Published in final edited form as:

Lang Learn. 2006 July 1; 56(S1): 99–125.

Convergence, degeneracy and control

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Abstract

Understanding the neural representation and control of language in normal bilingual speakers provides insights into the factors that constrain the acquisition of another language, insights into the nature of language expertise and an understanding of the brain as an adaptive system. We illustrate both functional and structural brain changes associated with acquiring other languages and discuss the value of neuroimaging data in identifying individual differences and different phenotypes. Understanding normal variety is vital too if we are to understand the consequences of brain-damage in bilingual and polyglot speakers.

Introduction: Scope and argument

A natural language allows us to coordinate action. Language is a tool to achieve such coordination. From this perspective, utterances are instructions to build a particular mental representation (the one a speaker has in mind) and speech production is a process of building such instructions. In acquiring a language we learn how to create instructions using a range of lexical, grammatical and prosodic means.

Languages differ in the weight they attach to these different linguistic means. In English, for instance, “who did what to whom” is conveyed by word order. In other languages, word order is less constrained and such information is conveyed by word endings or by prosody in tone languages (see Baker, 2003). These different linguistic means or signals require different neural devices for their processing. The particular properties of the language will affect the demands on particular processes. For instance, a tonal language will place greater demands on the neural devices involved in prosody. On the simplest assumption the acquisition of a second language will utilise existing devices and the particular properties of the language will affect the relative demands on these devices. So, for instance, acquiring a tone language will require using the system for intonation and prosody for purposes of lexical semantics. According to this proposal a natural expectation is that the neural representation of an L2 will converge with that of the native speakers of that language as proficiency improves (Green, 2003). Convergence predicts that the acquisition of another language will have both functional and structural consequences. We consider this issue in the first section (*Convergence: representation and control*) and draw out the role of neuroimaging studies in enhancing our understanding of how bilingual speakers control their languages.

In a second section (*Degeneracy and individual differences*) we argue that any challenge to convergence that relies on showing that different neuronal mechanisms are involved in task performance in L2 speakers needs to establish the extent to which different mechanism are in fact invoked by native speakers. For instance words in English can be read in different ways and task and individual differences may lead one strategy to predominate over another.

Neuroimaging data can help establish the range of phenotypes and their structural and functional bases.

Neuroimaging (in contrast to many current psychological models) points to the complexity of the circuits involved in language selection and control. In the third section (*Prospects*) we stress the need to discover how these processes are orchestrated. We argue that it is also important to devise studies that take account of the evolutionary context of language so as to obtain a more coherent view of the functional role that different neural regions play. We conclude that a cognitive neuroscience approach to second language acquisition is essential if we are to understand individual differences (phenotypes) in the ease of acquiring other languages or particular bilingual skills. It is vital too if we are to understand the intimate connections between language and the self and to theorise effectively about the consequences of brain-damage in bilingual and polyglot speakers.

Convergence: representation and control

A second language may be represented in different neural substrates or its neural representation may converge with the neural representations activated in native speakers. Proponents for the differential representation of a second language may appeal to evidence regarding the dedicated nature of neural machinery for language acquisition in infants especially in terms of grammar. Those in favour of converging representations can urge that particular substrates are better at processing certain types of information and will continue to do so (Green, 2003). We consider two kinds of consequence in the acquisition of another language: functional and structural. Structural consequences may arise as a result of functional demands. In functional terms, we focus on evidence concerning the neural regions activated in task performance.

Consider by way of illustration the acquisition of vocabulary in a second-language. Grant that a set of regions mediate the representations of words and their meanings (e.g., Vandenberghe, Price, Wise, Josephs & Frackowiak, 1996). Functional consequences will arise because words in different languages will access a common conceptual, sensory-motor system. Presenting words in one language will prime the semantic representation of its translation equivalent i.e., there will be a short-term neuronal adaptation. However individuals must also be able to distinguish words of one language from those of another. Conceivably then in some regions neuronal adaptation may be language-sensitive.

Other functional consequences of acquiring a second vocabulary are possible. One consequence arises because a given object can now be named in different languages and so individuals must select the relevant name thereby, potentially at least, giving rise to a problem of control.

