

# Understanding the link between bilingual aphasia and language control

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## Abstract

The study of bilingual aphasia is important because we need to be able to recommend treatments consistent with a plausible estimate of the course of recovery. Yet we lack a causal account of recovery patterns. We distinguish between the neural representation of a language network and the regions involved in the control of that network. Contrary to some claims, we argue on the basis of normal data that a single adapted network underlies the representation of more than one language and identify a frontal–(parietal)–subcortical network in its control. In terms of patient data, the broad expectation is that recovery of L1 and L2 will parallel premorbid levels of proficiency where there is no problem of language control. Recent advances mean that such an expectation can be tested on samples of patients rather than by sampling cases reported in the literature. Voxel-based morphometry can be used to relate variations in grey-matter density to variations in task performance. Understanding this relation can then help provide an estimate for future patients of the likelihood of improvement over time or a yardstick against which to measure the effectiveness of any intervention. In addition to this large sample approach, the study of individual cases remains key to achieving an understanding of the connections between representation and control and recovery patterns. We review recent cases of the effects of frontal–subcortical damage in bilinguals and argue that they provide evidence of effects on language selection and control rather than evidence for distinct neural networks underlying the processing of a second language. We conclude that there are good prospects for substantially improving our understanding of recovery patterns and that neuroimaging studies during recovery will provide further constraints on the mechanisms of control. © 2008 Elsevier Ltd. All rights reserved.

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## 1. Introduction

There is a pressing need to understand the causal basis of recovery patterns in bilingual aphasia in order to have a principled basis for treatment. As Paradis (1995) noted, we currently lack such an understanding yet the incidence of bilingual aphasia is likely to increase and become a clinical issue of primary importance because modern society is becoming more and more bilingual and multilingual. In the case of the United States, Paradis (2001) estimated, on the basis of census data, that there will be well over 45,000 new cases per annum. A similar incidence is to be expected in Western Europe because of a migrating workforce. In this paper, we argue for a specific approach to this problem.

### 1.1. Overview of the paper

We first distinguish between the language network and the circuits involved in its control that allow individuals to select one language over another or to translate between them. This distinction is relevant for understanding patterns of recovery in bilingual aphasics. For instance, the selective recovery of one language (see Paradis, 1998, 2004 for a description of the variety of recovery patterns, also Section 4 below) is consistent with a traditional “localizationist” view that different languages are represented in distinct processing areas. A lesion affects neural substrate supporting processing in that language. However, if the acquisition of a second language (L2) utilises, right from the start, the devices used for processing the first language (L1) then it is plausible to suppose that the languages of a bilingual are represented in a shared network rather than in distinct processing networks. We argue on the basis of both neuroimaging and neuropsychological data that languages are represented in a shared network (see Section 2). But if this is the case, we need another account of selective recovery. We argue for a more “dynamic” view in which selective recovery reflects an impairment of language control, i.e., the ability of the system to select one language over another. Cortical and subcortical (basal ganglia) circuits mediate such control and so damage to such circuits may affect the extent to which individuals recover full use of their premorbid languages.

Researchers may concede that a common substrate underlies the representation of words in different languages but hold different views on the way in which the grammatical aspects of two language are represented. We consider this matter in some detail. According to one proposal, the declarative/procedural model (Ullman, 2001a), the grammar of an L1 is represented in a procedural system that also mediates other kinds of skill whereas the lexical items of the language are represented in a declarative system that also represents other kinds of fact. Ullman (2001b) extended this notion and proposed that the grammar of L2 is likely to be represented in the declarative system. In fact, Ullman (2001b, 2005) argued for a version in which reliance on the procedural system increases with growing L2 proficiency. Neuroanatomically, the procedural system is held to be mediated by frontal–basal ganglia circuits. Indeed in the literature, Ullman’s model, has been used to account for the selective recovery of a language following damage to the basal ganglia. We therefore consider the claims of this model and, in particular, review evidence on the syntactic representation of L1 and L2 in bilinguals (see Section 2.1). We conclude in favour of shared representation of grammar for L1 and L2 and so argue for the importance of language control for understanding recovery patterns.

Traditionally, the focus of enquiry in the study of bilingual aphasia has been the single case and such cases remain very important for exploring the causal mechanisms of recovery especially when combined with neuroimaging data. Recent advances in whole-brain neuroanatomical techniques permit a complementary approach in which researchers examine the relationship between grey matter (or white matter) and behaviour in various tasks in larger samples. Our expectation, presented in Section 3, is that where individuals can use their language appropriately (i.e., there is no problem of language control), regions associated with good task performance in monolinguals will be those associated with good performance in bilinguals. Further, regions predictive of relative good performance on some task relative to another in L1, will also predict relative task performance in L2. Assessment of grey-matter density in a post-acute phase may then be used to estimate likely performance over time. In this way the benefits of any intervention can be assessed against the predicted profile.

The study of individual cases remains important because of the relative infrequency of certain types of lesion that may be associated with impaired control. Where there is selective recovery of a language, or an inability to speak in just one language, we argue (see Section 4), consistent with data discussed in Section 2, that such a pattern reflects impaired control induced by damage to frontal–basal ganglia circuits. We conclude by emphasising the value of the in-depth investigation of single cases using neuroimaging.

## **2. The language network, its adaptation and control**

Natural languages make use of a range of lexical, grammatical and prosodic means though they differ in the relative importance of these for conveying a speaker's meaning. In English, word order signals "who did what to whom". In other languages, word order is less constrained and such information is conveyed by word endings or by prosody in tone languages. These different linguistic means 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. The processing of its lexical, grammatical/morphological properties and its prosody, will lead to its representation in a network shared with L1 (Green, 2003, 2005; Green, Crinion, & Price, 2006). The particular properties of the L2 will affect the relative demands on these devices and as proficiency increases the profile for processing in L2 will tend to converge with that of native speakers of that language.

