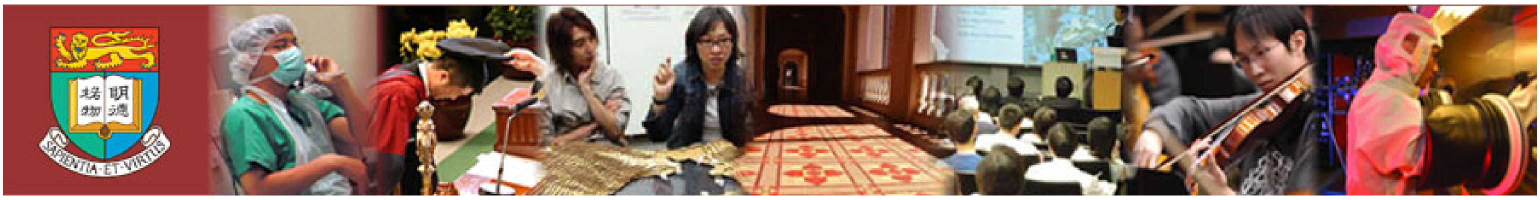

Second language naming predicts left temporal pole integrity in aging bilinguals

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Abstract

There is numerous of evidence showing the left temporal pole (TP) is involved specifically in object naming. It is believed which functions as a semantic hub (Lambon Ralph & Patterson, 2008) and is involved in lexical retrieval (Tranel, 2009). Interestingly, both naming ability and TP grey matter values deteriorate with age. In this study, we investigated the effect of increased proficiency in the first language (L1) and second language (L2) on TP structural values in healthy bilingual seniors. Thirty-six healthy bilinguals (55 to 78 age-old) were selected within the multilingual population in Hong Kong. They underwent structural MRI and the grey matter density (GMD) were analysed using Voxel-based Morphometry approach. Their bilingual demographic characteristics were examined and regressed with the structural values. The results indicated an age effect on the left TP, and a negative correlation between local GM values and the overall naming performance. Surprisingly, this correlation was significant only for naming in L2 but not L1. These suggest that there is a universal structural decline in the left TP for both monolingual and bilingual speakers. And, with better L2 naming, the left TP may be better tuned. This may induces structural benefits and protection effect against healthy aging.

Second language naming predicts left temporal pole integrity in aging bilinguals

Neural plasticity has long been reported in response to specific experience such as musical skills (Bermudez, Lerch, Evans, & Zatorre, 2009) and mathematic skills (Aydin et al., 2007). Recent research has also shown that using a second language with increased proficiency, or actually being a bilingual speaker, can also induce brain plasticity (Mechelli et al., 2004; Abutalebi et al., 2013; Della Rosa et al., 2013).

Bilinguals are people who can use two languages in daily communication (Grosjean, 2010). Given this definition, bilingual speakers enjoy a greater total lexicon pool than monolingual peers. To become bilingual, an individual needs to acquire words in a second language (L2) and it is assumed that such learning forms links with extant vocabulary of the first language (L1) and semantic knowledge (Kroll & Stewart, 1994). This increased vocabulary learning induces neurostructural advantages in bilinguals (Richardson, Thomas, Filipii, Harth, & Price, 2010). Besides these additional cognitive processes, bilingual speakers often need to switch between languages flexibly and quickly according to the discourse context. This enhanced capacity to switch between languages is believed to result in greater neurocognitive reserve and brain volume for bilinguals compared to monolinguals who are similar in age, education and socio-economic status (SES) (Abutalebi et al., 2012). The hypothesis of greater neuroplasticity for bilingual speakers will be tested in this project.

Evidence for the hypothesis of greater neuroplasticity in bilingual speakers comes from functional magnetic resonance imaging (fMRI) studies. Several studies have revealed neural adaptations in bilinguals during language and non-linguistic task switching in brain areas that are used in monolingual speakers for articulation and phonological processing (left putamen) (Abutalebi et al., in press), conflict monitoring (anterior cingulate cortex) (Abutalebi et al., 2012) and language control (left caudate nucleus) (Zou, Ding, Abutalebi, Shu, & Peng, 2011). Garbin et al. (2010) also reported that bilinguals can recruit language control regions (left inferior frontal cortex/ left striatum) in non-linguistic switching tasks for better performance. Supporting evidence comes from structural imaging studies reporting evidence of a bilingual brain volume effect in terms of increased grey matter volume (GMV) and grey matter density (GMD) in areas involving language learning and control such as the anterior cingulate cortex (AAC) (Abutalebi et al., 2012), the putamen (Abutalebi et al., in press), the left inferior frontal region (Garbin et al., 2010), the caudate (Zou et al., 2012), the inferior parietal region (Mechelli et al., 2004), the dorsolateral prefrontal cortex (Abutalebi & Green, 2007) and the supramarginal gyrus (SMG) (Richardson et al., 2010).

Among studies comparing bilinguals directly to monolinguals, Mechelli et al. (2004) reported that bilinguals had greater grey matter density in the left inferior parietal cortex than the monolinguals, with a similar trend in the right hemisphere. This suggests that the human brain can be altered by experience of learning a second language. Abutalebi et al. (in press) also report that the grey matter density in the left putamen of multilinguals was significantly greater than their monolinguals. They proposed a role for the putamen in processing complex articulatory repertoire, which is necessary for fluent multilingualism that actually induces structural brain plasticity. In a longitudinal study involving learning a second language, Stein et al. (2012) monitored ten English speaking students who started learning German. The authors compared the participants' grey matter before and after learning in specific brain areas. They found an increase in grey matter density in the left inferior frontal gyrus (LIFG) and left anterior temporal lobe (LATL) for the students after learning German for 133-224 days. The increase in GMD was also correlated with the increase in German proficiency. These studies provide evidence on both functional and structural adaptations in different brain areas for fine-tuning as result from learning a second language. Somewhat surprisingly, Zou et al. (2012) compared 14 Chinese verbal-Chinese sign language bilinguals with 13 matched monolinguals and found increased grey matter volume in the head of left caudate nucleus. Thus, regardless of language modality, bilingualism can result in neuro-structural advantages and does not depend on speech.