On the supposition that functional demands induce structural changes, acquiring the vocabulary of another language means that regions involved in registering the phonological-orthographic and motor mappings must adapt in order to cope with an increase in the number of words to be represented. Such structural adaptation should be detectable. If it is the case that acquisition increases the demands on the systems involved in controlling language there should also be evidence of structural changes in the regions associated with control. We consider evidence from our own work for such functional and structural consequences.

Functional consequences: neuronal adaptation

Prior neuroimaging studies on bilinguals have examined the existence of a common system using word generation tasks and metalinguistic judgement tasks that involve a large number

of other component processes. Other studies have used semantic judgement tasks using single words. For instance, Illes et al. (1999) required a group of fluent English/Spanish speakers to perform a semantic task (is the presented word abstract or concrete?) and a nonsemantic task (is the word in upper or lower case?) in both English and Spanish. They observed no language differences. Relative to the nonsemantic task, the semantic task on both English and Spanish words activated a common left inferior frontal region. Likewise, Pillai et al. (2003) found that Spanish/English bilinguals activated the same left frontal and temporal regions during a noun-verb matching task irrespective of whether the words were in English or Spanish. However, language differences did emerge in the Pillai et al. (2003) study during rhyming decision (do two presented words rhyme or not?) with increased activation in right frontal and parietal regions when the words were presented in English.

To dissociate language sensitive effects within shared semantic regions, we used a semantic priming technique in which a target word is preceded by a prime word that is closely related to it (for instance, the prime might be semantically-related to the target or be a translation equivalent of it). In behavioural research, normal proficient bilinguals show priming effects in both L1 and in L2 but the pattern of cross-language priming depends on the nature of task. When individuals are required to perform a lexical decision task, priming is greater from L1 to L2 than from L2 to L1. This pattern also obtains where the prime is in one script (an alphabetic one, for instance) and the target is in another script (a logographic one such as Chinese or Japanese –see Jiang & Forster, 2001). The lexical decision task is a metalinguistic task and arguably sensitive to strategic factors or to possible differences in the semantic organization of words in L1 and in L2 (see Finkbeiner, Forster, Nicol & Nakamura, 2004). In contrast, when moderately fluent bilinguals perform a semantic categorisation task, priming, at least for translation equivalents, is also robust from L2 to L1 (Grainger & Frenck-Mestre, 1998; Finkbeiner et al., 2004). We sought to minimise any effects of language direction and so used a property verification semantic task.

If words in different languages access the same neural populations for the meaning and the referents of concrete words then semantic priming should be the same in the between-language condition as in the within-language condition. The effect of priming should be to induce neuronal adaptation –decreased activation to a target primed by a translation-equivalent or by a semantically-related word.

Previous fMRI studies (Chee, Soon, & Lee, 2003; Nakamura, Dehaene, Jobert, Le Bihan & Kouider, 2005) have used priming techniques to examine script-specific language responses. In Chee et al (2003) English-Mandarin speakers silently read English words preceded either by the same or different word in English or in Chinese. There was evidence of neuronal adaptation irrespective of language but no evidence of language-sensitive neuronal adaptation. In Nakamura et al. (2005), native Japanese participants decided whether or not a target word referred to a natural object or to an artefact. Targets were preceded subliminally by same or different words written in either the same script or in a different script. Neuronal adaptation was sensitive to the script but it is unclear whether this effect arose at the visual or at the lexical level.

In our priming task (Crinion et al., submitted) individuals were presented with a property contrast (e.g., short-legs vs long-legs) and had to decide which property best described the object referred to by a target word. The target word (e.g., BULL) was preceded by a prime (for 250 ms) that was either related to it semantically (i.e., from the same category or sub-category, e.g., cow) or that was unrelated to it (e.g., locust). In addition, target and prime were either in the same language (either L1 or L2) or in a different language¹. Words were presented visually with the prime in lower case letters and the target in upper-case letters. To perform the task, individuals must recognise words, retrieve their meanings and a

representation of their referents, discriminate the referent of the target, verify a property of it and respond by pressing one response key or another.

We sought to identify regions that were sensitive to both the semantic relationship between the prime and the target and to the language of the stimuli (i.e., where semantic adaptation arises only when prime and target are in the same language but not otherwise).

