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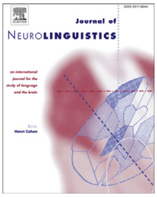

Neural changes underlying successful second language word learning: An fMRI study

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ABSTRACT

A great deal of research has examined behavioral performance changes associated with second language learning. But what changes are taking place in the brain as learning progresses? How can we identify differences in brain changes that reflect successes of learning? To answer these questions, we conducted a functional magnetic resonance imaging (fMRI) study to examine the neural activities associated with second language word learning. Participants were 39 native English speakers who had no prior knowledge of Chinese or other tonal language, and were trained to learn a novel tonal vocabulary in a six-week training session. Functional MRI scans as well as behavioral performances were obtained from these learners at two different times (pre- and post-training). We performed region of interest (ROI) and connectivity analyses to identify effective connectivity changes associated with success in second language word learning. We compared a learner group with a control group, and also examined the differences between successful learners and less successful learners within the learner group across the two time points. Our results indicated that (1) after training, learners and non-learners rely on different patterns of brain networks to process tonal and lexical information of target L2 words; (2) within the learner group, successful learners compared to less successful learners showed significant differences in language-related regions; and (3) successful learners

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compared to less successful learners showed a more coherent and integrated multi-path brain network. These results suggest that second language experience shapes neural changes in short-term training, and that analyses of these neural changes also reflect individual differences in learning success.

1. Introduction

In an increasingly globalized world like ours, more people are learning and speaking a second or a third language for travel, business, or other forms of intercultural communication. While the science of bilingualism has shown that knowing multiple languages confers long-term cognitive advantages to the learner in addition to the obvious social and economic benefits (see Bialystok & Barac, 2012 for a review), learning of a second language (L2) in general is much more difficult and often less effective as compared to learning of a first language (L1), especially when the learning takes place later in life. However, it is also clear that while some adults have significant difficulties at every step of L2 learning, others can grasp a second language in less time and with more success, given the same learning conditions. This type of individual difference in learning a new language is often discussed in terms of “language aptitude” differences (Dörnyei, 2006). Just what exactly underlies language aptitude is a matter of intense debate in the literature (see Doughty, 2014).

In the last few years a number of studies have examined the bilingual brain using neuroimaging methods especially functional magnetic resonance imaging (fMRI) (see Hernandez, 2013 for discussion). A particularly booming area of research is the study of the neural basis of bilingual language learning and cognitive control. Abutalebi (2008) and Abutalebi and Green (2007) laid out a picture for an inter-connected network in the frontal, temporal, parietal, and striatal regions that work together for monitoring the use of two or more languages and for resolving conflict associated with this process. The evidence so far suggests that bilingual learners have enhanced neural activity involving this control network for the effective use of the target languages while inhibiting the unintended language. Importantly, this enhanced activity is modulated by the degree of L2 proficiency: increased proficiency tends to lead to decreased brain activity, especially in the prefrontal cortex, indicating a more efficient use of the control network for language by the proficient bilingual (see, e.g., Chee, Hon, Lee, & Soon, 2001; Stein et al., 2009; Tatsuno & Sakai, 2005).

1.1. *Short-term L2 training studies: a brief review*

That the learner's L2 proficiency modulates the level of neural activity in specific brain regions is consistent with the idea that neural patterns may be shaped by the specific linguistic experience of the learner, in this case, experience with a new language. A first goal of our study is to capture the experience-dependent neural changes that underlie the successful learning of a second language by comparing L2 learners with non-learners. The extant neuroimaging literature indicates significant neural plasticity, both functional and structural, as a result of language experience with the L2 (e.g., Abutalebi et al., 2013; Mechelli et al., 2004; Tan et al., 2003; Wang & Zhang, 2007; Yang, Tan, & Li, 2011; see Li, Legault, & Litcofsky, 2014 for a recent review). One question that has been raised is how soon one may see neural changes as a result of short-term experience, especially linguistic experience (Li, Legault, et al., 2014). There has been some evidence for neural effects of very brief exposure to language (e.g., Kwok et al., 2011; McLaughlin, Osterhout, & Kim, 2004), but researchers have only recently begun to assess the effects from short-term language training studies in controlled experimental settings, to test just what amount and type of L2 language experience can causally affect neural patterns of response.

Wang, Sereno, Jongman, and Hirsch (2003) trained six adult native speakers of English to learn Chinese tones. During eight sessions of 40 min across two weeks, participants were trained to identify the four tones of 180 monosyllabic Mandarin words. The authors examined the learners' cortical activation

(Blood Oxygen Level Dependent or BOLD signals from fMRI) before and after the training in a tone identification task. Their results showed that increased tone-identification performance was associated with an increase in the spatial extent of activation in left superior temporal gyrus (STG) and adjacent areas (Brodmann's area or BA 22, BA 42), and the right inferior frontal region homologous to the Broca's area (BA 44). The left STG activation indicates that the learners were able to successfully treat tonal differences as linguistic differences rather than simply acoustic differences. Moreover, these findings suggest that the early cortical effects of L2 learning involve both the expansion of preexisting language-related areas (e.g., left superior temporal gyrus) and the recruitment of the right inferior frontal gyrus (IFG: BA 44), implying the plasticity of the linguistic brain in the acquisition of Mandarin tones.

Similar neuroimaging findings have also been reported by other studies. For example, Golestani and Zatorre (2004) asked native English speakers to learn Hindi dental-retroflex contrasts: during each 1-h training session with feedback, participants were asked to identify two sound stimuli. After five sessions of sound identification training on those contrasts across two weeks, increased activations were observed in the left STG, insula-frontal operculum, and inferior frontal gyrus in the learners. Wong, Perrachione, and Parrish (2007) conducted another tone-training study, in which seventeen native English speakers were presented with a novel word learning task. In this task, three tones (level, rising, falling) were superimposed on six English pseudosyllables to create 18 pseudowords, and the participants were trained to associate these 18 “words” with 18 different non-living objects depicted in pictures. This task resembled a real word-learning task, in that participants need to learn the same syllables that carried different tones (and are differentiated by tones in one out of three cases). Thus, learning of these words is much like the learning of real words in a tonal language (e.g., Chinese) in which pitch contour differences indicate lexical semantic differences. Participants were trained with feedback three to four sessions every week until their individual ultimate attainment was reached. Participants were tested at the end of each session; learners whose word recognition accuracy was 95% or above for two consecutive sessions were classified as “successful learners”, and those who failed to make 5% improvement or better for four consecutive sessions were classified as “less successful learners”. Wong et al. (2007) found that these two groups had distinct neural activation patterns, in that the successful learners showed increased activation in the left posterior STG (BA 22), whereas the less successful learners were characterized by increased activations in the right STG and right IFG, and in general a more diffuse network in the frontal and temporal cortical regions. This finding of the stronger left posterior STG activation for successful learners is consistent with our understanding of the important function of this area for phonological processing (see Hickok, 2009; Hickok & Poeppel, 2007; Zhang et al., 2011). More surprisingly, Wong et al.'s (2007) study demonstrated that the successful learners' neural patterns were distinct from the less successful learners even *before* the sound-to-word learning (i.e., before the behavioral training) began. The successful learners had greater brain activity in the posterior STG, compared with the less successful learners. Thus, it may be possible that we could predict, based on neural signatures, who might be the successful learners.

The above approach of using neuroimaging data to differentiate learner groups has also been adopted in other recent studies. Mei et al. (2008) recruited twenty-four native Chinese speakers to learn, within two weeks, a logographic artificial language that resembles Korean Hangul characters. During the first three days of training, participants learned the visual forms, phonology and semantics of 20 characters in 2-h training session per day and learned all the 60 characters for the remaining seven days (5 days per week for two weeks). The learners whose performance was above average during the training were classified as “good learners” and the remaining participants were “poor learners”. The authors found that before the auditory word learning, when participants passively listened to the unknown words, good learners showed more activation in the left posterior middle temporal gyrus (MTG)/the superior temporal sulcus (STS) relative to the poor learners, whereas the poor learners displayed stronger neural responses in the right IFG. These data again also suggested that it is possible to use patterns of neural activity to differentiate good learners from poor learners.