The finding of greater brain volume in selected neural regions supports the hypothesis of neuroplasticity in bilingual speakers. Yet, there is another crucial brain area for language, the temporal lobe, which is a likely candidate to show neuroplasticity in bilingual speakers. The human temporal lobe has long been regarded as the main site for declarative memory system including semantic memory and episodic memory. Furthermore, prior studies have proposed separate functional roles played by different regions in the declarative memory system, with the medial temporal lobe involving mainly episodic memory and the anterior temporal lobe involving mainly semantic memory (Kapur & Brooks, 1999).

A specific region of interest for spoken word production is the anterior temporal lobe. The anterior temporal lobe (ATL) consists of several anatomically distinct regions including the fusiform gyrus, inferior temporal gyrus, temporal pole, superior temporal gyrus and medial temporal gyrus. Decades of research on ATL using neuroimaging techniques (Mummery, Patterson, Price, Frackowiak, & Hodges, 2000; Nestor, Fryer, & Hodges, 2006), transcranial magnetic stimulation (TMS) (Lambon Ralph, Pobric, & Jefferies, 2009; Pobric, Jefferies, & Lambon Ralph, 2007), cases of semantic dementia (Mummery et al., 2000; Rogers et al., 2004) and epilepsy cases with and without resection (Lambon Ralph, McClelland, Patterson, Galton, & Hodges, 2001; Lambon Ralph & Patterson, 2008) revealed critical involvement of the region, bilaterally, in tasks such as verbal fluency, picture naming, drawing and object manipulation as well as in tasks involving episodic memory. By contrast, the ATL is not associated with procedural and working memory, and seems specifically linked with the declarative memory system (Lambon Ralph & Patterson, 2008; Lambon Ralph et al., 2009).

Within the ATL, the temporal pole (TP) is the rostralmost portion of the temporal lobe. It has also been labeled as the temporopolar cortex, BA38 and area TG. Lambon Ralph et al.

(2009) used rTMS to study the role of TP, bilaterally, in the semantic conceptual processing. They found that inhibiting TP activity temporarily resulted in reduced semantic performance. The authors proposed that TP bilaterally forms a vital substrate within the neural system that supports conceptual processing. Indeed, there are numerous reports of associations between TP lesions and anomia (Mummery et al., 2000; Tsapkini, Frangakis, & Hillis, 2011), a language disorder characterized by a specific word retrieval deficit. These strands of evidence converge on the critical participation of TP to function as a semantic hub and involve in word retrieval in the lexico-semantic system. Given that bilingualism depends on this system, it is likely that a bilingual brain volume effect will be observed in the TP region.

One known feature of the declarative memory system is reduced performance with age specifically reduced object naming, recalling and rapid learning ability. This is in association with reported evidence of effects of aging on temporal regions including TP. These processes are not a consequence of pathology since normal aging results in grey matter volume atrophy and cortical thinning in the whole temporal lobe demonstrated in cross-sectional studies (Bartzokis et al., 2001; Fjell et al., 2009b) and longitudinal studies (Driscoll et al., 2009; Scahill et al., 2003). Allen, Bruss, Brown and Damasio (2005) used high-resolution MRI to investigate the changes in grey matter in regions of interest (ROIs) including the TP and found accelerated decrease in grey matter volume in the TP for participants over the age of 70, fitting into a cubic regression model. Fjell et al. (2009a) also reported TP to be a region with the greatest reduction in grey matter volume (-0.56%) among all cortical regions in their one-year longitudinal study of healthy elderly participants.

An influential cognitive study by Bialystok and colleagues (2004) compared executive control performance of middle-aged and senior monolingual and bilingual adults using the Simon task. Healthy seniors typically show a greater Simon effect than young controls. The results of the study showed not only a smaller Simon effect for bilingual speakers, but also less increase in the Simon effect with aging in bilinguals when compared to monolinguals. This suggests that bilingualism can serve to lower any negative effects of aging on executive control performance. Two questions that arise from the Bialystok study are how the bilingual effect is manifest as a protective mechanism in the brain and consequently whether the effect is associated with neuroplasticity. Very little is known about interactions between bilingual effects at neurostructural level and normal aging. For instance, we do not know if there are any bilingual advantages that last as we age, and more specifically whether temporal regions are susceptible to age-related atrophy. It is also not clear whether any bilingual demographic characteristics can explain any TP neuroplasticity in addition to bilingual language use per se.

The aim of the current study is to understand how bilingual language experience shapes TP in bilingual speaking seniors with varying L2 proficiency. Our research questions are: 1) Is age-related TP atrophy in bilinguals similar to the pattern reported for monolinguals?, and

2) Does L2 proficiency predict age-related TP atrophy? With regard to the first question, we hypothesized that GM density in TP of bilingual speakers would decline with age, similar to monolinguals. With regard to the second question, we expected bilingual speakers to have a greater need for control in lexical retrieval with different languages during communication and a richer lexical-semantic network containing word representations from two languages. The increased control may practice and tune up the TP, and ultimately lessen aging effects on the TP. With higher L2 proficiency, the increase in lexicon size and semantic processing may be even larger, possibly leading to greater structural advantage and protection against aging. Hence, we hypothesized greater second language proficiency would predict GM values in TP.