We established generality and robustness using three different bilingual groups. One group of German-English bilinguals ($n = 11$) participated in a positron-emission tomography experiment (PET). A second group of German-English bilinguals ($n = 13$) and a third group of Japanese-English bilinguals ($n = 9$) participated in functional magnetic imaging (fMRI) experiments. All participants had moderate to high proficiency in English and indeed were equally accurate in both languages. As expected, relative to unrelated controls, individuals were faster to respond to targets when primed by a semantically-related word irrespective of language.

The neuroimaging data confirm and amplify the behavioural data. As expected, a common semantic system was activated. A semantically-related prime reduced activation in a region of the left anterior temporal region irrespective of the language of the prime or the target. This region was in a region of interest predicted on the basis of previous semantic priming effects in monolingual speakers (e.g., Mummery, Shallice & Price, 1999).

The most robust language selective response lay in a subcortical structure – the left caudate nucleus. Here a semantically-related prime only reduced activation (i.e., elicited neuronal adaptation) if it was in the same language as the target (whether that language was German, English or Japanese). Expressed differently, left caudate activation was higher for semantically-related words in different languages. Such sensitivity to the language of input is compatible with this region's involvement in language switching (see Abutalebi, Miozzo & Cappa, 2000) and in the present case would seem to imply a “cost” of switching languages. In the next section we consider the costs of using an L2 in a picture naming task.

Functional consequences: interference in naming

Functional data from bilinguals need to be interpreted in the light of the problems of control. For instance, demonstrating that bilingual speakers show increased frontal activation in certain tasks (eg., Abutalebi, Cappa & Perani, 2001) does not imply that the neural representation for L2 is more extensive than that for L1. It is more likely to reflect increased effort in selecting amongst competing alternatives or in producing the less familiar name (Abutalebi & Green, submitted).

In a PET study, De Bleser et al. (2003) examined picture naming in proficient Dutch-French bilinguals using a design in which subjects named pictures in either Dutch or French in the same experimental session. They found increased activation in naming in L2 for non-cognate names in a left inferior temporal region associated with semantic retrieval (e.g., Vandenberghe et al., 1996). There was also increased activation in regions of the left inferior frontal gyrus associated with phonological retrieval or decisions and semantic retrieval in the face of competition (see Devlin, Matthews & Rushworth, 2003).

¹There was one further condition in which the prime was the translation equivalent of the target word. Lexical primes yielded faster reaction times than semantically-related and unrelated primes but did not differ in accuracy. The largest effect of lexical priming was in the calcarine sulcus which may indicate less visual imagery when the prime and target refer to the same object than when they refer to two different objects.

We sought to extend our understanding of the production of non-cognate names by non-native speakers by using a range of tasks (e.g., semantic judgements, reading and naming). Relative to native speakers, relatively proficient L2 speakers may be slower to access meaning and slower to retrieve and to generate the phonological representation of a word. Processes associated with an increase in the difficulty of access, retrieval or generation may be contrasted with those specifically associated with resolving any competition between languages. Such a view suggests that it may be possible to identify separate regions in the inferior frontal cortex associated with naming objects versus reading words.

We contrasted the activation patterns of Greek-English bilinguals (of moderate to high proficiency in English, $N = 14$) with a group of native English speakers ($N = 16$) matched for task performance in a two by two design with the factors of task (semantic decision and naming) and modality (pictures of familiar objects and their written names). For each task by modality condition there was a specific baseline.

In the semantic task on words subjects decided whether the top word of a triad was more closely related in meaning to the lower left or lower right word (Figure 1.1a). Its baseline comprised three meaningless strings of symbols (Figure 1.1b) and subjects judged whether the top stimulus looked identical to the meaningless stimulus on the lower left or lower right. In the condition where subjects reached a semantic decision on pictures, they judged whether the top picture was related more closely to the picture on the lower left or lower right (Figure 1.2a). For the baseline task, they decided whether the meaningless object on the top was identical or not to the stimulus on the lower left or lower right (Figure 1.2b). In the reading task they read the three words aloud (Figure 1.1a) or said “one, two, three” to the set of meaningless strings (Figure 1.1b). In the naming task, subjects named all three pictures starting with the top stimulus then the lower left stimulus and finally the lower right stimulus (Figure 1.2a). Again, to control for visual input and motor output, the naming baseline task required subjects to say “one, two, three” while looking at the three meaningless objects (Figure 1.2b). Response accuracy and time were recorded for semantic or perceptual button presses and vocal responses (reading, naming aloud and saying “one, two, three”) were recorded and subsequently analyzed for accuracy.