This single adaptive network view contrasts with the views of Ullman (2001b) (see also Ullman, 2005 for a wide-ranging review of the application of the declarative/procedural model to second-language acquisition). The declarative/procedural model (Ullman, 2001a) proposes that in normal monolinguals, words are represented in a declarative memory system whereas grammatical rules are represented in a system that mediates the use of procedures including non-verbal skills. These two memory systems are held to be mediated by distinct neural systems: a frontal–subcortical circuit (including the basal ganglia) mediates the procedural system whereas a temporo-parietal system mediates the declarative system.

Given this distinction, Ullman (2001b, 2005) further argued that although the grammar of L1 is represented procedurally, the grammar of L2 can be represented in the declarative system. Such a proposal may be justified, at least for a language acquired late, on the

assumption of a critical or sensitive period for language acquisition. Paradis (1994, 2004) points out that whereas L1 is acquired implicitly an L2 may often be acquired explicitly in the sense that its grammar may be taught. Although the processes involved in perceiving or in producing words always remain inaccessible to conscious awareness, individuals may have declarative knowledge of the grammar in one case but not in the other. Conceivably, then, the grammatical aspects of an L2 may be represented differently from those of L1.

Paradis (1994, 2004) identifies differences between L1 and L2 in terms of the greater automatization of L1 and the implicitness of L1 across both lexical and syntactic aspects of language (see also Lebrun, 2002). Certainly differences in metalinguistic knowledge of L2 might help support recovery in bilingual aphasics. But is the actual use of grammatical knowledge different?

On the proposal advanced by Ullman (2001b, 2005) this depends on a person's proficiency in L2. As proficiency in L2 increases there is an increased reliance on the procedural system. It follows that the model can most readily account for the selective recovery of L2 over L1 when pre-morbid L2 proficiency is low.

Granted that L2 proficiency is critical, the declarative/procedural model needs to suppose a mechanism that allows a shift from the use of a declarative representation of L2 grammar to its procedural representation. In contrast, the notion that learners employ existing devices means that devices mediating the combinatory process of syntax or morphology, for instance, are used from the start. Performance will reflect the relative efficacy of these different devices as they adapt to the demands of L2. In contrast to the declarative/procedural model, the present proposal predicts that native-level responses to the processing of L2 syntax will be observed early in the acquisition process. Evidence discussed in Section 2.1 supports this prediction.

The single network approach advanced here distinguishes the network involved in the representation of word meaning, syntax and prosody from the circuits involved in the control of such a network (Green, 1986, 1998, 2005). The causal basis of selective recovery in bilingual aphasic patients can then be explored in terms of the dynamics of language control. Fabbro, Peru, and Skrap (1997) identify a number of circuits involved in language control. For purposes of this paper, we cite three of these. For language planning they identify an anterior loop. This loop they suggest comprises the prefrontal cortex, the caudate nucleus, the globus pallidus and the ventral anterior thalamic nucleus. For language comprehension they identify a temporo-prefrontal loop that also involves the caudate nucleus, the globus pallidus and the ventral thalamic nucleus. For lexical selection, they identify a posterior loop consisting of the temporo-parietal cortex and pulvinar.

In the case of bilinguals, the anterior loop may serve to select languages and eliminate competing alternatives (Abutalebi, Miozzo, & Cappa, 2000; Mariën, Abutalebi, Engelborghs, & De Deyn, 2005). In cognitive terms (see Green, 1998), it selects the language goal and the schema for producing words in one language rather than another (Abutalebi & Green, 2007). Evidence in support of this conjecture comes from neuroimaging studies showing increased prefrontal activity when individuals switch between languages (e.g., Hernandez, Dapretto, Mazziotta, & Bookheimer, 2001). A subcortical structure is also involved in language switching: the head of caudate is activated during a change in language (Crinion et al., 2006; Wang, Xue, Chen, Xue, & Dong, 2007). Bilinguals cannot only switch between languages, they can also translate between them. Distinct circuits may be involved in translation relative to language switching. Price, Green, and von Studnitz (1999) found increased left temporo-parietal and

subcortical activation during the translation of single words relative to a non-translation condition. Mariën et al. (2005) note that such a finding is consistent with the involvement of a posterior circuit. Further, as we discuss later (see Section 4), damage to a frontal–subcortical circuit can lead to uncontrolled switching between languages or to pathological language mixing (Abutalebi et al., 2000; Fabbro, Skrap, & Aglioti, 2000; Mariën et al., 2005) or to fixation on a given language.<sup>1</sup>

Given that we can distinguish between how languages are represented and how they are controlled (e.g., how they are selected), we can ask if there are reasons to believe that the languages of a bilingual speaker are represented in distinct processing areas. Specifically, is the grammatical knowledge of L2 represented in a distinct neural substrate?

### 2.1. *Convergence or the differential neural representation of L1 and L2?*

It is reasonable to suppose that the system mediating the meanings of words is common across language. Indeed, neuroimaging data from a priming task confirm that the anterior temporal pole is a common site for the representation of word meaning in both German–English bilinguals and in Japanese–English bilinguals (Crinion et al., 2006; see also Section 3 for research on the representation of vocabulary in bilinguals). In the case of the production of single words (as in picture naming), Indefrey (2006) concludes, on the basis of a meta-analysis of neuroimaging data, that although there may be no regions that are exclusively necessary for word production in one language across individuals there do appear to be sites that are only necessary for word production in one language. Relevant data come from studies using electrical stimulation to map eloquent language areas prior to surgery (e.g., Lucas, McKhann, & Ojemann, 2004). Interference of object-naming at a given site is interpreted as indicating that the site is necessary for production in that language. But the finding of stimulation-sensitive sites in naming is compatible with the single, adaptive network view. Such a view supposes that representations underlying word production are distributed in shared regions. It is also important to recognise that stimulation-sensitive sites do not inform us directly about which aspects of the word production process are disrupted.