Some researchers have used regression analyses to examine the neural substrates associated with successful second language learning. For example, Breitenstein et al. (2005), in an event-related fMRI study, explored brain regions associated with novel word learning. Participants learned 45 pseudo-word sound–picture associations over five training blocks (10 min per block) during the scans and they were asked to press a button intuitively to judge whether the associated pair was correct or not. The authors then used the learners' behavioral performance on a subsequent test of lexical knowledge as a measure of their vocabulary proficiency and correlated the proficiency level with their brain functional changes associated with learning. They found that the increase in novel word proficiency over the 50-min training session was paralleled by a linear decrease of BOLD signal changes in the left hippocampus. Therefore they claimed that learning-related hippocampal activity is a stable marker of individual differences in the ability to acquire new vocabularies.

In recent years several studies have used structural imaging data to examine successes of second language learning (see Li, Legault, et al., 2014 for review). For example, Hosoda, Tanaka, Nariai, Honda, and Hanakawa (2013) trained native Japanese speakers to learn English words in a lab setting for 16 weeks. They found that learners showed increased density of gray matter and white matter in the right IFG, and the increases correlated positively with their knowledge of English vocabulary. By contrast, the control participants who did not receive the English vocabulary training within the same period showed no such neuroanatomical changes in the brain. These structural imaging data provide stronger evidence for a causal relationship between language experience and neural changes than suggested by most current functional imaging data.

1.2. Brain network analyses of L2-induced neural changes: functional vs. effective connectivity

Given the surge of interest in neurocognitive studies of second language acquisition as reviewed above, in this study we aim to identify individual differences by examining the functional neural correlates associated with the learning of novel L2 words before and after training (i.e., L2 word learning experience). A key to understanding individual differences through brain data is to examine the functional brain networks underlying individual differences in L2 sound-to-word mapping. Recent interests in large-scale brain networks point to a new framework for understanding distinct vs. overlapping neural systems, and to identify the dynamic interactions among neural systems for both normal and impaired brain functions (Bressler & Menon, 2010; Poldrack, 2011; Sporn, 2010). This framework views cognitive functions as arising from the interactions between and within distributed brain systems, often constrained by context and mode of learning and processing. In short, it looks at not just activation of individual brain regions, but also the spatial and temporal relationships between multiple brain regions during cognitive and linguistic processing. The study of neurocognitive processes as supported by dynamically connected neural networks has the potential to reconcile some of the debates between brain localization and brain organization, and will undoubtedly lead to new insights into the bilingual brain in the years to come.

A number of studies have already taken the approach of brain networks toward language learning and processing. For example, Sheppard, Wang, and Wong (2012) [1] analyzed the Wong et al. (2007) data through a brain network analysis based on graph theory. Specifically, they wanted to see if auditory discrimination of the tones in the two groups might be characterized by the processing efficiency of the underlying brain networks for learning sound-to-word mappings. The researchers defined the efficiency of the brain networks in terms of the average number of connections (edges) between brain regions of interest (nodes): the fewer the number of edges needed to go from one node to the next, the more efficient the network is. Sheppard et al.'s analyses showed distinct patterns for the two learner groups, as estimated by the small-world network typologies (in a total of 998 nodes selected): the successful learners' network, on average, had reduced local efficiency but increased global efficiency as compared with that of the less successful learners, suggesting that a more cost-efficient network organization underlies sound-to-word learning abilities for the better learners. Moreover, the successful learners also showed more processing efficiency in key brain regions that have been implicated in working memory (e.g., dorsolateral prefrontal cortex and inferior parietal cortex) and language processing (e.g., middle and inferior temporal cortex).

Veroude, Norris, Shumskaya, Gullberg, and Indefrey (2010) examined the functional connectivity of key brain regions related to word learning. Participants in this study learned Chinese words by watching short weather report movies. They focused on six regions associated with phonological processing,

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[1] The authors were quite cautious in making their arguments, suggesting that any effects about the between-group differences must be interpreted as exploratory, given the small sample size (9 successful learners and 8 less successful learners).

including the pars opercularis, the left supplementary motor area, the left insula, the left supramarginal gyrus, the left posterior superior temporal gyrus and the left posterior middle temporal gyrus. During word learning fMRI scans, which were interleaved with resting sessions, participants watched weather charts and listened to continuous speech streams from a weather report in Mandarin Chinese (two 6-min sessions). Participants were further classified as learners and non-learners based on their performance on a post-training auditory word recognition task. Functional connectivity between the left and right supramarginal gyrus (SMG) during post-training resting state was stronger in learners than non-learners, which confirms the important role of SMG in lexical phonological form representation for language learning (see Section 4 for discussion of the role of SMG/IPL in lexical learning). In another study, Ghazi Saidi et al. (2013) further examined changes in the functional brain connectivity across different learning phases in which native Persian speakers learned French in an immersion course offered by the Quebec government for immigrants. The authors hypothesized that as L2 learning progresses from low to high proficiency, the learner's functional integration between language and control networks, which quantifies the total amount of interaction within a network or between networks, would decrease as L2 proficiency increases, reflecting more automatic processing as language proficiency increases. Indeed, the functional brain network of 21 nodes showed decreased integration in both between- and within-network levels as participants' language proficiency improved in successful recall accuracy from 35% (after one-week training) to 100% (after 30-day training).

Most of the previous studies in the network approach toward L2 have used “functional connectivity” analyses. Functional connectivity analyses are important as discussed, but they are only able to reveal correlational relationships between different brain regions implicated for learning. In the current study, we want to understand not only the correlational but also the causal interactions between key brain regions related to L2 word learning. Thus, we will perform “effective connectivity” analyses of our data, which involves the identification of the direction of influences between brain regions in addition to the strength of connections between these regions. Given that the directional influences in effective connectivity are very complex and may be both activity- and time-dependent, we need a technique that can incorporate both contemporaneous and time-lagged effects in a single model to provide an unbiased parameter estimation of our fMRI time-series data. Dynamic Causal Modeling has been a popular method in this regard, but it requires *a priori* specification of the connections among ROIs in a confirmatory approach (Friston, Harrison, & Penny, 2003). Data-driven approaches have recently been developed to enable researchers to examine both the activation and connection at a given time (contemporaneously) and their directions of influence across different times (sequentially). In particular, Gates, Molenaar, Hillary, Ram, and Rovine (2010) developed the unified structural equation modeling (uSEM) and the extended unified structural equation modeling (euSEM; see Methods for a description of uSEM and euSEM), which have allowed us to study brain networks of cognition and language (see two recent publications that have applied euSEM; Nichols, Gates, Molenaar, & Wilson, 2014; Yang & Li, 2012). In this study we will use both uSEM and euSEM to do effective connectivity analyses on our fMRI data, in order to show the dynamic interactions between key brain regions that subserve the learning of a second language vocabulary.

In sum, to better understand the neural correlates underlying second language word learning and to identify the neural mechanisms of successful vs. unsuccessful learning, the current study is designed to examine the functional changes in the brain that occur in the L2 word learners. Toward this goal, we designed an fMRI study in which participants were trained on a novel vocabulary and measured before and after the training (see details in Section 2.2). Our particular focus is the effective brain connectivity patterns that may characterize the way in which learners differ in their learning success. Our results may shed new light on the nature of L2 learning-induced neural changes and the issue of neural plasticity for second language acquisition.