As expected, during semantic decisions, both groups activated the left inferior and middle temporal regions that have been associated with semantic retrieval in many previous studies (e.g., Vandenberghe et al., 1996) and there were no group differences in activation for semantic relative to perceptual judgements on either words or pictures. Group differences did emerge, however, during the vocal conditions even when response accuracy was closely matched. Greek-English bilinguals showed increased activation in three left-lateralised frontal regions (premotor cortex, ventral inferior frontal cortex and dorsal inferior frontal cortex).

In the premotor cortex, the effect is likely to reflect increased demands associated with articulation because increased premotor activation in Greek-English bilinguals was observed for naming, reading and the vocal baseline (saying 1,2,3) but not during the semantic or perceptual matching tasks. In the ventral inferior frontal region, the effect is likely to reflect increased difficulty in semantic retrieval as this region is more involved in semantic than phonological retrieval (Devlin et al., 2003). Finally, in the dorsal inferior frontal cortex, the increased activation in the bilingual group was only observed for picture naming in comparison to reading. The latter result is consistent with the idea that naming elicits between-language competition. One test of this idea would be to examine the effect on this dorsal region of the left inferior frontal cortex after the name of the picture had been primed in the other language (see Kroll, Wodniecka, Bobb & Green, 2005, for behavioural research using this competitor priming technique).

Structural consequences: vocabulary acquisition

Acquiring another language involves acquiring additional vocabulary (word forms and morphemes) that must link to the conceptual, functional and sensory representations of their referents and interface with combinatorial syntactic and phonological processes. To the extent a common substrate is involved there may be adaptive changes in brain structure relative to monolingual speakers. We can address this question by examining differences in brain structure (morphometry) on a voxel by voxel basis across the whole brain. The technique, known as voxel-based morphometry (VBM), compares the density or volume of grey or white matter in stereotactically normalised structural MRI brain images. Prior research provides evidence of plastic changes as a function of expertise in various tasks (e.g., Maguire et al., 2000; Draganski et al., 2004).

Mechelli et al. (2004) examined the possibility of grey matter differences in the brains of bilinguals compared to monolingual controls. They found increased grey matter for bilinguals in the inferior parietal lobes and in a sample of Italian-English speakers, grey matter density in the same regions was found to correlate with second language proficiency. This same region is sensitive to vocabulary growth in children and young adults: as English vocabulary increases there is a concomitant increase in grey matter density in children and young adults (Lee et al., submitted) irrespective of verbal or nonverbal IQ or verbal fluency abilities.

In current work, we are examining the effect of acquiring multiple languages. Our opportunistic sample comprises 87 bilingual and multilingual individuals [53, bilinguals; 21, trilinguals; 8, quadrilinguals and 5 individuals with 5 or more languages]. We search the whole brain for language correlated effects, rather than focusing on any specific cortical region of interest. Preliminary analyses indicate an area in the left parietal cortex that shows a significant effect of the number of languages spoken. The peak of the effect is anterior to the area shown in the Mechelli et al. (2004) paper. Further comparisons (comparing between two languages, and three/four languages and three/four languages vs five/six/seven languages) suggest that the acquisition of multiple languages leads to an expansion of a grey matter, rather than greater grey matter density and we are currently exploring its basis.

Structural consequences: control

Work by Bialystok (e.g., Bialystok, Craik, Klein & Viswanathan, 2004) suggests that the acquisition of another language increases skills associated with selective attention in the young and protects against loss of skills in selective attention in the elderly. It is natural to wonder what structural changes this implies. If there are structural changes then this suggests that acquisition can have long-term effects because such structural changes should make the acquisition of other languages easier. However, in the normal case, i.e., where an individual develops no specialised skill such as becoming a simultaneous interpreter, it may not be the case that the regions associated with control become more extensive as the number of languages acquired increases. Conceivably, changes in the way lexical information is represented, reduce control demands. For instance, connections within the language may become stronger than those between the languages (see, for example, Paradis, 2004; Abutalebi & Green, submitted) and the acquisition of a further language may establish such linkage from the start.

