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Exploring cross-linguistic vocabulary effects on brain structures using voxel-based morphometry

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Abstract

Given that there are neural markers for the acquisition of a non-verbal skill, we review evidence of neural markers for the acquisition of vocabulary. Acquiring vocabulary is critical to learning one's native language and to learning other languages. Acquisition requires the ability to link an object concept (meaning) to sound. Is there a region sensitive to vocabulary knowledge? For monolingual English speakers, increased vocabulary knowledge correlates with increased grey matter density in a region of the parietal cortex that is well-located to mediate an association between meaning and sound (the posterior supramarginal gyrus). Further this region also shows sensitivity to acquiring a second language. Relative to monolingual English speakers, Italian-English bilinguals show increased grey matter density in the same region.

Differences as well as commonalities might exist in the neural markers for vocabulary where lexical distinctions are also signalled by tone. Relative to monolingual English, Chinese multilingual speakers, like European multilinguals, show increased grey matter density in the parietal region observed previously. However, irrespective of ethnicity, Chinese speakers (both Asian and European) also show highly significant increased grey matter density in two right hemisphere regions (the superior temporal gyrus and the inferior frontal gyrus). They also show increased grey matter density in two left hemisphere regions (middle temporal and superior temporal gyrus). Such increases may reflect additional resources required to process tonal distinctions for lexical purposes or to store tonal differences in order to distinguish lexical items. We conclude with a discussion of future lines of enquiry.

1. Introduction

An important question in neurolinguistics is the extent to which the universal ability to acquire language alters neuroanatomy as a function of the type and number of languages acquired. Understanding such changes will help identify the structures and networks involved in acquisition. In order to address this question we need a technique that can identify adaptive changes if they exist in an unbiased and objective manner. In order to undertake the exploration, we need reasons to believe that experience-dependent changes exist in other domains. Next, we need to sharpen our question. We focus on a fundamental aspect of language acquisition – the acquisition of vocabulary. We ask if there are neural markers for the acquisition of vocabulary and whether there are cross-linguistic differences in these markers. Our review paper follows this structure of enquiry.

In section 2 we outline a suitable method (see Appendix for a glossary of terms). In section 3, we describe studies in different domains showing evidence of experience-dependent

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changes. In section 4, we discuss data showing that structural changes occur in response to the acquisition of vocabulary in English and that this same region shows changes in response to the acquisition of another European language. In section 5, we report recent results showing that the acquisition of a language (Chinese), in which tone signals a difference in lexical meaning, creates structural changes in additional brain regions. We argue that there are specific neural markers for acquiring vocabulary and there are cross-linguistic differences in these markers. In section 6, we discuss what is required to establish the causal necessity of the structures for vocabulary acquisition and consider future work.

2. Computational Neuroanatomy

How can we investigate experience-dependent changes in the brains of living individuals? One technique, deformation field morphometry, captures macroscopic differences in brain shape (e.g., the position and size of various gyri in the two hemispheres of the brain). A second technique, voxel-based morphometry, VBM, captures differences in the local composition of brain tissue after eliminating macroscopic differences in brain shape. We focus on this approach here because it is more sensitive to small scale differences in the concentration and/or volume of different types of neural tissue. Two tissue types can be distinguished: grey matter (i.e., nerve cell bodies together with unmyelinated axons and dendrites, termed the neuropil) and white matter (i.e., myelinated axons connecting grey matter regions). One very important feature of the method is that the entire brain can be examined in an unbiased manner.

VBM identifies differences in grey or white matter based on structural MRI images. A number of steps are required but the basic sequence involves normalising the structural MRI images to a standard template image, segmenting the normalised images into grey and white matter and then smoothing these images before localising between subject differences in brain structure. For a more detailed discussion and critique see Mechelli, Price, Friston and Ashburner (2005).

3. The effects of learning and practice on brain structure

Originally applied to characterise structural abnormalities in patients, researchers have used computational neuroanatomy techniques to investigate the effects of learning and practice on the brains of healthy individuals. Stimulated by reports that experience alters structure in the brains of small mammals and birds (e.g., Lee, Miyasato and Clayton, 1998), researchers have examined the impact of skill acquisition and use in a number of domains such as playing a keyboard instrument (Gaser and Schlaug, 2003), navigation (Maguire, Gadian, Johnsrude, Good, Ashburner et al., 2000) and juggling (Draganski, Gaser, Busch, Schuierer, Bogdahn and May, 2004).

Gaser and Schlaug (2003) used VBM to search for neural markers of acquired keyboard skills by contrasting three matched groups (professional musicians, amateur musicians and non-musicians) who differed in their status as musicians and in the amount of regular practise. Grey matter volume increased as a function of expertise and use in regions involved in the planning, preparation and execution of bimanual sequential finger movements, in auditory regions (left Heschl’s gyrus) linked to the processing of tones, in a region that links visual stimuli to actions, and finally in the superior parietal cortex that is thought to play a crucial role in the integration of visual-auditory and somatosensory information. This pattern of results fully accords with expectations about the nature of musical expertise. Musicians must translate musical notation into motor plans (a visual-spatial to motor transformation) and use the simultaneous auditory feedback to check the mapping of visual patterns to motor programs (see Gaser and Schlaug, p. 9243).