Methods

Participants

Thirty-six healthy senior Chinese bilingual speakers (16 males, mean age = 64.25, *SD* = 6.83, ranging in age from 55 to 78 years old; 32 right-handed, three left-handed and one ambidextrous according to the Edinburgh Inventory) were recruited from the multilingual population in Hong Kong. Seventeen bilinguals were native residents whose L1 and L2 were Cantonese and English, respectively. Nineteen were previous immigrants from Mainland China. Fourteen spoke Mandarin as L1 and Cantonese as L2, and vice versa for others. Participants with medical history of head injury, neurological or psychiatric illnesses were excluded. All participants had normal or correct-to-normal vision and hearing, and were screened with the mini–mental state examination (MMSE, Folstein et al., 1975). The study was approved by the Human Research Ethics Committee for Non-Clinical Faculties of the University of Hong Kong. Written informed consent was required and obtained from all participants. They were paid with $150 HK dollar plus transportation allowance.

Behavioral measures

Questionnaires. Participants were required to complete a detailed questionnaire about their SES, education level and language backgrounds including the age of second language acquisition and frequency of daily exposure to each language spoken (Cantonese, English and Mandarin) for subsequent correlations with the GM values (see Appendix C and D).

Language proficiency. Object naming tasks were presented in the first acquired language (L1) and the second acquired language (L2) (see Appendix A for stimuli). Three sets of stimuli consisting different types of colored pictures (n = 30) comprising fruit and vegetables, animals and man-made objects matched for concept familiarity and visual complexity, were selected from the revised version of the Snodgrass and Vanderwart picture set (Rossion & Pourtois, 2004). Participants were invited to name items when presented for a two-second interval. An oral translation task from L1 to L2 was also administered. The text to be translated was 66 words long including low, medium and high frequency words without time constraint; word frequencies were also matched across languages (Appendix B).

MR Acquisition

MR images were acquired using a 3-T Achieva Philips MR scanner (Philips Medical Systems, Best, NL) equipped with an 8-channel head receive-only coil at the 3T MRI center of the University of Hong Kong. An axial high-resolution structural MRI scan was obtained for each participants (magnetization prepared rapid gradient echo, 150 slice T_1-weighted image, TR = 8.03 ms, TE = 4.1 ms; flip angle = 8°, FOV = 250mm x 250mm, matrix = 256, TA = 9.35 min, mode = 3D FFE, sense factor = 1, NSA = 1, resolution = 1 x 1 x 1 mm). Structural brain images were acquired and analyzed using voxel-based morphometry.

Data and statistical analysis

Voxel-based morphometry (VBM)

VBM was used with the VBM8 SPM8's toolbox (Wellcome Department of Imaging Neuroscience Group, London, UK), running on Matlab 7.6 (R2008a) (Mathworks, Natick, MA) to extract the grey matter value at different brain areas in the bilingual speakers. This approach can provide high sensitivity for localizing relatively regional and small scaled difference in brain tissue such as white and grey matter, and has been widely used in structural neural analysis (Mechelli et al., 2005). Preprocessing procedures to enhance sharpness for further segmentation included the following: 1) visual inspection on MR images; 2) automatic reorientation of structural images; 3) structural image segmentation; 4) application of DARTEL approach for further normalization and modulation.

Firstly, images were visually inspected to check for possible scan issues such as field distortion and movement artifacts, and origin was set to match the AC-PC line; one participant was excluded at this point due to a huge loss of signal in the occipital region, leaving 35 participants. Secondly, an automated Matlab script was used to align images according to the origin and orientation of the default GM tissue probability map (TPM) to maximize overlay between each structural scan and the TPM and thus increase segmentation accuracy. Thirdly, reoriented images were then segmented into grey matter, white matter and cerebro-spinal fluid according to the VBM8 tissue probability maps and registered to the East Asian brains ICBM space template through affine regularization (Mazziotta et al., 2001). Lastly, the GM segments were input into high-dimensional DARTEL to create non-linear modulated normalized GM images. The segmentation procedure was further refined by a denoising procedure applying a spatially adaptive nonlocal means filter (Manjon, Coupé, Marti-Bonmati, Collins, & Robles, 2010) and through a classical Markov random field approach. GM maps homogeneity was finally inspected by crossing all participants in a 35x35 covariance matrix. One participant was excluded as his GM map distance from the remaining participants exceeded 2 SDs, leaving us with a sample of 34 participants (14 males, mean age = 64.15, *SD* = 6.39, ranging in age from 55 to 77 years old). Non-linear modulated-normalized images were finally smoothed using a Gaussian Kernel with a full width at half maximum of 8mm, increasing statistical validity.

Correlational analysis

Smoothed non-linear modulated normalized images were then entered into a multiple regression analysis using age and education as covariates for testing any associations between the demographic characteristics of 34 bilingual participants and changes of GM. GM changes were regarded as significant if they reached a statistical threshold of 0.05 familywise error (FWE) corrected voxel-wise. Then, given our hypothesis that increased L2 proficiency can tune up the temporal region, and maintain brain plasticity despite aging, we extracted the GM values in our region of interest (TP), and correlated these with picture naming scores in L1 and L2 respectively to assess which predict age-related GM change in it.