In the first instance, evidence for specific effects might be better sought by examining the consequences of acquiring specific and unique skills associated with becoming bilingual. We examined structural effects in the brain (using VBM analyses of structural MRIs) of six simultaneous interpreters. Our preliminary analyses suggest that the acquisition of specific skills is indeed associated with changes in a number of subcortical regions.

We found grey matter density to be higher for our sample of 6 simultaneous interpreters compared to other monolingual, bilingual and multilingual speakers in three regions:- bilateral putamen, the inferior (and superior) colliculi and the bilateral dorso-medial thalami. We had expected an effect in the putamen on the basis of our prior imaging work on translation in normal bilinguals (Price, Green & von Studnitz, 1999) but had not predicted the latter findings. And, perhaps contrary to expectations, found no effects in the caudate. Based on Behrens et al. (2003) it is probable that the regions of the thalamus connect to both the temporal lobes and the prefrontal cortex. Further, these regions connect strongly to the inferior colliculi that are involved in auditory processing (the superior colliculi are involved in visual processing). It is conceivable then that these regions form part of the same circuit involved in the storage and manipulation of linguistic input.

In summary so far: current research indicates that the neural representation of an L2 converges with that of L1 and that this has both functional and structural consequences. Current structural studies need of course to be supplemented by longitudinal studies to examine plastic changes as a language or language skill is acquired. Our data point to the relevance of such studies especially if we are to disentangle effects of acquisition from pre-existing differences. The notion that the neural representation of an L2 converges with that of an L1 does not deny that there may be language-specific neuronal sites within these regions. Studies using cortical stimulation mapping (e.g., Ojemann & Whitaker, 1978; Lucas, McKhann & Ojemann, 2004) identify sites at which naming is selectively disrupted for one language but not for another. Such selective disruption may alternatively reflect differences in the relative computational demands for producing a particular word.

Degeneracy and individual differences

On the face of it, convergence is refuted by evidence that non-native speakers activate different substrates compared to native speakers of that language. For instance, given that the same anterior regions are involved in grammatical operations for comprehension and production within an L1 (Indefrey, Hellwig, Herzog, Seitz, & Hagoort, 2004), evidence that grammatical operations in L2 are handled by a distinct posterior system (see Ullman, 2001) would seem to refute the claim of convergence. Our aim is not to review the evidence on this point, nor its computational basis (see Green, 2003) but to consider the logic of any such challenge. A challenge of this type hinges on the presupposition that native speakers invariably process their language using the same method and a single substrate. But native speakers may use different methods and different substrates for achieving a common end: there may be functional degeneracy. Degeneracy (see Edelman & Gally, 2001; Price & Friston, 2002) refers to the ability of structurally-different elements to perform a similar function or achieve the same outcome.

Functional degeneracy operates when more than one system is sufficient for the same function. Friston and Price (2003) give the example of waving goodbye. The function “waving goodbye” is degenerate because waving with either the right hand or with the left hand will suffice. Redundancy (e.g. waving with both hands) contrasts with degeneracy and can only be expressed given a degenerate set (i.e., here, a set of two hands). Degeneracy is ubiquitous in biological systems (see Edelman & Gally, 2001, Table 1, p. 13764: e.g., in the immune response, populations of antibodies are degenerate- they bind equally well to the same antigen; in human communication there are many different ways to transmit the same message). Indeed degeneracy is prerequisite for natural selection because selection pressures can only operate on dissimilar organisms (Edelman & Gally, 2001, p. 13766). In general, different gene networks contribute to each phenotypic feature and since selection has no way to assign responsibility to particular gene loci, degenerate systems will be maintained and favoured (see also Tononi, Sporns & Edelman, 1999). The presence of a degenerate

structure or mechanism does not mean that each mechanism is functionally equivalent. Each variant offers novel properties. A degenerate system can therefore generate different outputs in different contexts. It is therefore adaptable in the context of different and perhaps novel environmental demands.

The concept of degeneracy allows us to take account of intersubject variability in a neuroimaging study (see Price & Friston, 2002, p. 417): a distinct pattern of activation in one subject may reflect not random error but a degenerate system for performing the task. The notion of degeneracy therefore provides a way to address the important issue of individual differences.