However, regional enlargement for each of a set of interlinked regions may not be the norm. Maguire et al. (2000) examined the effects of an acquired navigation skill in an expert group - licensed London taxi drivers. Compared with controls, there was a bilateral increase in grey matter volume in posterior hippocampus and reduced grey matter volume bilaterally in the anterior hippocampus. This regional expansion in the posterior hippocampi is consistent with functional neuroimaging studies that show activation of the posterior hippocampus when individuals are required to retrieve previously learned navigational information compared to when they are simply required to follow a trail (Maguire, Burgess, Donnett, Frackowiak, Frith and O'Keefe, 1998).

The study by Draganski et al. (2004) shows most directly that acquisition of a new skill (a three-ball cascade juggling routine) changes neuroanatomy rather than reflecting a pre-existing (genetic) difference. Twenty-four non-jugglers were scanned and then divided into two groups matched for age and sex. Subjects in the juggler group learned the juggling routine over a three month interval and were then rescanned when they had become skilled performers and then three months later after they had ceased to practise. VBM analyses of the scans before and after skill acquisition showed an expansion in grey matter in two motion-specific regions: bilateral mid-temporal areas and an area in the left posterior intra-parietal sulcus. The control group showed no such expansion. By the time of the third scan, the expansion in grey matter had reduced suggesting that training effects are transient unless a skill is practised. The areas showing expansion are ones used in the retention of visual-motion perception (see, for example, Sereno, Pitzalis and Martinez, 2001).

As Draganski et al. (2004) point out, all their sample had normal fine-motor skills, and so it is the perception and spatial anticipation of objects required for the juggling routine that drives structural change rather than the fact that hand movements have to be planned, coordinated and executed that implicate other cortical and subcortical regions (the supplementary motor area, the motor cortex, cerebellum and basal ganglia).

These studies illustrate a number of important points. First, they show that the traditional view that the adult brain does not alter in structure, except for changes induced by ageing or pathology, is incorrect. Second, they show that VBM analyses can identify regionally-specific structural changes particular to the acquisition of specific skills. The studies cited provide evidence of changes in grey matter volume but adaptive changes may also involve changes in grey matter density (e.g., in the neuropil) and in the nature of white matter. Third, functional neuroimaging studies may be helpful in corroborating the interpretation of structural changes on the principle that structural change follows functional demand. Fourth, not all components of a network involved in the performance of a task may show changes in grey matter volume or density.

Prior research has motivated researchers to use the whole-brain approach of VBM to discover regions that may mediate the acquisition of vocabulary either in one's own native language or in a different language. We consider this research in the next section.

4. Acquiring vocabulary in a first and in a second European language

Vocabulary is essential to daily communication Acquiring an item of vocabulary requires creating a representation that links the conceptual representation of the word's referent (the word's meaning) to a novel sound pattern and to syntactic processes. Phonological working memory is likely to play a crucial role. Unfamiliar sound patterns must be stored and rehearsed so that a more permanent representation can be constructed (Baddeley, Gathercole and Papagno, 1998).

Vocabulary acquisition in normal children is specifically related to the ability to repeat nonwords aloud and this relationship is preserved in adulthood especially for novel phonological forms dissimilar to familiar native words (e.g., Atkins and Baddeley, 1998: Gupta, 2003, see Gathercole, 2006 for a review). This suggests that the capacity to store novel forms is important in learning new words during the early stages of language acquisition in one's native language (Baddeley, Gathercole and Papagno, 1998) and in a novel foreign language (Masoura and Gathercole, 2005). At later stages individuals can make use of the structures already in place, by for instance, accessing the phonological representations of existing words (Gathercole, 2006). However regardless of the stage of acquisition individuals must represent a word's meaning (and its syntactic properties), and its phonology and bind these two sets of properties together. There must therefore be brain regions that achieve these effects.

4.1 Brain regions and vocabulary knowledge: monolingual speakers

Given the work reported in section 3, we expected there to be brain regions that are sensitive to vocabulary knowledge. One way to explore this question is to contrast the brains of individuals who differ in their vocabulary knowledge. In a recent study, Lee, Devlin, Shakeshaft, Stewart, Brennan, Glensman et al. (2007) selected 32 right-handed monolingual English-speaking adolescents (aged between 12 and 16 years) who differed in their vocabulary knowledge. Vocabulary knowledge was assessed using the vocabulary sub-test from the Wechsler Intelligence Scale for Children (WISC-III, Wechsler, 1955). In this subtest, a participant produces the definition of a heard word (e.g., what does the word "depart" mean?) or is asked what an object is (e.g., what is a "donkey"?). The tester rates the definition in terms of quality using a three-point scale (2 for a good definition, 1 for a poor definition and 0 for an incorrect response). The participants also completed two verbal fluency tests (sub-tests from the Phonological Assessment Battery (Frederikson, Frith, and Reason, 1997) in which they produced as many words as possible in one minute meeting a specific constraint. In the alliteration test, they produced words beginning with a particular letter (e.g., "T"). In the rhyming test, they produced words rhyming with a given word (e.g., "hat"). Like the vocabulary task, both fluency tasks involve speech production but only the vocabulary task indexes a participant's knowledge of words.