Indefrey (2006) notes that the left-inferior frontal cortex is one region that is reliably activated more strongly for L2 naming than for L1 naming. In the data of Lucas et al. (2004), it is also a region that only contains L1-specific sites. Indefrey (2006) offers a plausible interpretation of such data: individuals are seeking to adapt existing representations or processes to produce words in L1. Such an interpretation seems to us entirely compatible with the notion of a single network and the need to manage competition between languages. In the next section, we consider work that addresses the grammatical processes of L1 and L2 production.

#### 2.1.1. *The declarative/procedural model: neuropsychological data*

A key claim of the declarative/procedural model is that frontal–subcortical structures mediate grammatical processing (Ullman, 2001a). The proposal regarding the differential representation of grammar in L2 and its neural substrate, presuppose that this is the case. However, the current picture is not consistent with this claim.

<sup>1</sup>The role of the parietal lobes in language switching is considered more fully in Abutalebi and Green (2007).

A particular testing ground has been the contrast in English between regular verbs to which “-ed” is added to form the past tense (e.g., walk-walked) and irregular verbs (e.g., run-ran). The declarative/procedural model proposes that a fronto-striatal network (i.e., one that includes the basal ganglia) mediates the use of grammatical rules (i.e., computes regular forms for production and decomposes such forms for comprehension) whereas a temporo-parietal memory system subserves the storage of irregular verbs. Ullman argued that suppression of motor activity in Parkinsonian patients (a striatal dysfunction) correlates with greater difficulty in correctly producing the regular past tense whereas excess motor activity in individuals with symptoms of Huntington’s disease (again a striatal dysfunction) is associated with overactive grammatical rule use.

However, such data may not be decisive if only because damage to the basal ganglia has consequences for cortical regions too. More specifically, Longworth, Keenan, Barker, Marslen-Wilson, and Tyler (2005) found no association between striatal dysfunction and selective impairment in the ability to form regular past tense in patients with Parkinson’s disease and genetically proven Huntington’s disease. Conceivably high frequency regular forms are retrieved and understood as whole forms but even when restricted to low frequency verbs there was no evidence that the basal ganglia are necessary for computing the sequence of morphemes in the regular past tense. In fact, the evidence suggests that neocortical regions are critical for regular past tense processing. In healthy volunteers, the processing of regular past tense verbs is associated with increased activation in the left-inferior frontal gyrus and in the left-superior temporal gyrus (see for example, Tyler, Marslen-Wilson, & Stamatakis, 2005). On this account, basal ganglia activation is better interpreted in terms of the inhibition of competing alternatives (e.g., Crosson, 1985) and in suppressing alternatives in the process of integrating syntactic and semantic information (Friederici, Kotz, Werheid, Hein, & von Cramon, 2003), and as we indicated above and will argue further in Section 4, with the control of language in bilinguals.

In the bilingual context, De Diego Balaguer, Costa, Sebastián-Gallés, Juncadella, and Caramazza (2004) analysed the responses of two bilingual patients with aphasia on a morphological transformation task. The contrast between regular and irregular verb forms exists in both Spanish and Catalan and so it should be the case according to the declarative/procedural proposal that Spanish and Catalan agrammatic patients with anterior lesions should be poorer at producing the forms of regular verbs rather than those of irregular verbs. De Diego Balaguer et al. studied two such patients. Premorbidly, J.M. was a fluent Spanish/Catalan bilingual with Spanish as L1 whereas, M.P. was a fluent Catalan/Spanish bilingual with Catalan as L1 and educated in Spanish as L2. In the transformation task, the patients completed an auditorily presented sentence frame with a suitable spoken verb form. For instance in response to a statement, glossed in English, as “Today I eat, yesterday I ...” they would complete with the verb form “ate”. Contrary to the expectation of the model, both in Spanish and Catalan, both patients were better at producing regular compared to irregular forms. Accordingly, De Balaguer et al. argue that agrammatic patients, and these two bilingual patients with agrammatism specifically, have a deficit at the level of morphosyntactic processing independent of the regularity or irregularity of the verb. As in the classical view, they proposed that frontal structures are involved in morphosyntactic processing and not just rule-based processing. Regular verbs may be easier to produce for a number of reasons. One possibility is that regular transformations are more frequent than irregular transformations.



Their results are also relevant to the single network view: common tissue is recruited to perform comparable functions in the two languages though, as de Balaguer et al. note (p. 221), it remains to be seen whether selective deficits would be observed in patients speaking two languages that differ markedly in their morphosyntax (as in the case of English and Spanish).<sup>2</sup>

The bilingual data considered in this section involved early and highly proficient bilinguals. In the next section, we consider evidence for the common neural representation of syntax in L2 and L1 during the acquisition of an L2.

### 2.1.2. *Neuroimaging evidence for the common representation of syntax in L2 and L1*

Functional imaging data indicate regional sensitivity to different kinds of structural relations. The frontal operculum is sensitive to local phrase structure (e.g., Opitz & Friederici, 2004) whereas Broca's area (BA 44/45) is sensitive to long-distance dependencies as in the processing of embedded sentences (e.g., Stromswold, Caplan, Alpert, & Rauch, 1996). To what extent, is there evidence of the involvement of these structures in the acquisition of a second language?