2. Method

2.1. Participants

Thirty-nine right-handed (Snyder & Harris, 1993) healthy adults from the Pennsylvania State University participated in this fMRI study and received payment for their participation. All participants

Table 1
Novel word learning stimuli.

bip1[a] (fork)	gom1 (ball)	min1 (bed)	pok1 (sun)
bip2 (envelop)	gom2 (map)	min2 (rocket)	pok2 (hand)
bip3 (onion)	gom3 (shoe)	min3 (tie)	pok3 (leaf)
beng1 (piano)	guk1 (mountain)	mep1 (house)	pum1 (nose)
beng2 (drawer)	guk2 (door)	mep2 (camera)	pum2 (bowl)
beng3 (train)	guk3 (chair)	mep3 (rain)	pum3 (flower)
dit1 (ear)	kot1 (nail)	nop1 (peanut)	tik1 (foot)
dit2 (apple)	kot2 (telephone)	nop2 (moon)	tik2 (umbrella)
dit3 (window)	kot3 (banana)	nop3 (bone)	tik3 (sock)
dem1 (key)	kun1 (mirror)	nung1 (bridge)	tet1 (eye)
dem2 (ruler)	kun2 (pants)	nung2 (teeth)	tet2 (pen)
dem3 (car)	kun3 (belt)	nung3 (pear)	tet3 (candle)

[a] Indicates the tone as used in Mandarin Chinese.

were native speakers of English and had no prior experience learning a tonal language. They completed a Language History Questionnaire (Li, Sepanski, & Zhao, 2006; Li, Zhang, Tsai, & Puls, 2014), in which questions about their language history, usage habits, proficiency, and self-reported dominance were asked. The 39 participants were separated into a learner group (23 participants, 12 females; mean age = 20.61 years, SD = 1.04, range = 18.58–23.33 years) and a non-learner group (16 participants, 7 females; mean age = 20.8 years, SD = 1.73, range = 18.17–25.75 years). Both groups underwent MRI scans at two time points in a six-week period: once before training (pre-training, Time 1 or T1) and once after training (post-training, Time 2 or T2). Only the learner group underwent the L2 word learning procedure, that is, taking part in three training sessions per week for six weeks (see further details below), whereas the non-learners (NL) did not receive any training in the equal amount of time (i.e., six weeks). The study was approved by the Institutional Review Board of the Pennsylvania State University, and followed the research and ethics protocols used at the Penn State Social, Life, and Engineering Sciences Imaging Center.

2.2. Stimuli and training procedure

The L2 word learning procedure used in the current study was similar to that used by Wong et al. (2007) and Chandrasekaran, Sampath, and Wong (2010). The learners underwent 18 training sessions (three per week) in six weeks and learned 48 Chinese pseudowords (see a complete list of the stimuli in Table 1). The pseudoword stimuli were composed of 16 monosyllables of the CVC structure, to match the Chinese phonological structure for typical monosyllabic morphemes. Three different pitch contours were superimposed on each of the 16 syllables, resulting in 48 different monosyllables as the novel word stimuli for participant training (henceforth the ‘words’ or ‘stimuli’). The three pitch contours correspond to the first tone (level), second tone (rising), and fourth tone (falling) in Mandarin Chinese.[2] The 48 stimuli were produced by a native female speaker of Mandarin Chinese and were recorded in a sound-attenuated chamber. Each recorded word was further normalized using Audacity 2.0 (http://audacity.sourceforge.net), and when played back, was judged to be perceptually natural and accurate by four native Mandarin speakers.[3] Each word was paired with a picture of non-living familiar objects presented on a computer screen (summarized in Table 1). For example, the participant heard the syllable/bip2/(“bip” spoken with a rising tone, tone 2) while looking at a picture of an envelope on the screen. The pictures corresponded to high-frequency words and were selected from the UCSD

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[2] We did not use the third tone (dipping and rising) because of the complexity of the phonetic features of this tone, as has been noted in previous studies (see Wong et al., 2007).

[3] We had previously experimented with stimuli from multi-talkers (male and female voices) but pilot testing with such stimuli led to poor performance of learning for novice tonal language learners, probably due to the challenges posed by additional acoustic dimensions (voice differences due to gender and accents). In the current study we therefore used only a single talker in recording the word stimuli for training.

International Picture Naming Project (Bates et al., 2003) and a similar Chinese normed picture database (Liu, Hao, Li, & Shu, 2011).

Each training session lasted about 30 min, and had a study phase and a test phase. During the study phase, the 48 words were randomly divided into two blocks of 24 words for learning, and the participants were presented with the L2 word–picture pairs of the 48 words for three times. After each block of 24 word–picture pairs, they were asked to complete a mini-test with feedback; in this mini-test, the participants were presented with a word–picture pair and judged whether the association was correct based on their learned L2 word knowledge. After they made their judgments, they were shown the correct word–picture pair on the screen as a feedback, regardless of whether their choice was correct. After the mini-test, participants were refreshed with the 48 words (going through the 48 word–picture associations in random order). During the test phase, participants completed a recall test as well as a recognition test without feedback. In the recognition task, each trial started with a fixation of 500 ms, followed by simultaneous presentation of three candidate pictures lasting 3000 ms while the auditory word was also simultaneously presented (SOA = 0 ms; the duration was normalized to 500 ms for all word stimuli), and participants judged which of the three pictures was the correct association with the heard words. In the recall task, participants were asked to name aloud the English translation of each presented word and their naming latency and recall accuracy were recorded. In the recognition test, the participants heard a learned word and were asked to select the associated picture from three choices based on their training. Their response accuracy in the recognition task during the test phase of each training session was used to indicate their L2 learning success after that training session.

2.3. fMRI procedure

The participants in the learner and non-learner groups took part in a sound discrimination experiment during the pre-training fMRI scan, and then six weeks later the post-training fMRI scan, so that we could track the learning-related neural changes of the learner group when compared against the non-learner group. There were three experimental conditions in the sound discrimination experiment. In the tone discrimination condition (T), participants were presented with pairs of the 48 target words via headphone and were asked to perform a same-different tone judgment using an MRI-compatible response box (Resonance Technology Inc.; *www.mrivideo.com*), to indicate whether the two words in a pair were of the same or different tone regardless of the carrier syllable. In the onset discrimination condition (O), participants were asked to perform a same-different judgment on the onset of a pair of words (initial consonants of a pair of words). The stimuli pairs in tone and onset discrimination conditions were that half of the presented stimulus pairs contained the same tone pattern and the other half different tone pattern, and half of the pairs contained the same initial consonant and the other half different initial consonant. Finally, a nonlinguistic pitch judgment condition (P) was also included, in which the participants were asked to indicate whether the presented pairs of pure tones (low tone, 90 Hz vs. high tone, 100 Hz) were same or different.

For all the three conditions (T, O, and P judgments), participants pressed the right button of the response box with their right thumb for the “same” response and the left button with their left thumb for the “different” response when comparing the two stimuli of T, O, or P during each experimental trial. Each trial began with a fixation of 250 ms, followed by the first sound stimulus (pseudosyllable or pure tone, 500 ms), a short interval (250 ms), and the second stimulus (500 ms), and the participants were asked to indicate their responses within 3000 ms upon the onset of the second stimulus. The total time elapsed for each trial was 4 s (fixation, first stimulus, ISI, second stimulus). Each scanning run included four blocks of experimental conditions (T, O, P), interleaved with 16-s fixation blocks. Each experimental block began with a 2-s instruction followed by six 4-s trials (26 s in total). The order of the blocks was counterbalanced within each run.

The T and O discrimination tasks tested the participants' sensitivity to the segmental or suprasegmental feature of the learned words, which the non-learner participants may be able to complete without training. To examine whether the learner group processed the learned novel words using the tonal information linguistically, we asked the learners (not the non-learners) to complete a second task, the word–picture association judgment task, following the sound discrimination experiment during the post-training scan at T2. In this second task we used an event-related (er-fMRI) design rather than a blocked design as with the sound discrimination task; in the er-fMRI design, participants were presented with a fixation for 250 ms, followed by an auditory word for 500 ms, and then a picture for 2750 ms, and judged whether the auditory word and the picture matched with each other within the 3250 ms (counting from the onset of the picture). Half of the pictures matched the auditory words and the other half did not (all auditory words were among the 48 words that participants learned during training). The inter-trial interval (ITI) for this task was jittered, ranging from 2 s to 10 s, with an average of 6 s. Each of the 48 words used in the training was presented twice, in two separate runs (i.e., no repeat in the same run), so that half (24) were "Yes" trials and half (24) were "No" trials in each run. Participants pressed the right button with their right thumb for "Yes" responses and the left button with their left thumb for "No" responses.

2.4. MRI acquisition

MRI images were acquired on a Siemens Magnetom Trio 3T MRI scanner at the Social, Life, and Engineering Sciences Imaging Center, Pennsylvania State University, using a $T2^*$-weighted gradient-echo EPI sequence (TE = 30 ms; TR = 2 s; flip angle = 90°; matrix size = 80 × 80; FoV = 320 mm). Participants lay supine in the scanner with MRI-compatible VisuaStim Digit headphones for auditory stimulus presentation (Resonance Technology Inc., www.mrivideo.com), and they viewed the visual stimuli via a back-projection mirror, while their heads were immobilized with cushions. Functional images were reconstructed from 34 axial slices, with the thickness of each slice being 4 mm without gap. For each run, the functional scanning was always preceded by 6 s of dummy scans to ensure tissue steady-state magnetization. High-resolution ($1 \times 1 \times 1$ mm^3) anatomical images were acquired using a T1-weighted, 3D inversion-recovery gradient-echo (MP-RAGE) sequence.