The VBM analyses (modelling age, and verbal and non-verbal IQ as confounding variables) showed that vocabulary knowledge but not verbal fluency predicted grey matter density in a region of the left inferior parietal cortex (sagittal: x = -44; coronal: y = 54 and axial: z = 46) and in the homologous region of the right inferior parietal cortex (x= 52, y = -52, z = 44). In other words, there was a linear increase in density in both hemispheres as a function of vocabulary knowledge. These data provide evidence that vocabulary is a variable that can predict grey matter density in an inferior parietal region that we will refer to as the posterior supramarginal gyrus. Expressed the other way round, grey matter density in this region may be a neural marker for vocabulary acquisition, at least in monolingual adolescents[1].

How safe is this inference? This depends on the extent to which the analysis focuses on vocabulary. Our vocabularly measure, or a variant of it (the oral vocabulary subtest of the Word Knowledge Test, McCarthy, 1970), has been used in psycholinguistic studies of the factors affecting vocabulary knowledge (e.g., Gathercole, Service, Hitch, Adams and Martin, 1999) and the learning of new words (e.g., Papagno and Vallar, 1995; Gathercole, Hitch, Service and Martin, 1997). It has been used either singly (Papagno and Vallar, 1995) or in combination with other tests such as those testing receptive vocabulary (e.g.,

[1]In the aphasia literature, the parietal region has been linked to the ability to speak multiple languages (see, for example, Pötzl, 1930; translation in Paradis, 1983; Perani, 2005) and it is likely that it plays a role in a number of different functions.

Gathercole et al., 1997; Gathercole et al., 1999). The different measures of vocabulary intercorrelate (see Gathercole et al., 1997). But acquiring new words may also involve learning new facts about the world. Further, the ability to provide definitions may reflect metalinguistic understanding of what counts as a valid definition or a person’s capacity to produce an appropriate syntactic construction. To address this issue, Lee et al. (2007) compared the effect of vocabulary to the effect of the comprehension subtest of the WISC-III. In this comprehension task, participants must provide a verbal response to an everyday problem (“What is the thing to do when you cut your finger?” or to a social or precautionary rule (“Why do cars have seat-belts?”). A response in such cases typically requires a verb and a nounphrase/prepositional phrase (i.e., “put a plaster on it”, “to protect people”). Therefore it has similar metalinguistic and production demands as the vocabularly test. The results revealed that grey matter density in the posterior supramarginal gyri was predicted by scores on the vocabulary but not the comprehension task. This suggests that the posterior supramarginal gyri are more involved in vocabulary than either comprehension or fluency. The precise nature of this function, however, remains open to further challenge.

4.2 Brain regions and vocabulary knowledge: bilingual speakers

Vocabulary acquisition is not only critical to learning one’s native language, it is also critical to becoming proficient in a second language (see, for example, Nation, 1993; Waring and Nation, 1997). Green (2003) argued on computational grounds that a second language will utilise neural structures mediating the first language. Functional imaging studies support this claim (see Perani and Abutalebi, 2005) with any initial divergence in patterns of activation reflecting problems associated with retrieving a less familiar language perhaps in the face of competition from the more proficient language (Abutalebi and Green, 2007). If a common substrate is involved in acquiring vocabulary in different languages, then bilingual speakers, at least speakers of another European language, will show adaptive changes in the same region of the inferior parietal cortex. Below we discuss VBM data that are consistent with this proposal followed by more subtle evidence on the acquisition of novel or unfamiliar vocabulary.

Mechelli, Crinion, Noppeney et al. (2004) examined anatomical differences in the brains of bilinguals compared to monolingual controls. In their first study, they recruited three groups of participants: 25 English monolinguals with little knowledge of a second-language; 25 “early” bilinguals who had learned a second European language before the age of 5, and 33 “late” bilinguals who had learned a second European language after the age of 10 and who had used the language regularly for at least 5 years. Bilinguals compared to monolinguals showed increased grey matter density in the same left posterior supramarginal parietal region ($x = -45$, $y = -59$, $z = 48$) that showed sensitivity to vocabulary knowledge in English monolingual adolescents. There was also a corresponding trend in the right posterior supramarginal parietal cortex. The effect of acquiring a second language appears to be remarkably specific as there were no other significant grey or white matter differences when a correction was made for multiple comparisons across the whole brain.