One source of evidence in favour of the notion that the same structures are involved in the acquisition of an L2 comes from studies of artificial grammar learning. Friederici, Bahlmann, Helm, Schubotz, and Anwender (2006) showed that detecting violations in a sequence of syllables governed by a novel, and implicitly learned, phrase structure grammar differentially activated Broca's region in comparison to the detection of violations in a sequence of syllables governed by a novel, and implicitly learned, finite state grammar. The latter activated a region in the frontal operculum only. These results support the view that the acquisition of another language (albeit an artificial one) utilises an existing network mediating syntax in L1.

More direct support can be gained by examining the activation of different natural languages. Particularly relevant are studies of syntactic encoding. Indefrey and colleagues (Indefrey et al., 2001; Indefrey, Hellwig, Herzog, Seitz, & Hagoort, 2004) used a scene description task and showed that sentence level and local phrase level encoding activated a region caudally adjacent to Broca's area (BA 6) though other studies have identified a wide range of regions. Relevant here is a study by Golestani et al. (2006) that required moderately fluent late bilinguals in French and English either to read, covertly, words in L1 (French) or in L2 (English) or to produce sentences from these words, again covertly, in either L1 or in L2. Overall, there was relatively greater activation in left prefrontal cortex

<sup>2</sup>Although our focus is on studies of aphasic patients, it is noteworthy that the study of a bilingual patient with Alzheimer's disease, L.P.M. also revealed comparable deficits in her two languages (Hernández, Costa, Sebastián-Gallés, Juncadella, & Reñé, 2007). L.P.M. was 74-year-old right-handed, Catalan-Spanish speaker, highly proficient in both languages pre-morbidly, who had acquired both languages early in her life. In Catalan, L.P.M. showed severely impaired performance in using nouns compared to verbs. So, for example, she was better at naming the action associated with a depicted object (e.g., "brushing") compared to naming the object of the action (i.e., "broom"). A similar result was obtained in Spanish: L.P.M. found it more difficult to retrieve nouns compared to verbs. Taken together these findings of grammatical-category specific deficits in both languages suggest that common principles underlie the representation of words in the two languages and that a common neural tissue underlies both. Hernández et al. (2007) note two caveats. First, Spanish and Catalan, along with other Romance languages, have similar grammatical and morphological properties and so it remains to be determined whether or not selective deficits exist when bilinguals have learned languages that differ more markedly in their grammatical and morphological properties. Second, L.P.M. acquired both languages early and so it is possible that the common principles of organisation are restricted to circumstances in which this is the case.

in L2 compared to L1 indicating increased effort and, consistent with increased working memory or sequencing/executive demands in L2 compared to L1, increased activation in the left-inferior parietal region and in the right cerebellum. There was no systematic difference in the left prefrontal region activated in L1 as compared to L2 production and no shifts in the extent of activation with increased syntactical proficiency (measured outside the scanner). But interestingly Golestani et al. found that syntactical proficiency in English correlated with the distance in the peaks of activation for French and English. The distances between peak activation converged with an increase in proficiency. Golestani et al. suggest that such convergence might reflect the use of neural regions more tuned to syntax.

Likewise, Sakai, Miura, Narafu, and Muraishi (2004) using fMRI showed that the acquisition of grammatical competences in late bilingual twins is achieved through the same neural devices for processing L1 grammar (i.e., Broca's area). Twins were used as subjects in order to investigate whether shared genetic factors influence their language abilities and neural substrates for Japanese (L1) and English (L2). For 2 months, the students participated in intensive training in English verbs as part of their standard classroom education. The authors reported that the cortical plasticity for L2 acquisition led toward specialisation of the left-inferior frontal gyrus as in the case of L1, in spite of notable differences between L1 and L2 in the students' linguistic knowledge and in their performance in conjugating verbs. These findings indicate that cortical mechanism involved in L1 grammatical processing is involved at a very early stage in the acquisition of L2 grammar contrary to the expectation of the declarative/procedural model.

A further relevant finding of the Golestani et al.'s study was that increased proficiency was associated with increased involvement of the basal ganglia. Golestani et al. treated such involvement as consistent with the use of basal ganglia for rule-based processing. We have already pointed to data questioning the role of basal ganglia in rule-based processing and suggest that enhanced proficiency is associated with an increase in automaticity. In such circumstances, the basal ganglia may provide increased inhibitory control.

Although we have argued that languages are represented in a common network, this does not imply that the precise properties of this network are independent of the nature of the languages involved. In the next section, we briefly overview the nature of network adaptation by considering the consequence of acquiring the same L2 given different native L1s.

### 2.1.3. *Network adaptations*

Although all natural languages share properties they differ in their use of these properties. Such differences may well have consequences for the nature of acquisition. For instance, it may be more difficult to acquire distinctions that are not part of the repertoire of devices in one's native tongue. Recent functional imaging studies support the increased difficulty of comprehending sentences where the design features differ (see Zhang & Wang, 2007 for a review of neural plasticity in the context of phonetic learning of an L2).

By way of illustration, Jeong et al. (2007) contrasted the activation patterns of two different native language groups (native Korean speakers and native Chinese speakers) as they listened to sentences in English (acquired around puberty) and Japanese (acquired around 20 years of age). Chinese and English use a Subject (S), Verb (V) and Object (O) word order whereas Korean and Japanese use an SOV word order. As expected, Korean participants showed greater activation in processing English sentences in regions linked to



syntactic processing while Chinese participants showed an increase in processing Japanese sentences in such regions.