2.5. fMRI data analysis

2.5.1. Group activations

Preprocessing of the fMRI data was conducted using the Statistical Parametric Mapping software running under MATLAB (SPM8; Wellcome Department of Imaging Neuroscience, University College London, http://www.fil.ion.ucl.ac.uk/spm) before extracting BOLD time series data from ROIs for connectivity analyses. The first three scans (dummy scans) of each participant's data sets were discarded to allow for T1 equilibration. The remaining volumes were realigned to the first volume, normalized to the EPI template in SPM8 based on the Montreal Neurological Institute (MNI) stereotactic space, and then resampled into $2 \times 2 \times 2$ mm^3 cubic voxels. For each participant, functional images collected from the sound discrimination experiments were grouped into four sets according to the following conditions (see Section 2.4): Tone (T), Onset (O), Pitch (P) and F (fixation). Individual contrast images between experimental conditions (T/O/P) and the baseline condition (F) were assessed for each participant at the pre-training (T1) and the post-training (T2) time points. A two-way ANOVA of 2 × 3 factorial design was further carried out to reveal group differences (learners vs. non-learners) across the tasks at T2. Furthermore, to test the effects of training, learners' contrast images ($T > F$, $O > F$, $P > F$) at T1 and T2 were entered in a 2 × 3 factorial design. Learners' imaging data collected during the er-fMRI word–picture judgment experiment at T2 were preprocessed at the individual level using a similar procedure.

To examine the neural correlates underlying successful second language word learning, we separated the learners into successful learners (SL) group and less successful learners (LSL) group based on their response accuracy in the post-training word–picture judgment task. Participants whose accuracy rates were at or above 96% were categorized as successful learners and those whose accuracy rates were below 96% were classified as less successful learners. To compare the two groups, a 2 (Time: T1 vs. T2) × 2 (Learners: Successful learners vs. Less successful learners) × 3 (Task: Tone, Onset, Pitch) ANOVA factorial analysis was carried out to examine group differences between successful and less successful learners when they performed the word discrimination tasks ($T > F$, $O > F$, $P > F$) at T1 and T2, respectively. In addition, we also compared the two groups of learners when they performed the word–picture judgment task in the second fMRI experiment at T2: a two-samples *t*-test was conducted using contrast images of the experimental condition (word–picture association judgment) and the baseline condition (fixation) from both groups.

All the brain activations reported below survived an FWE-corrected cluster-level threshold (corrected, $p < .05$, number of voxels > 35).

2.5.2. Effective connectivity

Connectivity analyses were conducted on the time series data for the regions of interest (ROIs). Based on our review of the fMRI-based literature on language processing and second language learning (e.g., Ghazi Saidi et al., 2013; Price, 2010; Veroude et al., 2010; Wong et al., 2007; see also Li, Legault, et al., 2014; Li, 2014), we selected six ROIs on the left hemisphere for analyses for the tone discrimination task in the blocked fMRI experiments at T1 and T2, and for the word–picture judgment task in the er-fMRI experiment at T2 only: IFG (*pars opercularis*), middle frontal gyrus (MFG), supplementary motor area (SMA), insula (INS), superior temporal gyri (STG) and inferior parietal lobule (IPL). Averaged time course data of all the voxels within a sphere (i.e. 12 mm radius) in each ROI were extracted from each individual imaging dataset collected in the sound discrimination experiment and the word–picture judgment experiment.

Connectivity among the ROIs during the block-design sound discrimination experiment (T, O, P) at T1 and T2 were determined with the unified structural equation modeling (Gates & Molenaar, 2012; Kim, Zhu, Chang, Bentler, & Ernst, 2007). For the er-fMRI experiment of word–picture judgment task, the connectivity of the six ROIs was modeled with the extended unified SEM (euSEM) (Gates, Molenaar, Hillary, & Slobounov, 2011). The two different versions of the SEM method differ on the following: uSEM could be used to examine contemporaneous and lagged (sequentially) relationships between ROIs in a blocked-fMRI study, whereas euSEM is used for data from er-fMRI studies – the latter builds upon the former but is able to model the task and bilinear effects (i.e., how the relationship between two nodes changes in the presence of the task), in addition to the contemporaneous and time-lagged effects among nodes.

The procedure for using the uSEM and euSEM is similar to that of Yang and Li (2012), but with the addition of the recently developed Group Iterative Multiple Model Estimation (GIMME; https://www.nitrc.org/projects/gimme/), an automatic, freely distributed MATLAB-based program (Mathworks, 2010: *www.mathworks.com*). GIMME has been shown to outperform other methods to date that attempt to model the presence of directed connections among nodes at the group and individual levels (Gates & Molenaar, 2012). As with other SEM-based approaches, GIMME works from individual-level correlation matrices. For the sound discrimination experiment, correlation matrices were created for each of the individuals' ROI time series for the three tasks at T1 and T2, respectively. For the word–picture judgment experiment, the correlation matrices included the six nodes as well as the vector of event onsets and the six bilinear terms of the nodes multiplied by the onset vector. Model selection at the group and individual levels was then conducted with GIMME, implemented in the following steps.

First, Lagrange Multiplier equivalents (i.e., modification indices; Sörbom, 1989) were used to identify which effects (including connections among ROIs and for the euSEM, also the direct and bilinear experimental onset terms), if freed, optimally improved model fits *across all individuals*. The probability of detecting an effect across all individuals was set at 75%; selection of this criterion was informed by empirical and simulated studies on the likelihood of detecting a true effect should it exist in a given sample (Gates & Molenaar, 2012; Hillary, Medaglia, Gates, Molenaar, & Good, 2012). The program iterated until the 75% criterion was met. Second, the model was pruned by eliminating connections that were no longer significant for 75% of the group after other connections were freed. Third, individual-level models were estimated in a semi-confirmatory manner. All connections freed in the group model (described in the two steps above) were freed at the individual level. The automatic search procedure within LISREL then iteratively freed connections that optimally improved model fit, according to the Lagrange Multiplier equivalents (Gates et al., 2010). Finally, the model was pruned by eliminating individual-level connections that became non-significant after other individual-level connections were freed, and a confirmatory model was fit. Model fit parameters found to demonstrate reliability in simulation studies (Gates et al., 2010) and fMRI studies (e.g., Hillary et al., 2012) were chosen *a priori* so that two of the following four criteria were satisfied in the final model: confirmatory fit index (CFI) ≥ 0.90; non-normed fit index (NNFI) ≥ 0.90.

3. Results

Two participants in the learner group and three participants in the non-learner group did not complete the study across the six-week period so their data did not enter into the following behavioral and fMRI analyses that involved comparisons across the fMRI scans at T1 and T2.

3.1. Behavioral results

3.1.1. Learning attainment

For learners, averaged response accuracy for the recognition test on the last training session (18th session) was 85% ($SD = 0.17$), and the mean accuracy for their performance in the word–picture judgment in the T2 fMRI scan was 93% ($SD = 0.11$). The word–picture judgment task was performed by the learners only inside the scanner within one week after they finished the last training session. These recognition and word–picture judgment accuracy rates, although significantly different ($t_{20} = -3.35$, $p < .01$), were highly correlated ($r = 0.85$, $p < .001$). The enhanced performance shown in the word–picture judgment task as compared with their recognition performance might be due to task demand differences (word-to-picture pair matching vs. selecting the correct picture from three candidate pictures). Based on the learners' performance in the word–picture judgment task, 11 learners who achieved over 96% accuracy were classified as successful learners (SL), while the remaining learners were labeled as less successful learners (LSL).

3.1.2. Sound discrimination performance at T1 and T2 (learners and non-learners)

Response Accuracy: A 3 (Group: SL vs. LSL vs. NL) × 2 (Time: T1 vs. T2) × 3 (Task: T, O, P) ANOVA analyses showed significant main effect of Task ($F_{2,\ 62} = 89.9$, $p < .001$) and Group ($F_{1,\ 31} = 14.77$, $p < .001$), but there was no main effect of Time ($F_{1,\ 31}= 2.48$, $p > .05$). Interaction effects between the three variables were all non-significant ($ps > 0.05$). As summarized in Fig. 1a, successful learners, compared to less successful learners, performed more accurately in all three conditions of the sound discrimination task at T2. Furthermore, they outperformed the less successful learners in tone and onset discrimination tasks before training (T1).