What kinds of signature exist for the presence of degenerate systems in normal individuals? One signature is that where there are two degenerate systems, activation in one system is inversely related to activity in the other. Normal variability in performing the same task offers a strong guide as to the presence of distinct systems (see Price and Crinion, 2005). A second signature is distinct patterns of activation under different stimulus constraints, e.g., under noise, time pressure or mental load. In an innovative study on bilinguals, Chee, Soon, Lee and Pallier (2004; see Perani, 2005 for a review) contrasted two types of English-Chinese bilinguals in Singapore both with excellent first-language attainment but who differed in second-language attainment despite strong pressures to achieve high proficiency in both languages. They measured brain activation as a function of phonological working memory load using foreign language words (bisyllabic French words and pseudo words). Both groups showed activation changes as a function of load. A region in the left parietal lobe, linked to phonological storage, increased with load in both groups. Despite common performance levels in the two groups, the patterns of activation with increasing load differed in other regions. For the equal proficiency group there was a larger increase in the left insula and the left inferior frontal gyrus. For the unequal proficiency group, there was greater activation in the anterior cingulate gyrus and reduced activation in areas of the parietal cortex (frontal medial and posterior). These data suggest that bilinguals showing equal proficiency in both languages were better at engaging a system suited to vocabulary acquisition such as phonological working memory (see Baddeley, Gathercole & Papagno, 1998; Papagno & Vallar, 1995). The findings for the unequal proficiency group are consistent with the idea that they need to allocate greater attention to the task.

A third possible signature comes from brain-lesion data. So, for example, the apparent use of the right hemisphere post-stroke in monolinguals may reflect use of a pre-existing degenerate system (Crinion & Price, 2005). Such an inference (see Price & Crinion, 2005) may be explored by examining whether performance is further impaired or is improved by a temporary lesion induced in the right-hemisphere by transcranial magnetic stimulation (e.g., Thiel et al., 2005). In bilingual stroke patients, if the predominant pattern is of impairment then we can infer that there is a degenerate system. Post-stroke such a system becomes functionally useful. (The presence of such a degenerate system does not imply a greater incidence of aphasia in bilingual individuals with right-hemisphere stroke, see Fabbro, 1999).

Degeneracy is important in terms of understanding the neural effects of acquiring a given L2 in the context of different native languages. For instance, is it the case that different neural systems are involved in reading English by individuals whose first script is logographic (e.g., Chinese see Wang, Koda & Perfetti, 2003 for a relevant behavioural study and Tan et al., 2003, for a functional imaging study)? In order to address this question we need to know the range of normal variation in native speakers and we need to determine if non-native speakers show the same or different response when required, for example, to read aloud pronounceable non-words. Similar considerations apply when we consider the processing of regular and irregular verb forms in English. The regular past tense in English can be made

by adding the affix/-d/ to the stem of the verb [bless-blessed]. The irregular past tense associated with a closed set of about 160 verbs requires the rote learning of each instance (e.g., make-made). On the basis of priming data from normal, native speakers of English, Tyler, Stamatakis, Post, Randall and Marslen-Wilson (2005) argue that whilst irregular forms (teach-taught) are handled by a (bilateral) temporal lobe system storing whole forms, regular verbs (bless/blessed) require the additional involvement of left frontal systems supporting processes involved in assembly and disassembly (i.e., processes that identify the stem and affix, e.g., bless plus -ed). Whilst the past tense of irregular verbs must be learned as rote forms, it is possible that the past tense of regular words could be retrieved rather than computed (see Ullman, 2001). Any finding that non-native speakers use retrieval rather than computation does not by itself refute convergence. We need first to establish the nature of individual differences in native speakers where the precise method used for processing regulars may depend on the task and/or on individual differences in the ease of performing a given computation.

Different phenotypes may arise not only as a result of the nature of the first acquired language but also as a result of pre-existing structural or connectivity differences. A distinctive cytoarchitecture in right and left Broca's area seems implicated in the amazing facility of Emil Krebs (1867-1930) who spoke more than 60 languages (Amunts, Schleicher & Zilles, 2004). Work by Golestani, Paus and Zatorre (2002) suggests that individuals who acquire a difficult phonetic contrast more easily had more white matter in parietal regions, especially on the left. They speculate that this may reflect greater myelination allowing more efficient processing. Conceivably, small structural and or connectivity differences, triggered the different patterns of processing revealed in the study by Chee et al. (2003). If research should identify examples of the impact of prior structural or connectivity differences in the acquisition process then there will be practical consequences for the design of second language teaching.