Results

Behavioral Results

On average, participants acquired their L2 at the mean age of 18.18 (*SD* = 13.51), and received 13.44 (*SD* = 4.67) years of education. Daily language exposure was 7.14 (*SD* = 5.01) and 6.41 (*SD* = 5.80) hours respectively for L1 and L2, which were not significantly different from each other ($t < 1$). For the picture naming tasks, the mean accuracy was 77.45% (*SD* = 13.68%, ranged from 50% to 100%) for L1 and 59.9% (*SD* = 17.44%, ranged from 20% to 90%) for L2. Performance in L1 was significantly better than in L2, $t(33) = 4.91$, $p < .001$. Mean translation performance was 80% (*SD* = 20.15%) indicating relatively proficient bilingualism without time constraint.

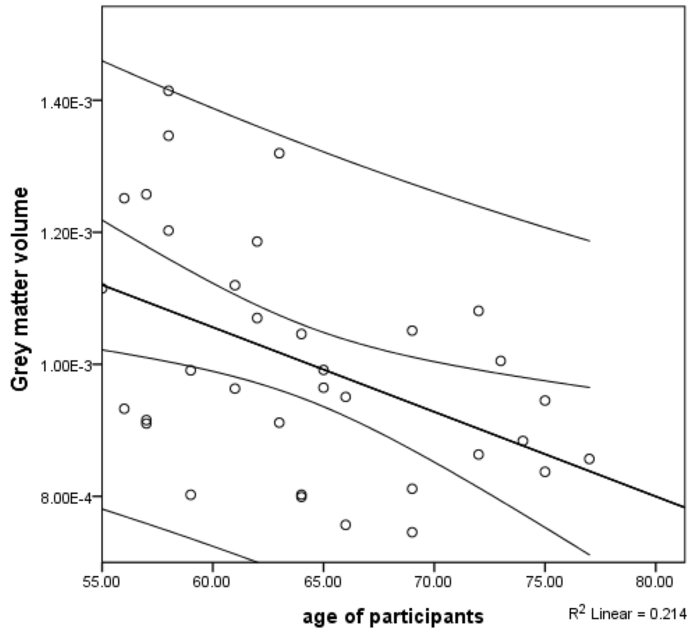

Figure 1. Scatter plot with mean and individual confidence intervals (CI) between age of the bilingual participants and the left temporal pole ROI grey matter volume (r = -0.462, p < .01).

Age-related GM density changes

As expected, a multiple regression analysis using Statistical Parametric Mapping (SPM) showed a significant effect of age on GM density in the left TP (peak coordinate: x = -42, y = 18, z = -32, corrected FWE p < .05) with age and education as covariates, specifically in the direction of young participants showing greater GMD in this area (see Figure 1 and 2).

GM values extraction and correlations with naming performance

We defined ROI by calculating median values of coordinates previously reported in the literature based on TP activity across a variety of tasks (Lambon Ralph et al., 2009; Pobric, Jefferies, & Lambon Ralph, 2010) but with a clear focus on picture naming effects (Price et al., 2005) highlighted in the TP within a specific range of coordinates on the x (-48 to -44), y (8 to 10) and z plane (-30 to -20).