Response Time: An ANOVA analysis of response times with the same variables (3 × 2 × 3) showed significant main effect of Task ($F = 141.51$, $p < .001$) but no main effect of Time ($F = 1.01$, $p > .05$) or Group ($F = 2.32$, $p > .05$). Interestingly, only the interaction between Time and Group factors was significant ($F = 4.85$, $p < .05$). As with the accuracy data, we carried out a one-way ANOVA of the response times, and found that the LSL group was significantly slower than the other two groups in all three sound discrimination tasks at T2.

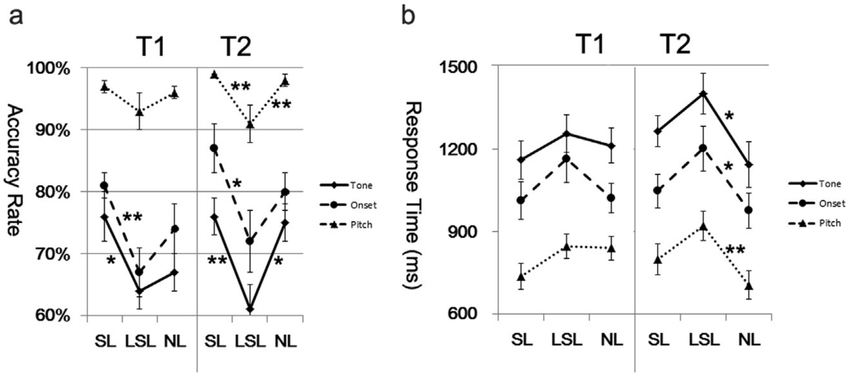

Fig. 1. (a) Response accuracy and (b) and reaction time in sound discrimination tasks at T1 and T2 for successful learners (SL), less successful learners (LSL), and non-learners (NL).

3.1.3. Word–picture association judgment performance at T1 and T2 (successful learners vs. less successful learners)

Independent-samples *t*-tests showed that successful learners on average performed faster in the word–picture judgment task during T2 scan (SL, mean = 1381 ms, SD = 232 vs. LSL, mean = 1509 ms, SD = 202; $t_{19} = -2.97$, $p < .05$). However, the two groups were not significantly different in terms of their response accuracy ($t_{19} = 1.35$, $p > .05$), although there was greater standard deviation in the LSL group (LSL mean = 87%, SD = 0.13) than in the SL group (SL mean = 98%, SD = 0.02).

3.2. fMRI results

3.2.1. Sound discrimination at T2: participants (learners vs. non-learners) × task (T/O/P)

Regardless of types of word discrimination tasks (T/O/P/), learners showed increased neural responses in bilateral posterior middle temporal gyri/angular gyri (BA 39) as compared with the non-learners, consistent with the findings of Mei et al. (2008). Increasing evidence indicates that the posterior middle temporal gyrus and angular gyrus are involved in semantic processing across a range of input modalities (e.g., Binder & Desai, 2011; Price, 2000; Rodd, Davis, & Johnsrude, 2005). Note that the angular gyrus forms part of the inferior parietal lobule (IPL) that we discuss in Sections 3.2 and 4. The greater activation in learners compared with the non-learners is consistent with the function of these structures and may suggest that after training, learners established the meanings of the spoken words and process their semantic information automatically when they were asked to judge the tonal information of the learned words.

To see the group differences more clearly, we further carried out group contrasts in each task condition of the fMRI data at T2. First, with regard to the pitch discrimination, learners and non-learners were not significantly different from each other. This suggests that processing of pitch differences as acoustic information did not differ between the participants. Second, with regard to tone discrimination, learners showed smaller neural responses in the left superior temporal gyrus (BA 22) and left cerebellum as compared to the non-learners. They additionally showed reduced responses in a few regions in the right hemisphere, including middle frontal gyrus (BA 46), insula, fusiform gyrus (BA 37), middle temporal gyrus (BA 21), inferior parietal lobe (BA 40), precuneus (BA 7), putamen, parahippocampal gyrus and cuneus. The reduced responses, especially in the left hemisphere, suggest that the learners are more efficient in processing the tones as linguistic units, consistent with neuroimaging work in prosodic learning and processing (see Wang et al., 2003; Wang, Sereno, & Jongman, 2006; Zhang et al., 2011). Third, in the onset discrimination task, the learners, as compared with the non-learners, showed more activation in the left posterior middle temporal gyrus/angular gyrus (BA 39), consistent with the roles of these structures in semantic processing (see further discussion below in Section 4). On the other hand, the non-learners showed more neural responses in the left inferior frontal gyrus, premotor area, bilateral middle temporal gyri and left superior temporal gyrus (BA 22). The inferior frontal gyrus and premotor areas subserve phonological loop of working memory, which suggest that the non-learners used a rehearsal strategy more than the learners as the tone discrimination task is more demanding for the non-learners (Logie, Venneri, Sala, Redpath, & Marshall, 2003; Smith & Jonides, 1997); bilateral middle temporal gyri and the left superior temporal gyrus are important for phonemic discrimination, especially tone discrimination (Ashtari et al., 2004), implying non-learners compared to the learners were less experienced in discriminating the tones.

3.2.2. Sound discrimination (learners): time (T1 vs. T2) × task (T/O/P)

To see the training effects more clearly, we further compared brain activities during sound discrimination tasks across the pre-training and post-training time points (T1 vs. T2) for the 21 learners (see Table 2). A significant main effect of Time was seen in the left superior temporal gyri (BAs, 41, 42, 22). In particular, for tone discrimination (vs. fixation) the learners showed reduced neural activity in bilateral superior temporal gyri (BA 22), right precentral gyrus and cuneus at T2 compared to T1. In addition, for onset discrimination (vs. fixation), the learners showed reduced neural activity in several regions at T2 compared to T1, including bilateral middle frontal gyri (BA 9), right inferior frontal gyrus (BA 45), right lingual gyrus, left inferior parietal lobe, bilateral insula, and left caudate tail. Finally, for

Table 2
Brain regions that show significant activation differences between learners and non-learners when performing sound discrimination tasks at pre- (T1) and post-training (T2) sessions.

Brain regions[a]	BA	MNI coordinate			Z
		x	y	z	
T2: main effect of group (learners > non-learners)					
Left middle temporal gyrus	39	−44	−72	28	4.71
Right middle temporal gyrus	39	52	−66	26	3.69
Learners' main effect of time (T1 > T2)					
Left medial frontal gyrus	6	−14	8	60	3.8
Right medial frontal gyrus	6	8	−2	66	4.14
Right middle frontal gyrus	6	24	−4	64	4.32
Right middle frontal gyrus	9	38	34	32	3.3
Right inferior frontal gyrus	45	62	12	16	3.21
Right inferior frontal gyrus	44	44	26	2	3.84
Right premotor area	6	46	−4	56	4.06
Left premotor area	6	−52	2	44	3.86
Left supplementary motor area	6	−4	8	66	3.34
Right supplementary motor area	6	2	−2	28	4.21
Left cingulate gyrus	24	−10	12	30	3.36
Right cingulate gyrus	24	2	−2	28	4.21
Left insula	–	−38	−24	18	4.19
Right insula	–	50	12	12	3.59
Left superior temporal gyrus	22	−52	−24	4	4.05
Left superior temporal gyrus	42	−62	−28	12	3.79
Left middle temporal gyrus	21	−50	−24	−6	3.87
T1 > T2 (learners: onset − fixation)					
Right middle temporal gyrus	21	48	−16	−4	5.25
Right superior temporal gyrus	22	56	−14	0	3.84
Right superior temporal gyrus	42	48	−22	8	3.4
T1 > T2 (learners: tone − fixation)					
Left middle temporal gyrus	22	−58	−40	14	4.1
Right middle occipital gyrus	19	36	−84	10	3.24
Left inferior occipital gyrus	19	−28	−84	−6	3.94
Left lingual gyrus	18	−18	−80	−8	2.8
Right cuneus	18	26	−96	18	3.57

[a] All activations reported here were thresholded at cluster level $p < .05$.

pitch discrimination (version fixation), the learners showed reduced neural activity in the anterior cingulate gyrus (BA 32).