Prospects

Neuroimaging data can help us discover how individuals become skilled users because they help us identify the network of control that mediates the use of language. Current psychological models of speech production in bilingual speakers often assume a single locus for language selection whether at the level of the goal, lexical node or at the stage of response (e.g., Costa, 2005; La Heij, 2005; Roelofs, 2003) and ignore the network.

At the most general level, as Sperry (1986) argued, language in the brain is asymmetrically organised and normal use may involve suppression of homologous areas in the right hemisphere so that their distinct contributions can be orchestrated effectively (e.g., syntactically organised sequences generated in the left and prosody and tone added in the right). Normal use then may involve the suppression of degenerate systems that could potentially carry out the task.

Even a cursory analysis of the task of speech production in bilinguals points to numerous processes in language selection and control². A particular type of pre-verbal specification may be required (de Bot & Schreuder, 1993), the goal to speak in one language rather than another must be maintained and competing tasks (e.g., translating the input or repeating it)

²Such a view is compatible with the recent framework proposed by Hagoort (2005) with the proviso that aspects of control permeate all of the functional components distinguished and not just the one labelled control. Hagoort distinguishes three functional components of language processing: a Memory component, a Unification component and a Control component. The Memory component comprises the types of language of language information including retrieval operations. The Unification component refers to the processes involved in representing multi-word utterances and the Control component refers to the use of language in a given situation and covers the selection of a language and turn-taking.

managed (Green, 1986; 1998a). It is likely that these different levels of control are mapped onto distinct components of a fronto-parietal-subcortical circuit (see Price et al. 1999; Abutalebi, Miozzo & Cappa, 2000; Abutalebi & Green, submitted). Given its unique connectivity to a wide range of sensory, motor and associative systems, the prefrontal cortex can exert “top-down” influences on a wide range of processes. It interconnects strongly with the parietal cortex and this circuit is implicated in the selection of competing responses. Subcortical regions, in addition to cortical regions, are essential to the acquisition of perceptual-motor mappings (Callan, D. et al., 2003) and to cortical control. A left basal ganglia-left prefrontal cortex circuit may subserve language planning and suppress competing responses (e.g., Friederici, Kotz, Werheid, Hein, & von Cramon, 2003; Longworth, Keenan, Barker, Marslen-Wilson & Tyler, 2005).

We have focussed primarily on the question of the nature of the neural systems involved. We also need to understand the dynamic orchestration of these neural systems and how that changes with proficiency. Does convergence in terms of the neural representation of a language imply that the dynamics of speaking an L2 will be identical to that in native speakers of that language? That is, does the processing profile in understanding a sentence or producing an utterance converge with that of the nature of speakers? If there is neural convergence then as we have already argued there is the possibility of competitive effects at output and at input (see Dijkstra & van Heuven, 2002).

Mapping conceptual intentions onto speech may also invoke competing grammatical operations. Indeed, the very act of acquiring another language may affect the grammatical options used in the person's native language. Convergence implies that the bilingual must adopt means to regulate two systems (e.g., Grosjean, 1998; Green, 1998a) but it leaves open the question of the extent to which systems under control evolve to become equivalent to those of the native system as proficiency increases (e.g., Paradis, 2004, chapter 7) and the factors (motivational, neural and social) that may limit or constrain such equivalence.

Identifying higher-order functions

Granted that different regions coordinate to achieve task performance, it is still puzzling that a particular region may activate in seemingly different tasks (see Stowe, Haverkort & Zwarts, 2005). There are a number of possible responses to this state of affairs (see Price and Friston, 2005). Conceivably, within a region, there is a specialisation of function that is outside the resolving power of current methods. Alternatively, the region may mediate some unknown higher-order function. The second does not preclude the first in that a higher-order function may require specialised circuits for particular domains (e.g., language). In order to explore the possibility that there is some higher-order function we need to examine a range of different tasks and to have some principle of selection. We offer one discovery heuristic based on the view that language is a tool for coordinated action.

On evolutionary grounds we might think there is a close connection between language and action even if specialised circuits evolve. Lewis Wolpert (2003) remarked that the primary function of brains is to control movement. We move of course to approach things that we want and to avoid things we do not want. But we also act to shape the world to create what we want and to avoid what we don't. We can consider possible future states of affairs and how to bring these about. We use our hands to shape the world and we use our hands to construct tools to better shape the world as we want it (see Johnson-Frey, 2003 for a review of the neural underpinnings of humans tool use). Language is one of the tools we use to achieve coordinated action to achieve goals³.