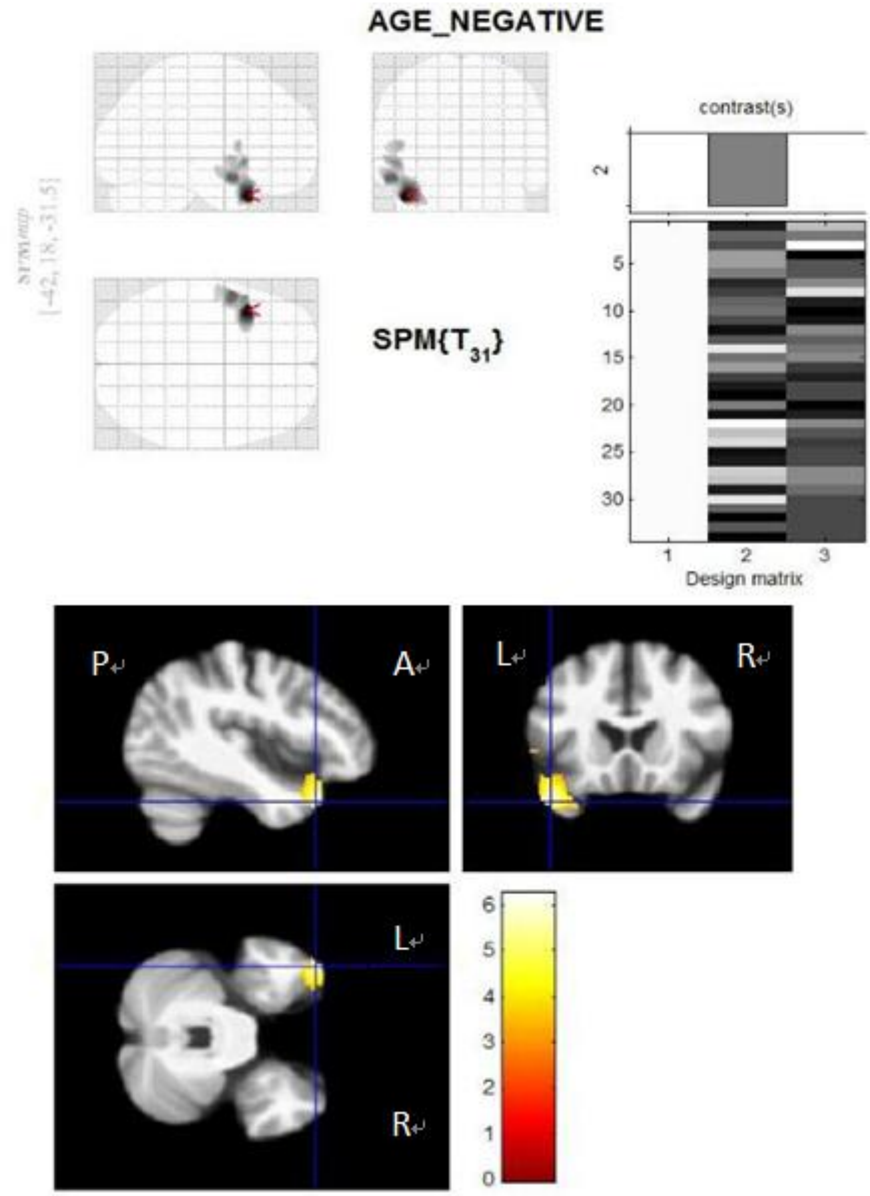

Figure 2. Correlation between age of participants and the grey matter density at temporal pole was tested in a voxel-based manner. From SPM, local gray matter density of left temporal pole showed a significant negative correlation with the age of participants. The peak coordinates in the left temporal pole were x = −42, y = 18, z = −32. At this point, T value was 6.25, and the cluster extent was 1730 voxels. R, L, A, and P indicate the right, left, anterior, and posterior sides of the participants, respectively. The color bar represents the T score.

We then extracted grey matter volumes (in litres) using the SPM5 Easy Volume toolbox from an 8mm spherical ROI centered on the median reference coordinates in the left TP (x = -46, y = 9, z = -25) as defined above on the basis of picture naming effects based on the non-linear modulated normalized GM images.

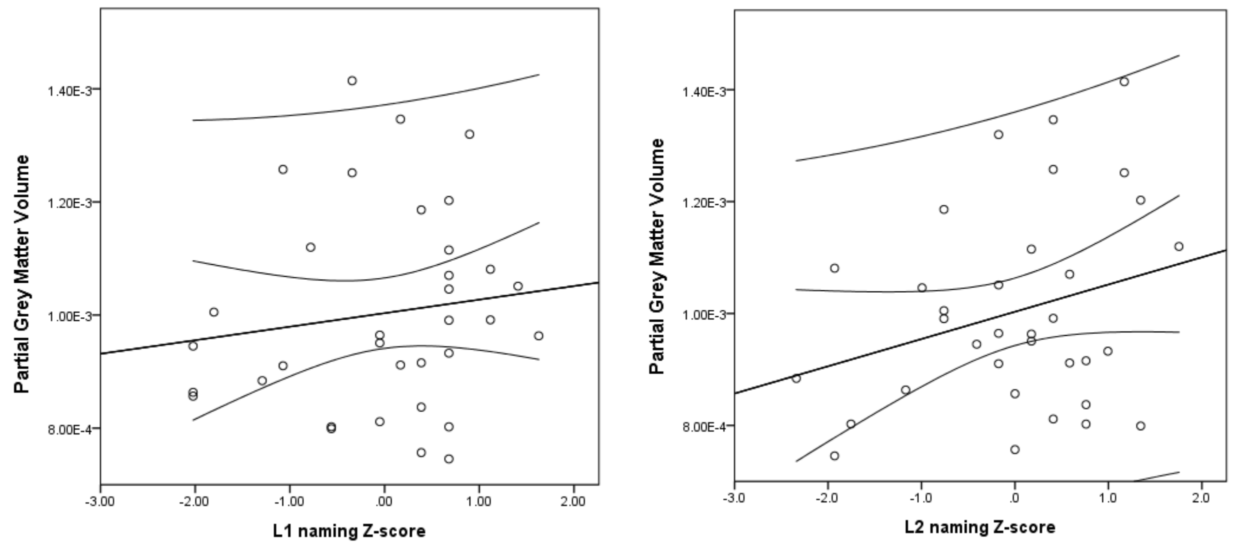

Figure 3. Scatter-plots (with mean and individual CIs) of the grey matter partial volume (in liter) in the left temporal pole (coordinate: x = -46, y = 9, z = -25) with the L1 naming z-score and L2 naming z-score. Left temporal pole grey matter partial volume correlates significantly with L2 naming z-scores but not L1 naming z-scores.

As indicated above, naming performances in L1, L2 and both were correlated with GM values extracted from TP to test whether naming performance in L2 is specifically associated with changes in GM values at TP, an area crucially involved in lexico-semantic processing. We assumed that L2 naming is a defining feature of bilingualism and that difference in naming performance can serve as an index of bilingual proficiency. Z-transformation was performed on naming performances for each subject to take account of the central tendency and variability in the distribution of naming scores for our whole sample. Extracted partial GM values were then correlated with naming performance z-scores in L1 and L2 using SPSS.

As expected, the overall naming z-score correlated with the GM volume ($r = .29$, $p = .051$). Surprisingly, L1 naming z-scores did not correlate significantly with GM volume at this 8mm spherical ROI in the TP ($r = .14$, $p = .22$); while the correlation between L2 naming z-scores and GM volume was stronger and near significant (r = .28, p = .055) (see Figure 3). We confirmed that second language proficiency predicts TP GM values. There were no significant correlations found between TP GM values and other bilingual characteristics.