As proficiency changes the adapted network view expects that there will be a degree of convergence with the processing profile shown by native speakers. Most research examining ERP responses to morphosyntactic features in L1 and L2 is consistent with this claim but it has only been conducted in Indo-European languages (Osterhout, McLaughlin, Pitkanen, Frenck-Mestre, & Molinaro, 2006; Rossi, Gugler, Friederici, & Hahne, 2006; Tockowicz & MacWhinney, 2005). In Chinese, unlike English and other Indo-European languages, grammatical morphology does not mark case, gender, or number; thus, subject-verb agreement in sentences is not required. In consequence, learning a syntactic agreement system such as English poses a challenge. Indeed, Chinese learners of English may show behaviourally similar patterns to native speakers but display different neural responses to morphosyntactic violations (Chen et al., 2007). Whether such a differential pattern is also shown by immersion learners of English remains to be determined.

The writing system of the original language may also be important when individuals come to read in L2. Perfetti et al. (2007) argue that Chinese readers may find it easier to assimilate the demands of an alphabetic system by continuing to use the basic system deployed to read Chinese characters. In contrast, in order to read Chinese, readers of English must make greater use of, or actively recruit, regions that are less well used in reading an alphabetic system. Adaptation may also yield more subtle effects. Readers of languages where the mappings between print and sound are regular (such as Spanish and Italian) may begin to use a more addressed route after learning to read English with its irregular orthography or even another language with regular orthography because of different mappings of print to sound.

In general it seems that constraints on the representation and processing of an L2 are less to do with some maturational timetable and more to do with the way in which learning a new language must adapt the network representations of an L1 (Hernandez & Li, 2007; Li & Farkas, 2002; Li & Green, 2007; Li, Zhao, & MacWhinney, 2007; but cf: Wartenburger, Heerkeren, Abutalebi, Cappa, Villringer & Perani, 2003). In order to understand such adaptations, we also need to know the different ways in which native speakers may construct or use their language network (including their reading networks) in order to determine whether or not the adaptation is outside the scope of normal variety and so inconsistent with the notion of a single adapted network.

In summary of this section, functional imaging data involving a range of tasks indicate substantial overlap in the regions activated in processing L1 and L2 (Perani & Abutalebi, 2005) as long as L2 proficiency is taken into account (Abutalebi & Green, 2007). Low levels of proficiency in L2 are typically associated with more extensive frontal activation. Further work is needed to establish more concretely the nature of the adaptation of language networks and so inform predictions about the likely consequences of stroke disrupting particular regions and their interactions under varying levels of premorbid proficiency, current usage and age of L2 acquisition.

It is reasonable to suppose that where there is considerable overlap in the representation of two languages that the effects of brain damage should be comparable in L1 and L2. Traditionally, assessments of such a claim have relied on published reports of single cases (e.g., Fabbro, 1999). Published case reports are not representative and do not lend themselves to inferences about any general relationship between damage and recovery. In the next section, we consider a complementary approach.

### 3. Computational neuroanatomical techniques for exploring brain–behaviour relations in large samples of bilinguals

In order to understand the factors that underlie recovery patterns, we need to establish the nature of the correlations between lesion site and behavioural deficit. Researchers have adopted different approaches to this problem. In what Bates et al. (2003) call the lesion-defined approach, patients with a common lesion (e.g., in a region of the frontal cortex) are grouped together and their performance compared with a control group or some other patient group. In the behaviour-defined approach, patients are grouped together in terms of whether or not they show a common deficit and their lesions are reconstructed on a common template and overlain to identify common areas. The overlapping region is compared to the overlapping regions of patients who do not show the deficit. Knowing common areas can be useful in terms of determining the functional role of a given region but information can be lost when patient performance is simply characterised as intact or impaired. Further, lesion-overlap approaches will inevitably reflect areas most prone to lesions and can say little about the impact of lesions remote from the overlap.

However, patients do not need to be grouped by lesion-site or by classifying their performance as impaired or not. In functional imaging research, changes in patterns of activation are described at the level of individual voxels. Likewise, lesions can be described at the voxel level and related to continuous rather than dichotomous behavioural data.

In a pioneering example, Bates et al. (2003) (see also Baldo, Schwartz, Wilkins, & Dronkers, 2006) used a voxel-based method to examine the impact of left-hemisphere lesions in 101 native-English speaking stroke patients on performance in tests of verbal fluency and auditory comprehension. Each lesion was reconstructed by hand onto a standard template. Next, for each voxel, patients were divided into those for whom that voxel was lesioned and those for whom that voxel was not lesioned. The researchers then computed a *t*-statistic of the difference in the behavioural scores. Their analysis was broadly consistent with the traditional picture that anterior lesions are more important for production whereas posterior regions are more important for comprehension. But they found that what was most important to fluency was not Broca's area but the left anterior insula and a deep parietal white matter tract. In contrast, what was most important to auditory comprehension was damage to the middle temporal gyrus together with damage to the dorsolateral prefrontal cortex and inferior parietal area (association cortex).

Bates et al. also demonstrated the value of the technique in establishing the causal role of a region in a given task by checking its importance when a potentially correlating region is partialled out. Their analyses showed the importance of damage to the insula even when damage to Broca's area was covaried out. Similarly, the middle temporal gyrus remained important for comprehension even when damage to Wernicke's area was covaried out. In contrast, Broca's area was not a significant contributor to fluency when insula damage was partialled out nor was Wernicke's area a significant contributor to comprehension when the insula damage was partialled out. Despite these results, the precise role of the left anterior insula in the network of regions supporting speech planning and execution still requires clarification. For instance, in a study of acute patients, Hillis et al. (2004) found that dysfunction in Broca's area was strongly linked to the classification of the patients' speech as showing apraxia.