In a second study, Mechelli et al. (2004) examined the effects of L2 proficiency and age of L2 acquisition on grey matter density. They tested 22 native Italian speakers who had learned English as a second language between the ages of 2 and 34 years. Participants completed a battery of standardised neuropsychological tests that covered receptive vocabulary (the English Vocabulary Test; reading and semantic subtests of the Psycholinguistic Assessments of Language Assessments in Aphasia), reading (e.g., the National Adult Reading Test) and naming (e.g., the Graded Naming Test). From these scores they used principal components analysis to extract an index of proficiency in English. The first principal component explained nearly half of the variance making it a useful index. Remarkably, VBM analyses showed that the more proficient the speaker the greater the grey

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matter density in exactly the same left posterior supramarginal parietal region. Grey matter density in this region also correlated negatively with the age of acquisition. However, speakers who were more proficient also acquired English at an earlier age and so it is possible that in this group of subjects the effect of age of acquisition is really an effect of proficiency. Further, although there are a number of cognitive differences between bilinguals and monolinguals including for example cultural knowledge, there is a major expansion of vocabulary when learning either a first or second language. Given the results of Lee et al. (2007), we suggest that the effects of proficiency on grey matter density may in fact reflect the number of words learnt. On this view, grey matter density in the posterior supramarginal parietal cortex is a neural marker for vocabulary acquisition regardless of age and language.

Precisely which aspects of grey matter account for the increase in density is presently unknown though an increase in dendritic arborisation and local synaptic density is most likely. What is the likely functional role of this region? There are two ways to address this question. First, by looking at data from functional studies of vocabulary acquisition. In fact, the region we have identified is not routinely activated in functional studies but the various regions that are activated, though not identical across studies, do suggest its functional role. The second way to address the question, or at least to constrain functional inferences, is to examine the anatomical connectivity of the region.

4.3 Functional studies of vocabulary acquisition in adults

Functional imaging studies have implicated the inferior parietal lobe in vocabulary acquisition but not consistently so. In a study, using an implicit learning task, Breitenstein, Jansen, Deppe, Foerster, Sommer, Wolbers and Knecht (2005) found just one region that showed activation increases following the learning of novel vocabulary. In this event-related fMRI study, young native German speakers (n=14), learned to associate 45 German pseudo-words with depicted objects over five learning blocks. Increased vocabulary proficiency (indexed by pressing a “yes” response key to the correct pairing of object and pseudo-word) was associated with increased activation in a region of the left inferior parietal cortex (the anterior supramarginal gyrus). They proposed, in line with other literature, that this region reflected the permanent storage of a word’s phonology. In fact, it is similar to a region where Golestani and Pallier (2006) found a positive correlation between white matter density and the ability to pronounce a novel speech sound.

Cornelissen, Laine, Renvall, Saarinen, Martin et al. (2004) asked young native-Finnish speaking adults (N = 5) to learn the Finnish names of 100 rare objects (archaic tools). Using magnetoencephalography, they identified effects in the vicinity of the posterior supramarginal gyrus. In a later study using similar materials, Grönholm, Rinne, Vorobyev and Laine (2005) tracked activation using positron emission tomography (PET) as older native-Finnish speakers (N=10) named 40 rare objects with their newly-learned names. Their results suggest that retrieving learned but unfamiliar names (i.e., novel vocabulary), relative to familiar names, increased activation in a region implicated in the storage of meaning (left anterior temporal region), and in regions associated with effortful retrieval (an inferior frontal region –roughly Broca’s area and the right cerebellum). They found no increased activation in naming unfamiliar compared to familiar objects in the posterior supramarginal gyrus and inferred that the result obtained by Cornelissen et al. (2004) reflected the need for subjects in that study to delay naming and so hold the phonological form in mind.

Such functional studies can indicate relevant regions (associated with meaning and sound) but the data are inevitably sensitive to task demands and to the neuroimaging technique. Current studies may also be limited in that they mainly assess changes following, rather than

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during word acquisition. Moreover, they used relatively few novel words even though, in natural language acquisition, a native adult speaker of English will typically know about 20,000 word families (covering a base word and its inflected and derived forms) with an acquisition rate of 1000 words per year from the age of five to adulthood (Waring and Nation, 1997).

4.4 Anatomical connections

The posterior supramarginal gyrus lies between an area (the anterior supramarginal gyrus) associated with phonological processing and a region (the anterior angular gyrus) associated with semantic processing (Demonet, Chollet, Ramsay, Cardebat, Nespoulous et al., 1992; Price, Moore, Humphreys and Wise, 1997; Devlin, Matthews and Rushworth, 2003). It is therefore well positioned to link phonological and semantic information about a word.

Lee et al. (2007) explored the anatomical connections of this region. Using diffusion tensor imaging (DTI) in a set of adult volunteers they identified local white matter anatomical connections from the posterior supramarginal gyrus to the area implicated in phonological processing, and to the area implicated in semantic processing. Critically, there was no evidence for direct connections between anterior supramarginal gyrus and anterior angular gyrus. This suggests that communication between these two language areas may be mediated via the posterior supramarginal gyrus that lies between them. In other words, this pattern of connectivity strongly supports the idea that the inferior parietal region of interest, as identified in the VBM studies, plays a role in linking new sounds to meaning.