3.2.3. Sound discrimination: time (T1 vs.. T2) × learners (SL vs. LSL) × task (T/O/P)

Table 2 shows the results of ANOVA analyses of the learner subgroups (SL > LSL), Time (T1, vs. T2) and Task (T/O/P) factors. These analyses showed that after six weeks of Chinese learning, at T2 the SL group had increased neural activation for tone discrimination than the LSL group, in regions including left SMA (BA 6), left superior temporal gyrus (BA 42), right angular gyrus, right superior parietal lobule and right fusiform gyrus. Bilateral precuneus, lingual gyrus, cuneus and putamen were also more activated in SL compared to LSL during tone discrimination at T2. Activation in these areas might be related to language functions, especially the temporal cortex and angular gyrus. Not surprisingly, SL participants also had more activation than the LSL participants in left inferior frontal gyrus (BA 46, 45) during onset discrimination of the training stimuli due to the role of these areas for phonological processing. In contrast, LSL displayed greater brain activation in bilateral middle occipital lobes during pitch discrimination (Fig. 2b). Compared to LSL, SL engaged more left SMA and left inferior frontal gyrus, which may suggest more automatic recruitment of the articulatory system and phonological

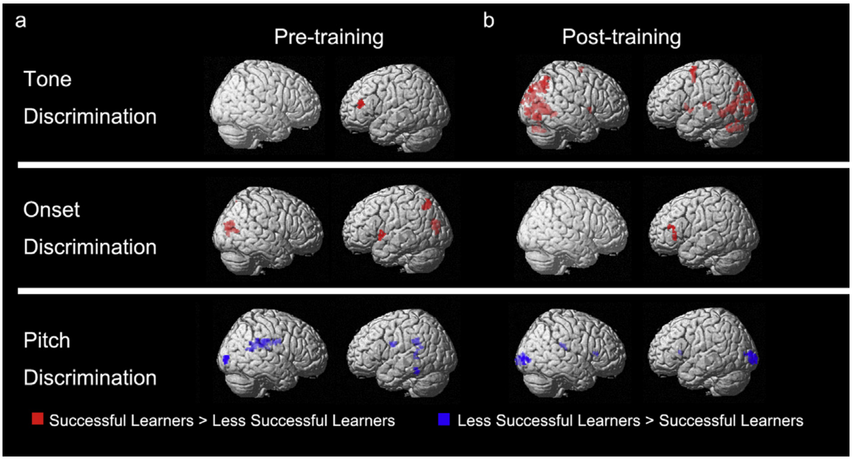

Fig. 2. Brain activations of successful learners (SL) and less successful learners (LSL) in sound discrimination tasks at T1 and T2. Red represents areas in which SL had more neural activity than LSL; blue represents areas in which LSL showed greater neural response than SL. *, $p < .05$; **, $p < .001$.

coding system. Furthermore, the stronger activation in the left superior temporal gyrus (BA42) in the SL group than the LSL group might reflect this region's role in processing phonological information of the lexical tones, consistent with Wong et al. (2007) and Zhang et al. (2011).

We also compared the fMRI data of the two groups at the pre-training session, T1, to examine whether their differences before training were related in any way to the distinct patterns at T2. As illustrated in Fig. 2a, at T1, SL displayed greater neural activity in left middle frontal gyrus (BA 46) during tone discrimination task, and in left superior temporal gyrus, left superior parietal lobe, precuneus and cuneus during onset discrimination task, as compared to LSL. On the other hand, LSL, compared with SL, had more activation in pitch discrimination at T1 in left inferior frontal gyrus (BA 44), right superior temporal gyrus (BA 22), right inferior parietal lobe and left fusiform gyrus (BA 37).

3.2.4. Word–picture association judgment (T2): successful learners (SL) vs. less successful learners (LSL)

Because the word-picture association task was only performed at T2, we wanted to see if SL and LSL participants would differ when they accessed the learned lexical knowledge. We did a two-samples *t*-test with the fMRI data from the two groups. As summarized in Table 3, SL showed stronger brain activations in left inferior frontal gyrus (BA 46), left insula, right lingual gyrus (BA 19) and left cuneus (BA 19). Left inferior frontal gyrus is often associated with semantic encoding and retrieval (for a review, see Fiez, 1997), while the lingual gyrus (BA 19) and left cuneus (BA 19) may also play a role in lexical processing (e.g., Joubert et al., 2004). Activation of these areas may suggest more lexical and semantic processing involved in the SL group compared to the LSL group for the same learned L2 material.

3.3. Effective connectivity analyses

3.3.1. Tone discrimination in SL, LSL and NL at T1 and T2

In addition to the group-level fMRI analyses above, we further conducted effective connectivity analyses to identify the brain network differences that characterize successful second language word learning. This analysis focused on lexical tones, using the method of the unified structural equation modeling (uSEM, Gates et al., 2010, 2011) as described in Section 2.5.2. The original time-series data of six ROIs (nodes; see Section 2.5.2), selected based on previous literature and current findings, were entered in the uSEM analyses. Fig. 3 illustrates the connections of the selected nodes for SL, LSL, and NL when they performed tone discrimination tasks at T1 and T2. Arrows in the connectivity maps

Table 3
Brain regions that show significant activation differences between successful learners (SL) and less successful learners (LSL) when performing sound discrimination tasks at pre- (T1) and post-training (T2) sessions, and when performing the word–picture association judgment task at T2.

Brain regions[a]	BA	MNI coordinate			Z	BA	MNI coordinate			Z
		x	*y*	*z*			*x*	*y*	*z*	
T1: tone discrimination	*SL > LSL*					*LSL > SL*				
Middle frontal gyrus	46	−42	36	20	4.26					
T1: onset discrimination	*SL > LSL*					*LSL > SL*				
Superior temporal gyrus	22	−54	10	−2	4.57					
Superior parietal lobe	7	−26	−66	46	3.91					
Cuneus	17	−4	−82	6	3.46					
	18	6	−76	22	3.82					
T1: pitch discrimination	*SL > LSL*					*LSL > SL*				
Inferior frontal gyrus						44	−32	−2	24	4.22
Superior temporal gyrus						22	32	−52	16	4.87
Inferior parietal lobe[a]						40	34	−32	28	4.36
Fusiform gyrus						37	−46	−40	−16	4.19
Cuneus						18	22	−94	−6	3.42
T2: tone discrimination	*SL > LSL*					*LSL > SL*				
Supplementary motor area (SMA)[a]	6	−22	−2	70	3.53					
Superior temporal gyrus[a]	42	−44	−22	10	3.63					
Middle temporal gyrus/angular gyrus	39	34	42	32	3.99					
Superior parietal lobe	7	40	−64	44	4.03					
Precuneus	7	−6	−76	44	4.38					
	7	18	−66	34	3.58					
Fusiform gyrus	18	24	−80	−12	3.7					
Lingual gyrus	19	−20	−48	−4	4.5					
	19	16	−64	0	4.5					
Superior occipital lobe	19	20	−82	24	4.15					
Cuneus	19	−6	−94	26	4.21					
	19	18	−66	34	3.58					
Cerebellum	–	2	−66	−32	3.94					
	–	−28	−58	−28	3.32					
Putamen	–	−16	8	2	3.41					
Caudate	–	16	10	2	3.86					
T2: onset discrimination	*SL > LSL*					*LSL > SL*				
Middle frontal gyrus[a]	46	−44	32	16	3.9					
Inferior frontal gyrus	45	−46	30	4	3.17					
T2: pitch discrimination tasks	*SL > LSL*					*LSL > SL*				
Middle occipital lobe						18	−24	−92	6	4.91
						18	30	−92	2	4.23
T2: word–picture association	*SL > LSL*					*LSL > SL*				
Inferior frontal gyrus[a]	45	−38	34	12	4.07					
Insula	–	−38	2	2	3.6					
Lingual gyrus	19	20	−70	28	3.92					
Cuneus	19	−8	−86	28	4.6					

[a] Indicates brain region on the left hemisphere that were selected as ROI in the effective connectivity analyses. All activations reported here were thresholded at cluster level $p < .05$.

represent the BOLD activity in one ROI that statistically predicts BOLD activity in another ROI: arrow widths indicate connection strength, and directions of arrows indicate the influence that goes from one node to the other. In addition, all the lines represent contemporaneous relations, after controlling for time-lagged relations. Finally, blue lines indicate node relationships at T1, while orange lines indicate node relationships at T2.