The technique used by Bates et al. (2003) and Baldo et al. (2006) does demonstrate the potential value of examining behaviour at the voxel level but is more restricted than

necessary. A more sensitive technique is to use voxel-based whole-brain method in which a continuous signal intensity value is assigned to each voxel. Voxel-based morphometry (VBM) identifies differences in grey or white matter based on structural MRI images. 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 (see Mechelli, Price, Friston, & Ashburner, 2005 for further discussion and critique).

The technique has proved useful in examining the impact of skill acquisition and use in domains such as playing a keyboard instrument (Gaser & Schlaug, 2003), navigation (Maguire et al., 2000), juggling (Draganski et al., 2004) and language. In the latter case, grey-matter density increases in a region of the parietal cortex (the posterior supramarginal gyrus) as a function of vocabulary knowledge in monolingual adolescents (Lee et al., 2007). One reason why this might be the case is that this region is well suited to connect the meanings of words to their sounds (see Lee et al., 2007). If there is a common aspect to the representation of vocabulary in different languages then this same region should show increased grey matter for bilingual compared to monolingual adults because on average a bilingual speaker will have two words for each lexical concept compared to one for a monolingual speaker. In fact, bilingual speakers do show increased grey matter density in this region. (Mechelli et al., 2004). However, there should also be evidence of differences between different bilingual groups when a language uses specific means to signal lexical differences. Chinese uses tone to signal lexical differences and VBM analysis showed additional regions of grey matter increase in bilingual Mandarin–English speakers compared to speakers whose L1 or L2 was not a tonal language (Green, Crinion, & Price, 2007).

These observations fit well with a series of VBM studies conducted by Golestani and co-workers (Golestani, Molko, Dehaene, LeBihan, & Pallier, 2007; Golestani & Pallier, 2007; Golestani, Paus, & Zatorre, 2002) who have shown structural brain differences within the parietal lobes for fast phonetic learners as compared to slow phonetic learners. In general, fast phonetic learners (i.e., subjects who successfully learn to distinguish or produce phonetic contrasts not present in their native language) have increased white matter density in both parietal lobes but more evidently so in the left parietal lobe.

VBM also provides a useful tool to examine the effects of brain damage on performance. It avoids a potential pitfall of hand-drawn lesion analyses that may be insensitive to small differences and has the potential to pick up the impact of stroke on a site remote from the apparent lesion (diaschisis). It has been used to examine the neuroanatomical bases of the different pattern of deficit in semantic dementia and herpes simplex encephalitis (e.g., Noppeney et al., 2007) and it would be useful to extend it to examine the effect of grey-matter changes on task performance in bilinguals. To the extent a set of regions is necessary for performance of a task, such as generating instances of a semantic category or generating words beginning with a particular letter or phoneme), grey-matter density should be predictive of relative differences in task performance in both languages of a bilingual aphasic patient. Current data are in line with this expectation (e.g., Grogan, Crinion, Ali, Green, & Price, 2007).

However, where a region in normal speakers shows expansion, or an increase in grey-matter density, in order to handle distinctions particular to that L2 (e.g., the use of tone in Chinese to signal lexical distinctions), then damage to such regions should lead to greater impairment in L2 compared to L1. But, crucially, the notion of a single adapted network predicts that the same correlation will be shown in native monolingual speakers of that language.

VBM analyses can help characterise brain–behaviour relations at the sample level but such studies need to be complemented by those of single cases. Published case reports indicate patterns of selective recovery and such instances have been attributed to the differential representation of languages acquired early versus those acquired late. We consider the evidence for this claim in the next section and argue against this interpretation on the basis of current data.

#### 4. Single case studies: longitudinal, behavioural and functional testing

On the basis of data from normal bilinguals, we argued earlier for the importance of frontal–subcortical circuits in language control (Section 2) and for the notion of a single adapted network (Sections 2.1.1 and 2.1.2). Imaging data fail to support the notion of the differential representation of syntax in L2. However, although neuroimaging data can provide information on which regions and regional interactions support task performance in bilinguals, they cannot establish which of these regions or interactions are necessary to the performance of the task (Green & Price, 2001). Single-case studies of bilingual aphasia with their striking features of recovery can help determine these (see Paradis, 1998).

Since the landmark study of the French neurologist Pitres (1895), who was the first to draw attention to the relative frequency of differential language recovery following aphasia in bilinguals, many different recovery patterns, in addition to the selective recovery or loss of one language, have been described (Paradis, 1998): parallel recovery of both languages, successive recovery (i.e., after the recovery of one language, the other language recovers), alternating recovery (i.e., the language that was first recovered is lost again due to the recovery of the language that was not first recovered), alternating antagonistic recovery (i.e., on one day the patient is able to speak in one language while the next day only in the other) to the pathological mixing of two languages (i.e., the elements of the two languages are involuntarily mixed during language production).

How may these data speak to the question of language representation and language control? Theoretical conjectures arising from the study of single case studies of bilingual aphasia developed along two distinct lines, a more traditional approach and a more dynamic approach. The traditional ‘localizationist’ view argued, for instance, that the specific loss of one language would occur because the bilingual’s languages are represented in different brain areas or even in different hemispheres, and hence, a focal brain lesion within a language-specific area may alter only that specific language leaving the other language intact (Albert & Obler, 1978). In this perspective, the declarative/procedural model lies within the localizationist tradition given its claim that different brain areas may mediate syntax in L1 and in L2.