A plausible conjecture (see Lee et al., 2007) given current functional and structural data is that three different inferior parietal regions are involved in representing and processing vocabulary: the anterior supramarginal gyrus where phonological information is processed, the anterior angular gyrus involved in the processing of word meanings and the posterior supramarginal gyrus that serves to bind sound and meaning together. Further work is needed to establish the connectivity of the posterior supramarginal gyrus to regions mediating the visual form of a word in the case of literate adults and to those regions implicated in establishing long-term memory representations of vocabulary (e.g., the left hippocampus, Breitenstein et al., 2005).

5. Behavioural, functional and structural studies of Chinese-English speakers

Speakers use a range of acoustic means to communicate meanings at the lexical and sentence level. In a study of Mandarin-English bilinguals, Gandour, Tong, Talavage, Wong, Dzemidzic et al. (2007) examined the neural processing of two sentence-level prosodic phenomena: contrastive stress (sentence initial or sentence final) and modality (declarative or interrogative) that are used in both English and Mandarin. They concluded that sentence-level prosody in Mandarin and English is mediated by a common neural system and one that involves an interplay between right-hemisphere and left-hemisphere systems (see also Friederici and Alter, 2004). It is unlikely then that there will be any brain differences between Chinese speakers and non-Chinese speakers as a function of differences in sentence level prosody.

However, in contrast to English and other European languages, Mandarin (along with other Chinese languages such as Cantonese, Hakka and Hokkien) is a tonal language. In a tonal language, it is not only consonants and vowels that distinguish different words (i.e., that carry lexical effects) but also pitch patterns. Clearly these two aspects of the speech signal must be coordinated and a plausible view is that synchrony is achieved with respect to each syllable (see Xu and Liu, *in press*). The processing of pitch so that it can achieve lexical effects constitutes a possible source of brain differences between Chinese and non-Chinese speakers.

The primary acoustic correlate of tones is the fundamental frequency of voice (F_0). The four tones of Mandarin, for instance, are conventionally labelled as tone 1, 2, 3 and 4 and differ in pitch height and the shape of the pitch contour (see Chao, 1968).. They can be described as high-level (tone 1), rising (tone 2), low-dipping (tone 3) and falling (tone 4). To take a conventional example to illustrate the lexical effects of tone in Mandarin, the syllable /ma/ means “mother” when spoken in the first tone (/ma^1/), “hemp” when spoken in the second tone (/ma^2/), “horse” when spoken in the third tone (/ma^3/) and a reproach when spoken in the fourth tone (/ma^4/).

When spoken in isolation, tones are easy to distinguish in terms of their F_0 contours but variability is introduced when tones are spoken in sentence contexts. In normal speech, pitch patterns must shift 5-8 times per second. Nonetheless, regardless of the preceding tone, the F_0 contour of the syllable associated with the tone converges over time with the characteristic of the underlying tone. In accounting for these data, Xu and Wang (2001) proposed that speakers aim to reach an articulatory goal associated with the lexical tone. More recently, Gauthier, Shi and Xu (2007) provided an existence proof, using a self-organising map simulation, that listeners could use the movement of the contour towards the underlying pitch target (the velocity of F_0) to categorise the tone. In their view the object of speech perception is the articulatory gesture. In the next section, we review what is known about the neural regions involved in processing tone.

5.1 Behavioural and functional studies of tone processing

Behavioural studies using dichotic listening techniques (e.g., Wang, Jongman and Sereno, 2001) indicate that the ability to identify lexical tone is primarily lateralised to the left hemisphere. In contrast, other pitch-related abilities with no lexical effects appear to be predominantly lateralised to the right hemisphere (e.g., Blumstein and Cooper, 1974; Warrier and Zatorre, 2004). Neuroimaging data support the importance of left hemisphere structures in tone perception but also indicate the continued relevance of right-hemisphere structures.

In a PET study, Klein, Zatorre, Milner, and Zhao (2001) contrasted the neural basis of pitch perception in two groups of speakers (n =12 in each): Mandarin-English speakers and native English speakers. Participants judged whether a pair of monosyllabic Mandarin words was identical or not. Half the word pairs had the same tone (e.g., /$t'ou^2$/) and half had a different tone (e.g., /fei^2/ /fei^1/). Most relevant here is the researchers’ comparison of the two language groups performing the tone discrimination task relative to a silent baseline. Consistent with previous findings on the perception of pitch (Zatorre, Evans, Meyer and Gjedde, 1992), native English speakers showed greater activation in right frontal and right temporal regions indicating that these regions mediate the processing and maintenance of pitch information. In contrast, for the Mandarin-English group, relative to the English group, all the observed differences were in left hemisphere frontal, temporal and parietal regions. This differential outcome supports the view that it is the linguistic-relevance of complex auditory stimuli that determines which neural mechanisms are engaged (e.g., Gandour, Wong, Hsieh, Weinzapfel and Hutchins, 2000, see also Gandour, 2006 for a review). For Mandarin speakers, tone carries lexical significance leading to the activation of left hemisphere networks.