As shown in Fig. 3, at T1, the six ROIs were not much connected or related for the brain networks of the LSL and NL groups: the only connection seen was the influence from left IFG to left MFG. However, for the SL group, the six nodes were closely connected even at T1: in addition to influences from left IFG to MFG, the MFG influences INS, which then feeds to STG; STG forwards information to the IFG and thus forms a complete frontal-temporal network. Left SMA served as an extra relay station for this MFG-dominated network: SMA influences both MFG and IPL, whereas IPL does not connect with the other four regions. The medial and ventral area of the frontal pole has been reported to have connections with the thalamus, occipital extrastriate cortex and temporal cortex. These direct connections might be bidirectional and subserve fast forward access of sensory information to anterior frontal cortex and bottom-up perceptual processes. We speculate that the connections from frontal regions to the temporal areas are involved in encoding novel words or processing feedback information (Catani et al., 2012). At the same time, there is a connection from frontal regions to the IPL via SMA, which may reflect a network that the SL group uses for phonological working memory and lexical phonological retrieval, given the important roles of these regions in this regard (see further discussions in Sections 3.3.2 and 4).

At T2, when performing the same tone discrimination task, the NL group showed increased connections between MFG, IFG, STG and INS, while SMA and IPL were both isolated in the network. The increased connections in the NL group might reflect a practice effect, as they were tested with the same materials over T1 and T2 (although there was a six-week interval). As compared with the NL group, the LSL group showed a more closely related network after training: INS sends its influence to SMA, STG, and MFG respectively and MFG also influences IFG directly. It seems that after training, the brain network for tone discrimination for the LSL group was largely controlled by the INS. In contrast, the SL group displayed a more coherent and connected brain network, as compared with the LSL and NL groups: as with the LSL group, the hub of the network, the INS, has an influence on the STG, which then feeds to the MFG; INS forwards information to the IPL, which sends influence to MFG; MFG also has a large impact on IFG. However, the SMA to IFG influence is only seen in the SL group. Somewhat surprisingly, we would expect the STG to play a more important role in the SL group (in light of the data from Wong et al., 2007) but this was not the case.

Taken together, these data indicate that successful learners have a more coherent multi-path network compared to less successful learners and non-learners. One pattern to note here is that the insula, which was a relay station before training in SL group, became the hub of the network at T2, connecting posterior temporal and parietal regions with frontal areas. Another interesting pattern to note is that the SL, LSL and NL groups all showed stronger MFG and IFG connections, although with different directions at different times: at T1, MFG feeds to IFG, whereas at T2, IFG influences MFG. We

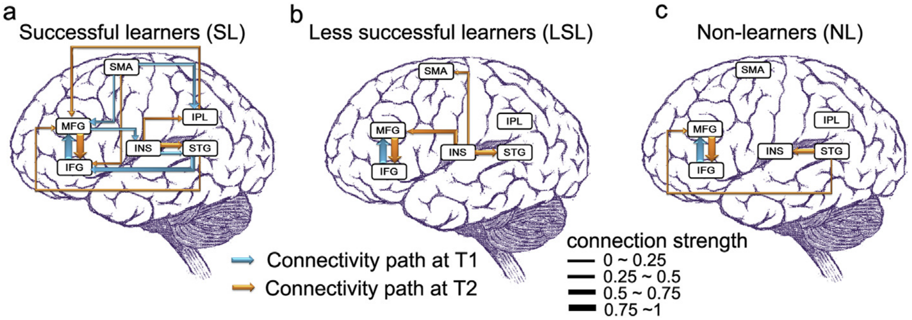

Fig. 3. Effective connectivity maps based on six ROIs in (a) successful learners (SL), (b) less successful learners (LSL) and (c) non-learners (NL) when they performed tone discrimination at T1 and T2. Arrows in the connectivity maps represent the BOLD activity in one ROI that statistically predicts BOLD activity in another ROI: arrow widths indicate connection strength, and direction of arrows indicate the influence that goes from one node to the other. In addition, all the lines represent contemporaneous relations, after controlling for time-lagged relations. Blue lines indicate relationships at T1, while orange lines indicate influences at T2. IFG, inferior frontal gyrus; MFG, middle frontal gyrus; SMA, supplementary motor area; INS, insula; STG, superior temporal gyrus; IPL, inferior parietal lobule.

speculate that these local connections in frontal areas may be involved in bottom-up perceptual processing at T1 and top-down modulation at T2 as all three groups were tested with the same set of stimuli twice.

3.3.2. Word–picture judgment in SL and LSL groups at T2

To reveal brain network differences between processing of tonal information and lexical-semantic information of the learned words, we also conducted effective connectivity analyses of the fMRI data from SL and LSL learners when they made word–picture judgments at T2, using the same six ROIs as the network's nodes. The word–picture judgment task likely involved participant's access of the lexical knowledge of the trained words, which may differ from the sound discrimination tasks discussed above.

As shown in Fig. 4a, for the SL group, MFG directly and positively influences the neural responses at the IPL, INS and IFG; IFG then feeds to SMA and indirectly modulates the neural responses of IPL. As in the network for tone discrimination for the SL learners at T2, STG shows a direct influence on the neural responses at MFG, suggesting the importance of feedback from STG during lexical processing. In Fig. 4b, for the LSL group, it seems that the MFG is the hub in modulating the brain network for information processing: MFG feeds to IFG, and IFG, in return, feeds to the INS, which influences STG; MFG also directly influences IPL and SMA, the latter of which passes information to INS directly. The strong reliance on the MFG for the LSL group suggests that these learners may be recruiting this area for cognitive control purpose, as MFG and its adjacent areas have been implicated in working memory and other control tasks (Cohen et al., 1993; Hopfinger, Buonocore, & Mangun, 2000).

Comparison of patterns in Figs. 3 and 4 indicates that successful and less successful learners differ from each other in their brain networks for processing lexical semantic information vs. tonal information, and this difference occurred even at T1 before training. For example, the strong direct connection between STG and MFG in the SL group (which is missing in the LSL group) might reflect the particularly important role of this connection for auditory word learning and retrieval. Another important pattern is that in the tonal processing networks (see Fig. 3a–c), the IPL played no major role (except for the SL group), whereas in the lexical processing networks (Fig. 4a–b), IPL is well connected with MFG, STG, or SMA (more so for the SL group than the LSL group). This pattern highlights the role of IPL in that the participants, especially the SL learners, may be actively engaging the lexical-phonological representations of learned words in the word–picture judgment but not in the sound discrimination task (see Discussion below on the role of IPL in second language lexical learning). In short, these data indicate that learning of new L2 words helps learners to achieve a well-connected and

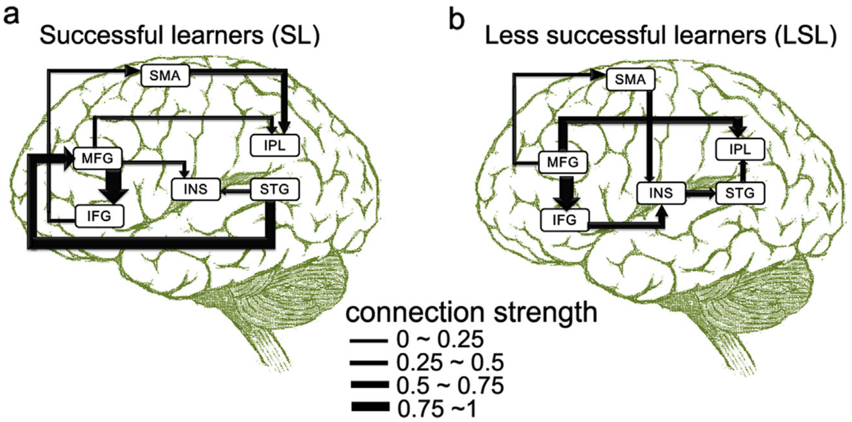

Fig. 4. Effective connectivity maps based on six ROIs in (a) successful learners (SL) and (b) less successful learners (LSL) when they performed the word–picture association judgment task at T2. IFG, inferior frontal gyrus; MFG, middle frontal gyrus; SMA, supplementary motor area; INS, insula; STG, superior temporal gyrus; IPL, inferior parietal lobule. Solid lines represent positive influence; negative influences from one node to another (from IFG to MFG and SMA) in SL are not shown here.

efficient neural network, and the more successful the learning, the more connected the network may be (e.g., comparing Fig. 4a with 4b).