Discussion

The aim of the present study was to determine whether increased proficiency in L2 induces structural neuroplasticity in healthy bilingual speaking seniors. The VBM results suggest that TP atrophy in bilinguals is similar to that reported in monolinguals (Allen et al., 2005; Fjell et al., 2009a). However, GM values at an established reference coordinate in TP reported to be necessary for naming (Price et al., 2005), showed a positive correlation with L2 but not L1 naming performance. These aspects will be discussed below in turn.

Is the age-related TP GM change in bilinguals similar to that found with monolinguals?

Currently, there are only two structural imaging studies with monolingual speakers that report structural deterioration at the TP along with healthy aging. One of them adopted a longitudinal design investigating the one year-decline in GM values (Fjell et al., 2009a). The other studied monolinguals with a relatively wide age range from 22 to 88 years old (Allen et al., 2005). The findings from the present study are in line with those studies by relating normal aging with a decline in grey matter specifically in the left TP. However, unlike previous studies, there were no significant effects of aging in other commonly reported age-vulnerable brain regions including the frontal lobe (Bartzokis et al., 2001; Fjell et al., 2009a, 2009b), medial temporal regions (Fjell et al., 2009a, 2009b; Mu, Xie, Wen, Weng, & Zhang, 1999) and parietal regions (Fjell et al., 2009b). These divergences maybe attributed to methodological differences or lack of statistical power.

There is an enormous amount of methodological variability across studies, which can lead to differences in the results. For example, some studies used manual structural outlining (Mu et al., 1999), while our study used an automatic segmentation of brain tissues based on the VBM approach. This may account for our significant age effect in left TP. Most previous studies of aging used 1.5T MRI machines, compared to the 3T MRI machine used here, therefore, we likely had more sensitive brain imaging in our study (Pinker et al., 2007). Participant selection criteria may also make a difference. Previous studies on monolinguals either used a longitudinal design by following seniors over years (Driscoll et al., 2009; Fjell et al., 2009a; Scahill et al., 2003), or included a relatively wide age range (Allen et al., 2005) or used young controls (Bartzokis et al., 2001; Fjell et al., 2009b; Mu et al., 1999). We studied only senior bilinguals and found an aging pattern in the left TP. The lack of comparison with young participants, and the possible bilingual structural plasticity may account for the absence of aging effects in other frequently reported brain areas.

Our study shows that TP GM density declines with aging in senior bilinguals. This extends reports of an aging effect on TP from other studies on monolinguals. Such findings suggest a universal structural decline in left TP for both monolingual and bilingual speakers.

Can second language proficiency of bilinguals predict TP GM values?

It is well know that TP is critically engaged in lexico-semantic processing as revealed by studies of monolingual speakers (Lambon Ralph et al., 2009; Price et al., 2005). In reality, more proficient bilingual speakers are assumed to have larger total vocabulary pool (semantic representation). Hence, increased semantic control is resulted from a larger competition across and within languages in retrieving words for daily communication. We therefore hypothesized that more proficient bilingualism may induce experience drawn neurostructural plastic changes in TP. If this is the case, we would expect a significant correlation between TP GM values and L2 naming performance instead of L1 naming.

Indeed, we found a higher value of local GM volume in this region was significantly associated with L2 not but L1 naming. These results are consistent with our hypothesis and, strikingly, we revealed a neurostructural association with L2 proficiency within the left TP for the first time. This observation of structural superiority with higher L2 proficiency is in agreement with the notion that bilingualism tunes the brain and induces structural plasticity in areas involved in language learning including the left inferior parietal region, dorsolateral prefrontal cortex, left inferior frontal region, SMG, AAC, left caudate and left putamen (Abutalebi & Green, 2007; Abutalebi et al., 2012, in press; Garbin et al., 2010; Mechelli et al., 2004; Richardson et al., 2010; Zou et al., 2012). Hence, we suggest that increasing proficiency in bilingual speakers is manifest in the left temporal pole and specifically reflects more proficient use of lexico-semantic processing.

However, our current finding of structural association with L2 proficiency in the left TP is not compatible with the results of Mechelli et al. (2004) or Stein et al. (2012). They reported correlations between L2 proficiency and GM values in the left inferior parietal region (x = -48, y = -59, z = 46); the LIFG (peak coordinate within BA 46) and the LATL (peak coordinate within BA 28) respectively. At least two alternative explanations for the discrepancy between study results may be considered.

The first explanation concerns characteristics of the participants recruited. In Mechelli et al. (2004) and Stein et al. (2012), relatively young bilingual speakers were examined. Given that the TP is one of the areas that are most susceptible towards healthy aging (Fjell et al., 2009a), we would argue that the observed correlation in our bilingual seniors is likely due to preservation against healthy aging that results, at least partially, from lifelong bilingualism. This proposed protective mechanism with higher L2 proficiency may possibly lessen the aging effect on the temporal pole; which would intensify the discrepancy in TP GM values along with increasing L2 proficiency and makes the association between L2 proficiency and TP GM more detectable. Moreover, Stein's participants were within their first year of L2 learning while our senior bilinguals had already experienced many years of L2 learning and use. As for the null finding on the left inferior frontal gyrus, it may be possible that the LIFG is involved only in the initial stages of learning a second language, and thus not detectable in our study; while our finding on the left TP may be more apparent during an aging phrase.