The four tones of Mandarin bear an imperfect relationship with any one property of patterns of prosody in English (stress, accent and intonation) and so in order to acquire vocabulary in Mandarin, native English speakers might need to develop novel processes in order to integrate tones and phonetic contrasts (see Wang, Sereno, Jongman and Hirsch, 2003; see also Zhang and Wang, 2007 -this issue). Wang et al. used a focussed programme to help six native English speakers distinguish lexical tones as part of their efforts to learn Mandarin as a second language. In their fMRI study, participants identified the tone of a spoken Mandarin word. Wang et al. found that the learning of lexical tones was associated with increased volume of activation in existing language areas (Wernicke's area) and in a neighbouring area of the left superior temporal gyrus. They also found increased volume of activation in the right inferior frontal gyrus which they linked to pitch processing. Thus they suggest that when native speakers of English acquire lexical tones, they increase demands on existing language areas (e.g., Wernicke's area) as well as on those involved in pitch processing.

Turning now to work on connected speech, theorists have tended to emphasise the importance of Wernicke's area because lesions in this left posterior temporal region are most typically associated with aphasia (e.g., Turner, Kenyon, Trojanowski, Gonotas and Grossman, 1996). Narain, Scott, Wise, Rosen, Leff, Iversen and Matthews (2003) argue that the left posterior temporal cortex is likely to be a core component of working memory network specialised for language comprehension (Aboitiz & Garcia, 1997) with more anterior regions important for language comprehension (e.g., Crinion, Lambon-Ralph, Warburton, Howard and Wise, 2003). For instance, patients with semantic dementia, who suffer a progressive loss in knowing the meanings of single words, typically show deterioration in the anterior and ventral temporal lobe (e.g., Mummery, Patterson, Price, Ashburner, Frackowiak and Hodges, 2000). Further, both anterior and posterior regions of the left temporal lobe are activated in the passive comprehension of both connected speech and writing (Spitsyna, Warren, Scott, Turkheimer and Wise, 2006, see also Narain et al., 2003). Although activity is higher in left temporal lobe regions for the passive comprehension of speech and writing, there is also activity in the homotopic right cortex (see Spitsyna et al., p. 7330). In short, language comprehension in English utilises temporal lobe regions in both the left and right hemispheres.

What of the processing of connected speech in Mandarin compared to English? Using baselines controlling for the acoustic complexity of the speech signal (as in Narain et al, 2003; Spitsyna et al, 2006), Scott (2004) examined the neural correlates of the passive perception of English and Mandarin sentences in native speakers of these languages. As would be expected, the intelligibility of the stimulus sentences determined relative regional activation. As in Narain et al (2003), for native English speakers (n =8), intelligible English sentences strongly activated the length of left lateral temporal neocortex, with peaks in a posterior region (Wernicke's area) and in a more anterior region (anterior superior temporal sulcus). For native Mandarin speakers processing intelligible Mandarin sentences, the right superior temporal gyrus and sulcus was also strongly activated. Scott observed too that the activation in the right posterior superior temporal sulcus was close to the region associated with the processing of lexical tone independent of the intelligibility of the sentence.

In summary, current imaging data do not allow us to draw a strong function-structure inference. However, they are compatible with the notion that proficient Chinese speakers make extensive use of right hemisphere temporal lobe regions in processing Chinese. And so, on the assumption that structural change follows functional demand, we might expect anatomical differences in the brains of Chinese and non-Chinese speakers. In the next section, we consider existing literature on the neural markers for the acquisition of a tone language.

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5.2 Whole-brain structural studies of Chinese speakers

Kochunov, Fox, Lancaster, Tan, Amunts, Zilles et al. (2003) looked at differences in brain shape between 20 English-speaking Caucasians born in the USA and 20 Chinese-speaking Asians born in mainland China and currently living in the USA. They analysed MRI scans using deformation field morphometry (see section 1) that identifies brain surface differences between groups and report that right parietal, left frontal and left temporal regions were larger in the Chinese-speaking group while a left superior parietal region was larger in the Caucasian group.

Their basic position is that the observed differences reflect anatomical plasticity and derive from the different processing requirements for Chinese over English rather than genetic differences in the morphometry of Asian and Caucasian brains. The differences, they argue, are consistent with evidence from functional imaging studies although they note that the role of the parietal cortex in Chinese-language processing is unknown (p. 963). This study offers useful initial evidence that the processing requirements of a tonal language may induce changes in brain anatomy. One caution is that the study matched the samples for age, educational level and handedness but not for the number of languages spoken – the Chinese-speaking Asians were most likely bilingual in Chinese and English - so we cannot know for sure which if any of the observed differences may be attributable to the acquisition of an additional language.

In the next section (5.3) we report work-in-progress on grey-matter differences between Chinese and non-Chinese speakers.

5.3 VBM study on Chinese-English speakers

In order to examine the effects of the acquisition of a tone language, Crinion et al. (*in preparation*) compared grey-matter density in four different groups of subjects that comprised the factorial combination of (1) Chinese speaking or not and (2) English as a first language or not. They were therefore able to look for the effect of speaking Chinese that was common to both Asian and English subjects thereby excluding any confounds from differences in the morphometry of Asian and European brains. The 78 participants ranged in age from 18 to71 years (30 male, 48 female; mean age 31.5; sd = 14.4) and the number of languages spoken ranged from one to seven (mean 2.8, sd = 1.4)[2].