In contrast, according to the ‘dynamic’ view, the patterns of recovery so far observed in bilingual aphasics would arise because of compromise to the system of language control (Abutalebi & Green, 2007; Green, 1986, 1998; Green & Price, 2001; Paradis, 1998). A selective loss of a language arises because of increased inhibition, that is, of a raised activation threshold for the affected or lost language or even because of an imbalance in the means to activate the language because of the lesion (i.e., the so-called activation threshold hypothesis (Paradis, 1998)). It is worth underlining that Pitres himself (Pitres, 1895) proposed a ‘dynamic’ explanation of language recovery in bilingual aphasics: language recovery could occur only if the lesion had not entirely destroyed language areas, but only temporarily inhibited them through a sort of pathological inertia. The dynamic

view may not only explain the selective recovery of a language but can also explain many reported recovery patterns in bilingual aphasia. As outlined by Paradis (1998), a parallel recovery would then occur when both languages are inhibited to the same degree. When inhibition affects only one language for a period of time, and then shifts to the other language (with disinhibition of the prior inhibited language) a pattern of antagonistic recovery occurs (Green, 1986). Selective recovery would occur if the lesion permanently raised the activation threshold for one language, and pathological mixing among languages would occur when languages cannot be selectively inhibited anymore. These latter observations emphasise the need to distinguish, when discussing the bilingual brain, between devices responsible for language representations (i.e., language network) and devices involved in controlling these representations (i.e., language control).

Neuropsychologically, the broad contrast between the language network and circuits involved in its control would be supported by cases in which there is normal comprehension and production in L1 and L2 but a difficulty in controlling the use of one language over another. S.J. (see Fabbro et al., 2000) had damage to the anterior control loop (see Section 2) with a lesion to the left prefrontal cortex and part of anterior cingulate plus involvement of the left striatum (see Mariën et al., 2005, p. 396). S.J. showed normal comprehension in both Italian and Friulian and intact clausal processing in both languages. However, S.J. was unable to avoid switching into Friulian (his L1) even when addressing an Italian speaker who spoke no Friulian. Likewise when required to speak Friulian only, S.J. would switch into Italian (his L2). We infer that damage to the anterior loop led to a problem in maintaining the current language goal (e.g., speak in L1) perhaps because of difficulty in inhibiting the alternative language goal.

What of cases illustrating the selective recovery of one language rather than another? According to the declarative/procedural model (Ullman, 2001b), damage to neocortical temporal/temporal–parietal regions will impair performance more for L2 than for L1 for those linguistic forms that depend on grammatical processing in L1. In contrast, damage to the basal ganglia will impair performance more in L1 than in L2. We consider two cases apparently supporting this double dissociation before reviewing recent studies (post 2000).

The first case concerns the impairment of L2. Ku, Lachmann and Nagler (1996) report the case of a 16-year-old native Chinese speaker who had been living in the United States for 6 years and who had received intensive training in English over this period. He suffered a circumscribed lesion to the left temporal lobe (as a result of herpes simplex encephalitis). The ability to understand and speak English was lost for 3 weeks post-onset though naming in Mandarin was normal. Ullman (2001b) argued that this case is consistent with the differential representation proposed in the model. However, it is not clear that the prediction of differential impairment of L2 can be made on the basis of the model. The patient was relatively proficient in English and so according to Ullman (2001b, 2005) grammatical processing in L2 should rely on the procedural system and the lesion did not directly affect the frontal–basal ganglia circuits. Further, the data do not fully support the claim that L1 syntax was unimpaired. The syntax of the patient's spoken Mandarin was simplified and so this case is not decisive support for the claim that grammatical information is represented differently in L2. An alternative possibility is that there was a problem of language control: the threshold of access to the lexical representations of L2 was raised (Green & Price, 2001) because of damage to the control loops involved in comprehension and lexical selection (see Section 2).



The second case concerns the impairment of L1. Fabbro and Paradis (1995) (see also Agliotti, Beltramello, Girardi, & Fabbro, 1996) reported the case of E.M. (E.M. 1 here) with damage to the basal ganglia. Consistent with the expectations of the declarative/procedural model, her spontaneous speech in her L1 (Venetan) was poor whereas her speech was better in her L2 (Italian) that she rarely used prior to the lesion. Ullman (2001b) noted a similar proportion of word-finding difficulties in both languages but a tendency for poorer grammatical performance in L1 (e.g., the omission of grammatical function words in obligatory contexts). However, these effects were small and the overwhelming difference is her spontaneous use of L2 in preference to L1. These results might reflect the more automatised use of L1 consistent with the views of Paradis (1994) but equally it may reflect a pathological fixation on L2 (Agliotti et al., 1996). Language control (here the ability to select between one language and another) is also mediated by frontal–basal ganglia circuits—the anterior control loop (Section 2).

Turning now to more recent cases, García-Caballero et al. (2007) reported the case of a 91-year-old right-handed female Galician–Spanish bilingual who stopped speaking her L1 (Galician) and started speaking Spanish (L2) which she rarely spoke in her household though she did watch Spanish TV and read Spanish literature on religious topics. Her everyday behaviour indicated mild disinhibition such asking her guests for coffee rather than offering it to them. Language testing showed spared comprehension in both L1 and L2. She was fluent in L2 but not in L1 and showed impaired repetition in L1 sometimes translating into L2. When spoken to in L1 she replied in L2 though in context such behaviour is not entirely inappropriate as both languages are spoken. Verbal fluency was impaired as reflected in a reduced ability to name instances of a given semantic category. One year after initial testing, her spontaneous speech in L1 remained minimal and she showed a small disadvantage in auditory comprehension in L1 but she was able to name objects in her L1.

