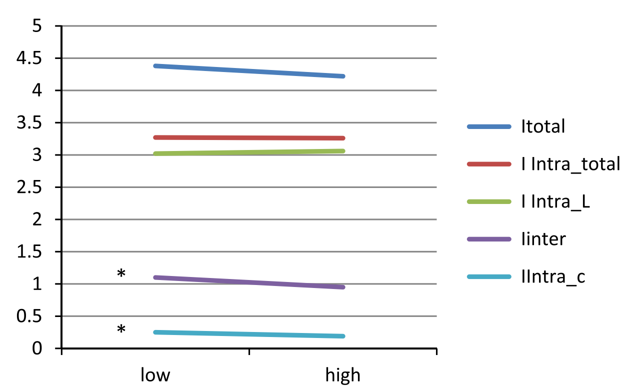

Fig. 4. L1 Integration values of the total (I_{total}), between networks (I_{inter}), within the language network (I_{Intra_L}) and within the control network (IIntra-C) for the group of L2 learners. The asterisks correspond to significant effects.

differences was T2 > T1 = 0.01. (See Table 4 and Fig. 3 for a summary of all significant differences.)

For L1, the total integration values for the language and control networks were calculated at the shallow phase (T1) as I_{total} = (-*M* = 4.3825, SD = 0.1103), and at the consolidation phase (T2) as I_{total} = (*M* = 4.2227, SD = 0.1071), and the probability of differences was T2 > T1 = 0.1510.

The total within-system integration value for the language network and the control network was measured at the shallow phase (T1) as I_{Intra_total} = (*M* = 3.2786, SD = 0.094642) and at the consolidation phase (T2) as I_{Intra_total} = (*M* = 3.2632, SD = 0.093499), and the probability of differences was T2 > T1 = 0.4510. The within-system integration value for the language network at the shallow phase (T1) was measured as I_{Intra_L} = (*M* = 3.0278, SD = 0.0900), while at the consolidation phase (T2) it was (*M* = 3.0692, SD = 0.0904), and the probability of differences was T2 > T1 = 0.6400. The value for the within-system integration for the control network was measured at the shallow phase (T1) as $I_{Intra\text{–}C}$ = (*M* = 0.2507, SD = 0.0237) and at the consolidation phase (T2) as (*M* = 0.1940, SD = 0.0204); the probability of differences was T2 > T1 = 0.0400.

The total between-systems integration value for the language network and the control network at the shallow phase (T1) was measured as I_{inter} = (*M* = 1.1039, SD = 0.0452), and at the consolidation phase (T2) it was (*M* = 0.9595, SD = 0.0413); the probability of differences was T2 > T1 = 0.008.

Thus, the results for French (L2) show that, as proficiency increased, the total integration value for the language network and the control network (I_{total}) decreased. Moreover, with increased proficiency, the total within-system integration value for the language network and the control network (I_{Intra_total}) decreased. However, while the within-system integration value for the classic language network (I_{Intra_L}) decreased, the value for the within-system integration for the control network ($I_{Intra\text{–}C}$) did not change. The total between-systems integration value for the classic language network and the control network (I_{inter}), decreased as well.

For Persian (L1), the total integration value for the language network and the control network (I_{total}), the total within-system integration value for the language network and the control network (I_{Intra_total}), the within-system integration value for the language network (I_{Intra_L}), the within-system integration value for the control network ($I_{Intra\text{–}C}$) and the total between-systems integration value for the language network and the control network (I_{inter}) remained unchanged across the phases (Fig. 4).

4. Discussion

The purpose of the present study was to describe brain connectivity patterns in a group of Persian speakers learning new vocabulary in French. For each measure point (T1 and T2), measures of functional integration (Marrelec et al., 2008) were calculated for the language network (Price, 2010) and the control network (Abutalebi & Green, 2007), and they were compared to those of the mother tongue. It was expected that increased proficiency at T2 would be observed concurrently with decreased functional integration in the language and control networks, whereas no changes should be observed in the L1 functional integration levels, across measures.

The behavioral results showed that L2 words were named significantly faster and more accurately at the consolidation phase than at the shallow phase, providing evidence for increased proficiency across learning phases with L2 words. Higher accuracy rates and faster responses thus confirmed successful L2 vocabulary learning. It should be noted, however, that the marginally significant difference in RT with L1 words cannot be interpreted as a learning effect with mother tongue, but most probably reflects a familiarity effect. Participants had been repeatedly exposed to the same pictures during lexical learning; repeated exposure to the same stimuli leads to increased stimulus familiarity, which has been reported to reduce naming latency (Mitchell & Brown, 1988; Gernsbacher, 1984; Snodgrass &Yuditsky, 1996; Feyereisen, Barter, Goossens, & Clerebaut 1988).