The analyses to date indicate highly significant effects of speaking Chinese. Compared to English monolinguals and European multilinguals, Chinese speakers showed highly significant enhancement of grey matter density in two regions of the right hemisphere: the superior temporal gyrus, anterior to Heschl’s and a region in the inferior frontal gyrus. In the left hemisphere, the Chinese speakers showed two regions of increased grey matter density: one in the middle temporal gyrus and a second in the superior temporal gyrus (posterior to Heschl’s gyrus), see Figure 1. Critically, the difference between Chinese speakers and monolingual English speakers and European multilinguals was shown both by Chinese speakers with Chinese as L1 and those with Chinese as L2. Such data confirm that the observed effect is a language effect rather than an effect of ethnicity.

In addition, speaking more than one language, whether European or Chinese, yielded an increase in grey matter density in the posterior supramarginal parietal region identified by the Mechelli et al. (2004) study. That is, there is a commonality of effect consistent with this region’s role in the integration of sound and meaning. Chinese speakers must also

[2]In classifying the number of languages spoken by our Chinese participants for purposes of analysis, we adopted a conservative approach. Individuals who spoke Mandarin and English clearly speak two languages. If a Mandarin-English speaker also spoke either Cantonese, Hokkien or Hakka they were treated as speaking three languages.

coordinate tone with other aspects of the speech signal for speech perception and production and this coordination demand may utilise the additional right hemisphere and left hemisphere structures identified in the VBM analysis.

6. General Discussion

6.1 Summary of line of argument and findings

Research using voxel-based morphometry (VBM) has established that the adult brain shows experience-dependent changes in a range of tasks, such as navigation, music and juggling consistent with the functional demands of those tasks. In accord with such evidence, we have presented and discussed data from English adolescents indicating that a specific region of the inferior parietal cortex (the posterior supramarginal gyrus) shows increased grey matter density as a function of vocabulary knowledge. Further, Italian-English bilinguals, relative to matched monolingual English controls showed increased grey-matter in exactly the same region consistent with their larger working vocabulary.

In terms of the functional role of this region, we proposed that it is well suited to linking the sound of a word (its phonology) to its meanings by virtue of its anatomical connections to other parietal regions involved in processing phonology and meaning. As such it should play a role in the acquisition of all languages.

Languages offer a number of means to signal lexical differences. A Chinese language such as Mandarin uses pitch patterns (tones) as well as consonants and vowels to distinguish different words. The representation of a lexical item must bind together all components. A Chinese-language speaker may therefore show additional regions of increased grey matter density relative to speakers of European languages. Ongoing work indicates that Chinese speakers do show increased grey matter density in additional right-hemisphere and left-hemisphere regions. Such increases may reflect neural resources allocated to process tonal distinctions for lexical purposes and/ or the requirement to store tonal differences in order to distinguish different lexical items.

6.2 Future lines of enquiry

Neuroplasticity and causal necessity—We have proposed that posterior supramarginal gyrus is sensitive to vocabulary knowledge and is part of a network of parietal regions involved in the representation and processing of vocabulary and one with a specific functional role: the binding of sound and meaning. We have treated the data as evidence of neuroplasticity. It is conceivable, however, that the data reflect consistent, pre-existing differences. In other words, those with greater grey-matter density are better at acquiring vocabulary. Such an interpretation seems implausible in the context of English adolescents, and, given the diverse reasons that lead individuals to become bilingual or multilingual (e.g., migration, schooling, career), it also seems implausible in the case of bilinguals and multilinguals. However, longitudinal studies of structural changes as individuals acquire another language (tonal or non-tonal) will provide stronger evidence of neuroplasticity.

Longitudinal studies will also permit an investigation of how the region of interest changes its interaction with other regions involved in the representation of vocabulary. We should expect that activation in the posterior supramarginal part of the parietal lobe will increase during the acquisition of vocabulary and this increased activation will be accompanied by changes in the interactions between this region and the regions subserving sound and meaning. In the case of acquiring a tone language such as Mandarin, changes in connectivity will also be relevant to interpreting the role of regions showing increased grey-matter density.

We have proposed a particular functional role for this region. Is this region therefore necessary for the acquisition of vocabulary? We cannot provide a definitive answer though parietal regions are implicated in vocabulary loss. Patients with head injury to the left parietal cortex in early adulthood, relative to patients with left temporal lobe damage, do show greater decline with age in their performance on vocabulary tests (they also show greater decline on arithmetic tests), Corkin, Rosen, Sullivan and Clegg (1989). There is also evidence of training induced changes in left inferior parietal cortex in relearning of words after left hemisphere damage (Cornelissen, Laine, Tarkianen, Jarvensivu, Martin and Salmelin, 2003).