4. Discussion

The purpose of the present study was to examine neurocognitive signatures of successful learning of new vocabulary in a second language. Toward this goal, we wanted to track the functional brain changes induced by the learning of novel words of a tonal language that resembles the phonological structure of Mandarin Chinese.

In our experimental design, we had two groups of participants, the learners who were trained to learn 48 novel words in a six-week session, and the non-learners who, in the same period, did not receive any novel word training. We used a pre-vs. post-training paradigm to test both groups of participants at two time points, T1 (pre-training) and T2 (post-training). First, with regard to the behavioral data, the pattern was somewhat counter-intuitive: the successful learners and the non-learners did not differ significantly in their sound discrimination abilities before and after training, whereas the less successful learners performed much worse than the non-learners at T2 (in both accuracy rate and response time). The lack of differences between SL group and NL group may be due to the following reason. Our training did not focus on the sound discrimination ability, thus the behavioral performance of learners may not improve significantly in the sound discrimination task; instead, it is possible that the less successful learners invoked more cognitive resources to handle lexical processing, compared to the non-learners. However, despite the lack of differences between learners and non-learners in their behavioral performance, their brain activation patterns differed significantly. Specifically, the learners, as compared with the non-learners, showed increased activation in bilateral posterior middle temporal gyri/angular gyri (BA 39) in the sound discrimination tasks at T2. Left posterior middle temporal gyrus (pMTG) is reliably found to be active across a wide range of semantic tasks (e.g., Price, 2000; Rodd et al., 2005). Angular gyrus also has been implicated in tasks involving semantic processing, word reading, number processing, and memory retrieval (see Seghier, 2013 for review), and is also a critical area related to lexical and conceptual processing (Binder & Desai, 2011; Mechelli et al., 2004; Price, 2010). Increased activation of bilateral pMTG/angular gyrus for our learners at T2 suggests that the learners are treating tonal information as lexical information that has semantic contents, consistent with previous findings with L2 learning of Chinese tones (Mei et al., 2008; Wang et al., 2003, 2006) and processing of tones in native speakers (Zhang et al., 2011). This pattern contrasts with the non-learners, who can only treat tonal information at an acoustic level and therefore showed more neural responses compared to the learners in left superior temporal gyrus (BA 22).

To identify individual differences in learning, we further divided the learners into successful (SL) and less successful (LSL) groups based on their lexical knowledge of the learned words. In the behavioral data, SL performed more accurately than LSL in discriminations of tone, consonant onset, and pitch after training. Interestingly, even before training, the two groups showed differences: the SL group performed better than LSL in discriminating tones and onsets, although not pitch. This may suggest that the SL learners are well suited to learning a vocabulary in which lexical tones make up the critical information.

The effects of training on the brain can be identified by examining the differences in brain activation between T1 and T2. In general, compared to non-learners, the learners showed decreased activation in bilateral medial, middle and inferior frontal gyri, supplementary motor areas, anterior cingulate cortex, insula, and middle temporal gyri (BA 22) at T2 than at T1. It is well documented that decreases of brain activation tend to be associated with increases in cognitive skills, including enhanced language proficiency or motor skills (Chee et al., 2001; Seitz & Roland, 1992; see Hernandez, 2013; Patel, Spreng, & Turner, 2013 for reviews).

One important area for phonological processing, the left posterior superior temporal gyrus (BA 22), also showed less activation at T2 than at T1 for our learners, and when learners were compared to the non-learners at T2. This decrease differed from the pattern observed in Wang et al. (2003) and Wong et al. (2007) who found an increase pSTG in general with increased proficiency for tones. However, in Wang et al. (2003), the most successful learner, compared to other learners, did show a decreased activation in this brain region. To understand the decrease rather than increase of activation in pSTG, we compared the SL and LSL learners at T2, and found that the SL group activated a more extensive network, including the left middle frontal gyrus, superior temporal gyrus (BA 42), fusiform gyrus, precuneus, lingual gyrus, cerebellum, and the putamen. By contrast, LSL learners had more neural activity in bilateral occipital lobes than SL at both T1 and T2 for non-linguistic pitch processing. The decreased activation including the STG in our data of the SL group, as compared with the more focused and increased activation as in Wong et al. (2007), may be partly due to the different tasks involved in the two studies (more vs. fewer words to be learned, longer vs. shorter duration). It is also possible that the SL group became more efficient in phonological processing of the novel words and therefore automatically engaged semantic processing. However, such discrepancies in terms of activation increases or decreases need to be further studied.

To specifically capture individual differences in the learner groups (SL vs. LSL), in this study we also identified the brain networks that characterize successful second language word learning. We performed effective connectivity analyses of the key brain regions by comparing the SL and LSL learners, before (T1) and after training (T2). Our brain network analyses revealed several important findings in this regard.

First, SL learners and LSL learners recruit different networks and hubs to handle the same lexical task, as revealed in Figs. 3 and 4. What's more surprising is that our connectivity analyses indicate that the two groups show differences in their brain networks even when L2 learning experience has not yet begun. The SL group not only demonstrate a more integrated brain network at T2, but also a better connected network at T1: the connections between IFG, MFG, and STG indicates a frontal-temporal network at work at T1. Thus, the SL learners may have a system that provides fast forward access of sensory information to frontal and temporal cortical regions for information processing. Using such a network approach, we may be able to predict as well as to differentiate the good learners from the poor learners.

Second, a more coherent and integrated brain network underlies successful second language learning, as compared with less successful learning or non-learning. At T2, the brain network of the SL group during tone discrimination is characterized by both local and global integration: anterior and posterior brain regions are not only connected by key hub nodes, such as SMA and INS, but also communicate with each other directly, such as the feedback from STG to MFG, and from IPL to MFG. This multi-path feature of brain network provides the SL group more efficiency and flexibility in the learning of a new vocabulary. However, for the LSL group, in the same tone discrimination task, the IPL, important for phonological representation of learned novel words, is isolated from the other nodes; and the posterior regions have no direct communication with the frontal areas, which suggest a less efficient and integrated network in the LSL group. Our findings are in general consistent with those from Sheppard et al. (2012), although the two studies are based on different network analytics.

Finally, lexical processing of acquired word knowledge relies on the path between MFG and IPL. When the SL participants process the tonal information of novel words in the tone discrimination task, they automatically activate lexical knowledge with IPL sending information to MFG; LSL learners, on the other hand, lack this automatic connection. In the word–picture judgment task, when learners perform lexical processing of the learned words, MFG sends retrieval order to IPL for both SL and LSL groups. As lexical retrieval is more demanding for the LSL group, the positive influence from MFG to IPL in LSL group is larger than that in the SL group. The IPL consists of two adjacent regions at a macroanatomical level: the supramarginal gyrus and the angular gyrus, and our data are consistent with the important role of IPL in lexical learning that has been previously documented in the literature. There is now increasing evidence that the left IPL (and to a certain degree the right IPL) plays a key role in lexical phonological representation, semantic integration, and second language vocabulary learning (Abutalebi, Canini, Della Rosa, Green, & Weekes, this volume; Della Rosa et al., 2013; Mechelli et al., 2004; Richardson & Price, 2009; Veroude et al., 2010; see Li, Legault, et al., 2014; Li, 2014 for reviews). The importance of IPL could also be related to the function of this region for phonological working memory (see Baddeley, 2003), which is critical for the formation and maintenance of lexical representations that in turn helps the acquisition of novel words in a new language (see Baddeley, Gathercole, & Papagno, 1998).

Taken together, the present study presents a first systematic attempt to identify the brain networks underlying successful (vs. less successful) second language word learning with a short-term training paradigm. Learning of a new language in adulthood involves a great deal of cognitive and linguistic efforts. The neurocognitive approach and the novel word learning paradigm (in a pre-vs.-post-training comparison) used here may allow us to capture the neural changes that accompany L2 learning experience, while at the same time identifying the neural correlates of individual differences in the learning of vocabularies in a new language.

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