Whatever the nexus of changes that led to the emergence of natural language (see Arbib, 2005) and its subsequent cultural development, in acquiring language we become skilled in

using a tool that allows us to coordinate actions. The cognitive operations involved in retrieving meaning and constructing sentences are analogous to the operations we would use in achieving some change in some actual or imagined world.

One discovery heuristic for identifying higher-order functions is this:- contrast patterns of activation on verbal and non-verbal tasks that involve actions. For instance, what is the relationship between generating a sentence specifying a sequence of actions on particular objects and imagining or performing that sequence of actions?

The precise nature of our actions depend on the tool. Clearly, language production involves control over oral-facial muscles as part of the production of vocal gestures. Moving, or envisaging moving a hand, involves a distinct system (though there is a connection, see Gentilucci, 2003) so the interest lies in the nature of any patterns of common activity linking regions associated with the representation of objects, their position in space and the semantics of changing one state into another. Our actions depend not only on the tool and its properties (for instance, consider the difference between tennis and badminton) but also our proficiency in using it. By contrasting activation patterns in different domains we can identify higher-order functions mediated by particular neural regions and so begin to probe different acquisition trajectories and different bilingual phenotypes in a more coherent fashion.

Language as a neuroprosthesis

There is an important relationship between tool use and the human body which may be relevant to our understanding about the effects of language acquisition. One of the phenomenological consequences of proficient tool use is that the tool becomes an extension of the body. Prior to that point, use is subjectively unnatural. We can think of language as a neuroprosthetic device - it helps shape how we sense and perceive the world. The use of a language becomes part of the self although the extent to which it does so - and becomes natural - depends on our proficiency.

The autobiographies of bilingual writers point to the importance of language to the sense of self ("this language is beginning to invent another me", see Pavlenko, 2001; Green, 1998b). Language also functions as a means for the internalisation of cultural values. Marian & Kaushanskaya (2004) confirmed earlier work showing how the language in which memories are to be recalled affected the content of what is recalled and the manner of its description. Recalling memories in Russian as opposed to English increased the use of group pronouns ("we", "our") over personal pronouns ("I", "me") consistent with the more collectivist nature of Russian culture. The switching of cultural frames of reference may also be expected to shift personality differences in a direction consistent with the cultural values (see Ramirez-Esparza, Gosling, Benet-Martinez, Potter & Pennebaker, 2006 for results consistent with this notion).

Acquisition then involves a potential shift in the way in which individuals engage in the world. Neuroimaging studies of bilinguals might be expected then to contribute to a deeper understanding of ourselves as languaging beings.

³Certainly recursiveness, considered the key feature of natural language (Hauser, Chomsky & Fitch, 2002) is also a property of composite tool construction (Ambrose, 2001). Composite tools, such as an axe, are structured compositions of different units (a shaft, a stone insert and binding materials). Variation in basic units and alternative compositions create functionally different tools (e.g., a scraper, a spear). The formal analogy is to grammatical language where different structured sound sequences convey different phrases. Perhaps such a relation is unsurprising and is a correlate of a change in the capacity of the brain, as a result of an increase in connectivity (see Treves, 2005), to generate infinite sequences of elements from a finite set of such elements.

Conclusions

Acquisition of another language induces both functional and structural brain changes. Functional neuro-imaging methods offer a way to understand individual differences in the process of acquisition and in the manner in which proficiency is expressed both in terms of the nature of the neural representations involved and in their control. Understanding such variety is vital if we are to understand the nature of recovery patterns in bilingual and polyglot speakers. We need, for instance, to know the extent to which recovery is mediated by a normal degenerate system or solely by spared tissue.

Acknowledgments

We thank the Wellcome Trust for support. We thank Bob Turner and Japanese colleagues, Joe Devlin and members of our immediate team Alice Grogan and Nilufa Ali. A number of MSc students, Kath Stockton, Christos Pliatsikas, Marie-Luise Mechias and Sylvie Orabona also contributed, and we thank them for their efforts.

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Figure 1.
Examples of types of stimuli used in the fMRI naming study of Greek-English bilinguals