The second explanation concerns the behavioral measures used to assess language proficiency. Mechelli et al. (2004) employed a standardized test involving reading, writing, speech comprehension and production as an index of global language proficiency. Stein et al. (2012) adopted translation and fill-in-the-blanks tasks, which involved semantic as well as syntactic knowledge. Instead, we used picture naming task as a proficiency measure, which stressed the retrieval of lexical forms from semantic memory. Previous studies suggest that TP makes a strong contribution in semantic processing (Lambon Ralph et al., 2009; Pobric et al., 2010), especially on picture naming tasks (Price et al., 2005; Tranel, 2009). Pathological studies of anomia, a language disorder characterized by specific difficulties in naming has long reported an association with TP damage in patients suffering from aphasia (Tsapkini et al., 2011) and semantic dementia (Mummery et al., 2000). A recent study showed that rTMS of peri-TP regions selectively hindered picture naming performance (Pobric et al., 2010). Taken together, we contend that TP is more vitally engaged in naming of objects or pictures. In other words, TP is specifically involved in word retrieval from lexical semantic memory. As the present study selectively used picture naming as the index for language proficiency, this must have heavily tapped the TP and thereby obtained the significant correlation between L2 naming performance and the local partial GM volume.

Some may argue that the current result could be explained by an aging effect on TP, which leads to a deterioration in L2 performance more than L1 performance. However, this is not likely to be the case. TP has been reported essential for the whole semantic system in general, regardless of the mode or language used (Pobric et al., 2010; Rogers et al., 2004). A large number of studies have also reported TP is a crucial area for naming in monolinguals (Lambon Ralph et al., 2009). Hence, in bilingual speakers, TP is assumed to be important for naming in both L1 and L2. If an effect of aging on TP contributes significantly to the main findings, we would expect associations between the structural values in the TP and both L1 and L2 performance. However, we found only L2 performance-structural association in our bilingual participants, ruling out the alternative hypothesis. Some may criticize that the result could be attributed by subtle discrepancy in education level or SES. We would not exclude this possibility, but we found no significant correlation between L2 naming performance with education (r = .16, p = .18) or SES (r_s = .013, p = .47). Moreover, to date, there have been no researches reported effects of education level and SES on the ATL GM. Thus, we suggest that greater L2 naming is associated with a larger lexico-semantic network, and this is likely to reinforce left TP and induce structural plasticity to a larger extent. This indicates a neuro-advantage at the left TP and maybe a protection mechanism in aging bilinguals who enjoy greater L2 naming performance.

Limitations

We scanned bilingual seniors using structural MRI and assessed naming performance in terms of accuracy only. Possible directions for future research include whether changes in functional neuroplasticity are observed in senior bilinguals and whether naming reaction time predicts neuroplasticity. One possible limitation is exclusion of senior monolingual or young bilingual controls. Hence we are not confident enough to claim that neuroplasticity against aging is totally attributable to bilingualism. There may be subtle undetectable differences in education or SES that are correlated with bilingualism and contribute to these observations. However, the present study is part of a larger scale project investigating the effects of bilingualism on aging. Young bilingual and senior monolingual controls might be examined to strengthen evidence on the bilingual neuro-advantage against aging. Different levels of bilingualism and neuroplasticity across different language pairs (Cantonese-English, Cantonese-Mandarin and Mandarin-English) could be explored in future studies. We tested object naming only as a proficiency measure, precluding a more refined analysis of possible associations between a more global L2 proficiency measure and structural GM values. More research will be needed to address the above limitations.

Conclusion

In conclusion, we found an aging effect on GMD in left TP among healthy Chinese bilingual speaking seniors, confirming that a pattern of aging related atrophy in the left TP is similar in bilinguals and monolinguals. More importantly, the results suggest that proficient bilinguals are more likely to have neurocognitive benefits located on functions that depend on the TP. The higher demand in lexico-semantic processing during everyday's learning and use of a second language may eventually induce structural plasticity in the left TP. We have, for the first time, demonstrated a beneficial effect with higher L2 naming in bilingualism at a neurostructural level in the temporal region, suggesting that in bilinguals the structural integrity of the left TP during aging may be protected by better L2 naming performance. In respect to the clinical implications, the current study reveals a more in-depth relation between TP lesion and naming performance in L1 and L2 for bilingual patients with language disorders. This has some implications for choice of therapy in aphasia. For example, localised TMS could be applied to the left TP to improve naming in patients who have anomia. There may also be long term benefits of TMS on the decline of lexical-semantic processing in healthy aging in bilinguals.

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Appendix A

Stimuli for naming tasks

Cantonese	Mandarin	English
袋鼠	連衣裙	Watch
海馬	馬	Train
水壺	獅子	Tennis racket
外套、褸	房子、屋	Lips
鉛筆	烏龜	Book
蝴蝶	蛇	Necklace
書包、袋	帽子	Roller skate
皇冠	山、雪山	Whistle
牙刷	電話	Bird
外衣、褸	桃子	Eagle
燈膽	澆水壺、水壺	Celery
電單車	窗户	Spider
手指、食指	螞蚱、草蜢	Comb
釘	鼻子	Guitar
螺絲批	扳手	Ear
床	皮靴、鞋子	Piano
台燈、燈	笛子	Potato
錘	座鐘	Shoe
熨斗	熊	Monkey
圓號、喇叭	紡車、衣車	Airplane
指甲鉎	寫字台	Wagon
小丑	紅綠燈	Pliers
皮帶	豎琴	Pumpkin
插頭	兔子	Suitcase
士多啤梨、草莓	磨坊、風車	Nut
大象	陀螺	Arm、hand
桶	剪子、剪刀	Pants、trousers
鴨	圓凳、凳	Toe
毛蟲、蟲	玉米	Giraffe
貓頭鷹	甲蟲	Goat