Individual differences in the ease of acquiring other languages—Individuals differ in the ease with which they can acquire a novel language skill. There may be some factors that play a general role (e.g., hippocampal activity, see Breitenstein et al., 2005) and others that may be specific to language (Chee, Soon, Lee and Pallier, 2004, see Perani, 2005 for a commentary). Pre-existing structural or connectivity differences may lead individuals to acquire languages in different ways and so give rise to different bilingual phenotypes (Green, Crinion and Price, 2006). VBM analyses offer a way to examine such differences. Understanding the nature of such differences is also of practical relevance as it can inform interventions in second-language teaching.

One aspect of vocabulary acquisition is perceiving a novel speech sound. Golestani, Molko, Dehaene, LeBihan and Pallier (2007; see Golestani, Paus and Zatorre, 2002) found greater parietal lobe asymmetry in faster compared to slower learners. Both white matter and grey matter volumes were greater on the left compared to the right for faster learners. Conceivably, as they suggest, differences in connectivity between left auditory cortex and left inferior parietal language regions predict speech sound learning. In a production study, Golestani and Pallier (2007) found that individuals who were better at producing a novel speech sound had higher white matter density in regions implicated in articulation and phonological working memory.

It will be interesting to know which differences predict the ease of learning lexical tone.

7. Conclusion

Prior research showed that computational neuroanatomy techniques such as VBM can be used to determine the brain changes consequent on the acquisition of a non-verbal skill. Can such techniques be used to examine neural markers for vocabulary acquisition that is a key component of language use? Our review gives a positive answer. The VBM technique helps identify neural markers for vocabulary acquisition both in monolingual, bilingual and multilingual individuals. A region of the parietal cortex (the posterior supramarginal gyrus) shows increased grey matter density as a function of vocabulary knowledge. Chinese languages which use tone to help mark lexical distinctions show additional right and left hemisphere differences that may reflect processing requirements. Further cross-linguistic and longitudinal studies are required to develop our understanding of the role of this region and its linkage to other regions in the acquisition process. Neuroanatomical studies, we suggest, will play a vital role in understanding the neural requirements for acquiring different natural languages.

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Appendix 1 Glossary of terms

Diffusion tensor imaging (DTI): this magnetic resonance imaging technique provides information on the orientation of white matter tracts using information about local water diffusion for each voxel

Grey matter: nerve cell bodies together with axons and dendrites (see neuropil)

Magnetic resonance imaging (MRI): is a non-invasive imaging technique that uses properties of nuclear-spin resonance to build an image of tissue. Structural MRI allows a differentiation of grey and white matter (not possible under earlier techniques such as computerised-tomography). The term “structural” distinguishes these images from those of functional MRI that assesses short duration changes based, for example, on blood oxygenation

Neuropil: unmyelinated axons (and dendrites) within the grey matter

Voxel: a **vo**lumetric pi**xel** is a value in a three-dimensional space analogous to a pixel that refers to two-dimensional image data

Voxel-based morphometry (VBM): a whole-brain technique that characterises differences in brain volume and density on a voxel by voxel basis using structural magnetic resonance images (see text for outline description).

White matter: myelinated axons connecting grey matter regions

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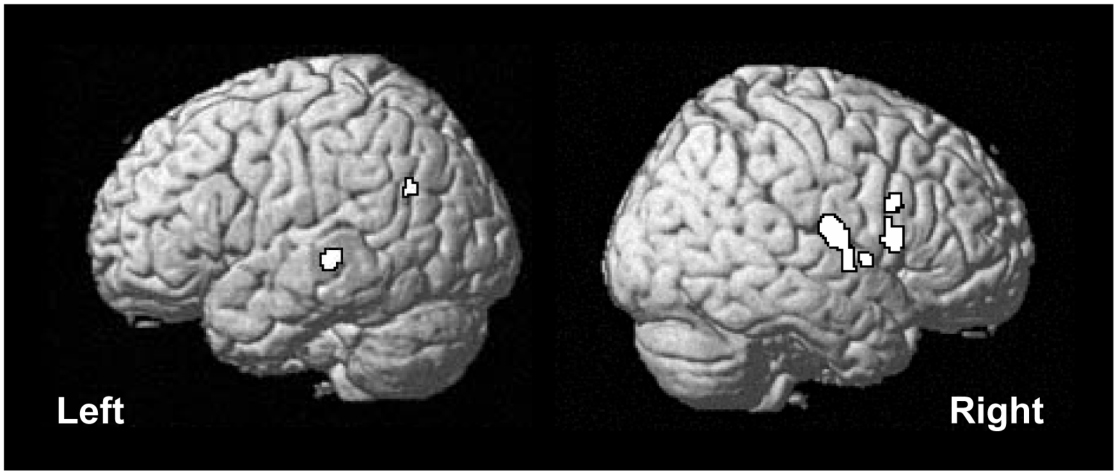

Figure 1.
Positive effect of speaking Chinese or not (Chinese and English learning Chinese> English monolinguals and European multilinguals) P=0.05 corrected for whole brain analyses.

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