Although the head of caudate was apparently spared, there was right capsuloputaminaal atrophy and small lesions of subcortical white matter. García-Caballero et al. (2007) propose that the data from this patient are consistent with the differential representation of L2 (citing Ullman, 2001b) and specifically that L1 may be represented more implicitly with the structures of the basal ganglia playing a key role. Certainly, formal education in her L1, Galician, was prohibited under the Franco regime and so the patient never learned to read or write in her L1 and was not exposed to Spanish (her L2) until 8 years of age. However, she was relatively proficient in her L2 (it was the language she used for reading and watching television). According to Ullman (2001b, 2005) reliance on the procedural system increases with proficiency. If so, L2 should be impaired along with L1. There are reasons to doubt then that the selective recovery of L2 in this patient reflects the declarative representation of L2 grammar. Further, neuroimaging data cited above (Section 2.1.2) indicates use of a common substrate in the acquisition of L2 grammar early in the process of acquisition.

García-Caballero et al. noted that her mild disinhibition might reflect disruption of fronto-subcortical circuits (the anterior loop, here) and, indeed, in our view this case may be as readily interpreted as indicating a loss of control of L1 (i.e., an inability to select it) that may have been occasioned by a temporary problem in accessing words in L1 and a decision to talk only in L2 that led to improved restitution of function in that language.

Two examples of the impact of subcortical lesions on language switching and mixing speak most directly to the role of subcortical circuits in control. Abutalebi et al. (2000)



report the case of A.H. with a lesion of the white matter surrounding the left head of caudate. A.H., a 74-year-old right-handed trilingual woman [Armenian (L1), English (L2) and Italian (L3)] produced normal phrases in spontaneous speech but unintentionally mixed elements from different languages even when speaking to monolingual Italian speakers: “I cannot comunicare con you”; when describing a picture in English: “I bambini steal the biscuits from the armadio”. In this case then there is no specific deficit associated with L1 as a result of dysfunction of the striatum, rather the problem is one of unintentional switching between languages which is more consistent with the view that the basal ganglia are involved in language control.

The final paper we discuss here is exemplary in that it charts the course of recovery and shows that relief of the symptoms of inappropriate language switching is associated with improved functioning of the frontal–subcortical circuits. Mariën et al. (2005) report the case of E.M.—here E.M. (2). E.M. (2) was a 10-year-old, right-handed boy with English (L1) and with Dutch as L2. Premorbidly, oral proficiency was good in both languages. Following a left thalamic lesion L1 recovered but fluent aphasia persisted in L2 despite speech therapy in L2 and greater exposure to L2. Five months post-stroke recurrent bleeding led to fluent aphasia in both L1 and in L2. Further, when speaking to monolingual speakers of either language, E.M. (2) showed pathological language switching and mixing though L2 intrusions were common in a task requiring the use of L1 only. Brain imaging showed hypoperfusion in the left fronto-parietal and temporal regions and in the left caudate nucleus. [Other defects were noted in the left thalamus and lenticular nucleus combined with reduced flow in the right cerebellum.] Remission of the symptoms of language mixing and switching was associated with increased perfusion of left frontal lobe and left caudate nucleus. In this later phase, where switching occurred it was under conscious control as a means to overcome word-finding difficulties. However, perfusional deficits remained in the left temporo-parietal areas and left thalamus. Indeed, E.M. (2) continued to display fluent aphasia in L1 and in L2 and could not perform the Stroop task. He also showed impaired translation at the single word and sentence level in both directions. Such data support the view of the necessity of frontal–basal ganglia circuits in the control of language and point to the need to understand in more detail the nature of the posterior loop involved in translation. In the latter case, stronger evidence would be obtained where the patient can name objects in both languages or describe simplified scenes but cannot perform a translation based on utterances that can be produced spontaneously.

## **5. Conclusions and future directions**

The research reported above points to a common network for producing and perceiving speech in L1 and L2. One important aspect of understanding how an L1 network adapts in the acquisition of an L2 is to have a much clearer idea of the range of normal variation in L1. There may be a number of ways in which a given language task (e.g., reading a word) is performed and so if we are to understand the nature of an adapted network we need to understand the range of this variation (Green et al., 2006). Understanding the nature of normal variation is important too if we are to understand the nature of any changes induced through brain damage.

We have discussed the value of whole-brain techniques such as VBM for allowing a clearer picture of the relationship between grey-matter (or white-matter) density or signal

and task performance. Understanding this relationship will allow a predicted profile of task performance and so provide a baseline against which to examine the effect of any intervention. Our basic expectation is that where there is no problem in selecting the intended language then the typical pattern of recovery will be the parallel recovery of both languages (Paradis, 2001). Where there is a problem of control (even if mild as in difficulty in managing interference in a Stroop task) then it is reasonable to expect the weaker language pre-morbidly to be more at risk. However, it is not only pre-morbid proficiency that is likely to be important. A language used in preference post-stroke will become more proficient and the ability to use and manipulate structures in that language will be facilitated especially in circumstances where there are reduced resources to control the use of two languages. Where there is selective recovery for example, of L2, we have argued against the notion that it reflects a differential representation of grammar of L2. Instead, current data support the view that selective recovery, pathological switching or mixing have the same underlying cause: a damage to the circuits involved in language control. Further advance requires more detailed specification of how damage to these circuits can lead to the varieties of impairment in language control.

The longitudinal study of behavioural recovery in bilingual aphasic patients will begin to fulfil its promise when researchers also undertake functional imaging research in order to understand how the different parts of the recovering network work together to achieve the behaviour.

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