Different functional connectivity patterns with L1 and L2 were observed across measure points. As expected, functional connectivity within the mother tongue language network remained unchanged across learning phases, thus, reflecting no learning effect with mother tongue. Furthermore, in line with previous literature (Heath et al., 2012; Whatmougha, Chertkowa, Murthaa, & Hanrattya, 2002; William et al., 2007; Yi & Chun, 2005), the pre-post training significant decrease in integration values within the control network ($I_{\text{Intra–C}}$), and between the control and language networks (I Inter) reflects a familiarity effect. Hence there is evidence that repeated exposure to the same stimuli results in a familiarity effect, which is reflected by decreased activity in cognitive control processing areas (William et al., 2007; Whatmougha et al., 2002; Heath et al., 2012; Yi and Chun; 2005).

With L2, changes in connectivity were observed after lexical learning. Specifically, total, inter- and intra-integration levels decreased as proficiency improved. These results are in line with previous evidence from motor learning studies, showing decreased functional integration with motor learning consolidation. Thus, Coynel et al. (2009) showed that four weeks of practising an explicitly known sequence of finger movements significantly decreased the functional integration between the premotor and sensorimotor networks. Our results also converge with previous research on second language learning. Thus, a comparison between good and poor learners of Chinese showed that decreased functional connectivity in phonological processing areas was observed only in the group of good learners (Veroude et al., 2010). Along the same lines, differences in L2 proficiency have been related to distinct functional connectivity patterns in short-term memory circuits, including the left intra-parietal sulcus and bilateral superior temporal and temporo-parietal areas (Majerus et al., 2008). Thus, the evidence from the present study and earlier ones suggests that L2 proficiency affects functional integration in a variety of systems, including the language system and the short-term memory system.

Furthermore, the evidence from this study can be interpreted with reference to cognitive control issues in L2 proficiency. Thus, it has been argued that, among bilinguals, language tasks in the less proficient language require more cognitive control and cognitive demand than those in the more proficient language (Abutalebi & Green, 2007; Favreau & Segalowitz, 1983; Segalowitz & Hulstijn, 2005). Moreover, it has been argued that the cognitive resources required for L2 comprehension and production may change according to L2 proficiency. Specifically, according to Abutalebi and Green (2007), low L2 proficiency levels entail effortful processing, and thus attentional and executive resources are required, as reflected in the recruitment of a control network, including the left prefrontal cortex, the basal ganglia, the anterior cingulate cortex, and the posterior temporal and inferior frontal cortices. Abutalebi and Green argue that these circuits become disengaged with increased L2 proficiency. In line with this perspective, and similar to previous studies (Coynel et al., 2009; Dodel et al., 2005; Majerus et al., 2008; Prat et al., 2007; Veroude et al., 2010), the evidence from the present study shows that decreased integration within and between the language and control networks is observed at T2, together with optimal behavioral performance (100% success rate and decreased RTs) on the trained list, reflecting more automatic processing due to increased proficiency in L2 naming. The concept of automaticity reflects task performance with low cognitive effort and attention (Segalowitz, 2005), and encompasses both quantitative and qualitative characteristics of a cognitive activity (Segalowitz & Hulstijn, 2005). Quantitatively, automatic tasks are performed faster (DeKeyser, 2001; Segalowitz, 2005), whereas qualitatively, they may imply changes in underlying processes (Segalowitz & Gatbonton, 1995). For example, there is evidence that the number of areas involved in a task decreases as automaticity increases (Fischler, 1998; Haier, Siegel, MacLachlan, et al., 1992; Haier, Siegel, & Tang, 1992; Raichle et al., 1994). In line with previous claims (Marrelec et al., 2008), integration changes in L2 observed over time show that the information flow in the system decreases with increased proficiency.

To summarize, the results of this study show that language proficiency modulates functional integration levels within contributing circuits in L2 vocabulary learning. The present study documents such changes for the first time, particularly with regard to the language processing circuit, as described by Price (2010), and the control circuit, as described by Abutalebi and Green (2007). Moreover, the finding of decreased functional integration between the language and control systems over time provides evidence for the dynamic role of language processing and control networks, as a function of practice with L2 vocabulary.

It should be noted, however, that these changes were observed in persons who were just beginning to learn L2; more advanced L2 learners, whose proficiency has improved, could show different functional connectivity patterns. Moreover, this study was conducted on Persian native speakers whose mother tongue is distant from French (L2). Given that cross-linguistic transfer effects vary as a function of language distance (Ringbom, 2007), it is possible that different functional connectivity patterns could be observed in linguistically close L1 and L2.

Finally, it should be noted that the ROI approach used in the present study limits the observations to the regions examined. However, given the novelty of the technique and topic, the ROI approach was considered to be the most suitable, so that data analysis was performed on two well-known networks, namely the control network and the language network. Hence, the ROI approach has the advantage of providing homologous functional areas across subjects and is the best choice for testing connectivity between the constituents of a brain network that is already known (Hunton, Miezin, Buckner, Raichle, & Petersen, 1996). Future studies could adopt a data-driven approach to examine functional connectivity patterns in networks emerging from BOLD data, as a function of proficiency or of distance between L1 and L2.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.bandl.2012.11.008.

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