Appendix B

Stimuli for translation task

High frequency		**Medium frequency**		**Low frequency**	
男人	man/men	膊頭/肩膀	shoulder	資產	asset
口	mouth	主人	master/Host/ Owner/lord	青年	youth/ teenager
魚	fish	角落	corner	覆蓋	cover
探訪	visit	火柴	match	費用	fee/charge
麻煩 (n)*	trouble/ annoyance	婚姻	marriage	噪音	noise
付款 (n)*	payment	罪行	crime/Sins	槍	gun
女士	woman/ lady/ female	真相	truth	護士	nurse
假期	holiday/ vacation	安全 (n)*	safety	箭	arrow
重要 (n)*	importance	信任 (n)*	trust	部隊	troop/army
椅子	chair	痛苦 (n)*	pain	時尚 (n)*	fashion
內容	content	危機	danger/Crisis	屋頂	roof
卡	card	評估 (n)*	assessment /appraisal/ evaluation	撕裂	tear
溝通 (n)*	communication	耕種	farm	律師	lawyer
太陽	sun	僱主	employer	成就	achievement
女人	woman/ lady/ female	連接 (n)*	connection	囚犯	prisoner/inmate
主席	president/ chairman/ chairperson	債	debt/load	女性	female/woman/ lady
講座	talk/ seminar/ lecture	木	wood	乘客	passenger
河流	river	跑	run	根	root
屋	house	農夫	farmer	欄	column
反對 (n)*	opposition/ objection	交通	traffic	製造商	manufacturer/ producer
意見	opinion/ view	歌曲	song	形成 (n)*	formation
星星	star(s)	晚餐	dinner	廢料	waste

*Note: (n) means the target translations were told to be nouns.

Appendix C

Questionnaire for socio-economic status and education level

QUESTION 1.
Think of this ladder as representing where people stand in their communities.

People define community in different ways; please define it in whatever way is most meaningful to you. At the **top** of the ladder are the people who have the highest standing in their community. At the **bottom** are the people who have the lowest standing in their community.
Where would you place yourself on this ladder?
Please place a large "**X**" on the rung where you think you stand at this time in your life, relative to other people in your community.

QUESTION 2.

Think of this ladder as representing where people stand in Hong Kong.

At the **top** of the ladder are the people who are the best off – those who have the most money, the most education and the most respected jobs. At the bottom are the people who are the worst off – who have the least money, least education, and the least respected jobs or no job.

The higher up you are on this ladder, the closer you are to people at the very top;
the lower you are, the closer you are to the people at the very bottom.

Where would you place yourself on this ladder?

Please place a large "**X**" on the rung where you think you stand at this time in your life, relative to other people in the United States.

QUESTION 3. What is the highest grade (or year) of regular school you have completed? (Check One)

Elementary school:
1___
2___
3___
4___
5___
High school
6___
7___
8___
College
9___
10___
11___
12___
13___
Graduate School
14___
15___
16___
17___
18___
Other (Specify)

__

QUESTION 4. What is the highest degree you earned?

____High school diploma or equivalency (GED)
____Associate Degree (junior college)
____Bachelor's Degree
____Master's Degree
____Professional (MD, JD, DDS, etc...)
____Other (specify)
____None of the above (less than high school)

QUESTION 5. Which of the following best describes your currently main daily activities and/or responsibilities?

____Working full-time
____Working part-time
____Unemployed or laid off
____Looking for work
____Keeping house or raising children full-time
____Retired

QUESTION 6.With regard to your current or most recent job activity:

a. In what kind of business or industry do (did) you work?

……

b. What kind of work do (did) you do?

……

(For example: registered nurse, personnel manager, supervisor of order department, gasoline assembler, grinder operator)

c. How much did you earn, approximately, during the past 12 months?

⋯.Less than 5.000 Euro // 52 430HKD
⋯.5.000 through 20.000 Euro // 52430- 209 721 HKD
⋯.20.000 through 40.000 Euro // 209 721-419 443 HKD
⋯.40.000 through 75.000 Euro // 419 443-786 455 HKD
⋯.75.000 Euro and greater // 786 455 above HKD

QUESTION 7. How many people are currently living in your household, including yourself?

…. Number of people
…. Of these people, how many are children?
…. Of these people, how many are adults?
…. Of these adults, how many bring income to the household?

QUESTION 8. Which of these categories best describes your total combined family income for the past 12 months?

These should include incomes from all people in the household, real estate and movable capital.

⋯.Less than 5.000 Euro // 52 430HKD
⋯.5.000 through 20.000 Euro // 52430- 209 721 HKD
⋯.20.000 through 40.000 Euro // 209 721-419 443 HKD
⋯.40.000 through 75.000 Euro // 419 443-786 455 HKD
⋯.75.000 Euro and greater // 786 455 above HKD

Appendix D

Questionnaire of Language Exposure

語言背景問卷

姓名: 出生日期: 性別:

您的母語(L1)是: 廣東話/ 普通話/ 英文/ 其他 (請註明)____________________

您第二常用的語言(L2)是: 廣東話/ 普通話/ 英文/ 其他 (請註明)______________

您所讀的高中,是以那種語言授課的? 廣東話/ 普通話/ 英文/ 其他 (請註明)______

請填寫您**平均**每天使用以上兩種語言所用的時間。

日常活動		廣東話	英文	普通話
1	電視			
2	收音機/ 音樂			
3	家庭			
4	課程			
5	同學			
6	朋友 (不包括同學)			
7	男/女朋友			
8	興趣活動			
9	閱讀			
10	寫作			
11	工作			
語言習得年齡				