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Bilingual language production: The neurocognition of language representation and control

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Abstract

Despite an impressive psycholinguistic effort to explore the way in which two or more languages are represented and controlled, controversy surrounds both issues. We argue that problems of representation and control are intimately connected and we propose that data from functional neuroimaging may advance a resolution. Neuroimaging data, we argue, support the notion that the neural representation of a second language converges with the representation of that language learned as a first language and that language production in bilinguals is a dynamic process involving cortical and subcortical structures that make use of inhibition to resolve lexical competition and to select the intended language.
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1. Introduction

Until recently most psycholinguistic research has aimed to understand the representation and use of a single language. However, a substantial proportion of the human population speak more than one language and over the past few years there has been an impressive effort to explore the way in which more than one language is represented and

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processed (see, for example, Kroll & De Groot, 2005). As underlined by Grosjean (1998, 2001) the bilingual speaker should not simply be considered the sum of two monolingual speakers, and hence, monolingual language production models generally fail to explain the particularity of bilingual language production. Bilinguals have conceptual representations linked to two different lexical representations (de Groot, 1993; Francis, 1999; Kroll & Stewart, 1994) that are used by different grammatical systems. That is, the lexico-semantic system in a proficient bilingual consists in the main of distinct lexically-and syntactically-specified concepts and their associated word forms. By what process do bilingual speakers produce the correct name of an object in the intended language? Behavioural techniques have yielded considerable progress but current data leave a number of questions unresolved and do not reveal the full scope of the control processes involved. In this paper we argue that neuroimaging data can help inform the current controversies and illuminate the control problem. We first illustrate the nature of the controversies and then consider the scope of the control problem.

1.1. Current controversies

Compared to monolingual speakers, bilinguals are slower to name pictures but do not differ in the time required to access their meaning in order to classify their referents as human-made or natural (Gollan, Montoya, Fennema-Notestine, & Morris, 2005). Conceivably, a relative delay in naming reflects the fact that bilinguals (who speak each of their languages equally often) are in fact less practised in naming words in either of their languages. Words in their mental lexicon are effectively at a lower level of functional frequency. Consistent with this claim (see Michael & Gollan, 2005 for a review), diary studies and experimental studies indicate that bilinguals are more susceptible to tip-of the tongue states, except where the target is a cognate or a proper name. In both these cases, the same word (or a very similar word form) can be produced in either language.

However, these findings with bilinguals are also compatible with an alternative possibility. For bilinguals, expressing and comprehending a communicative intention may be an inherently competitive process. They must manage competing phonological, syntactic and prosodic systems and in reading they must manage distinct mappings of orthography to phonology. More specifically, lexical nodes or lemmas, i.e., syntactically-specified lexical concepts in different languages may compete for selection (e.g., Green, 1986, 1993, 1998; Hermans, Bongaerts, de Bot, & Schreuder, 1999; Kroll, Bobb, & Wodniecka, 2006; Lee & Williams, 2001; Poulisse, 1999). If competition is a fact of life, then bilinguals may become adept specifically at selecting responses in the face of competing cues even in a non-verbal task: a prediction proposed and confirmed by Bialystok (Bialystok, Craik, Klein, & Viswanathan, 2004; Bialystok, Craik, & Ryan, 2006).

According to the Inhibitory Control (IC) model such competiton is resolved by inhibiting any active, non-target language competitor (e.g., Green, 1998). But the extent and nature of competition and the nature of its resolution has provoked a lively debate informed by a range of behavioural data with no current resolution. We illustrate with findings from two different paradigms: a picture naming paradigm and a language switching paradigm. The patterns of data in these two paradigms are not readily explained by differences in the functional frequency of words and so although functional frequency may provide an account of word finding difficulties when bilinguals speak solely in their L1, it does not offer a general account—nor was it intended to do so.

In the picture naming paradigm, individuals name pictures in the context of superimposed words varying in their semantic or phonological similarity to the target word and whether they are in the same or in a different language. One key finding is that words that are semantically-related to a picture slow the time needed to name the picture even when they are not in the language required for naming (e.g., Costa & Caramazza, 1999; Hermans et al., 1999). On the face of it such a finding suggests that words (lexical nodes or lemmas) in different languages compete for selection and that bilinguals face the problem of resolving such competition in order to name a picture in one language rather than another.

In the language switching paradigm, a key finding is that in naming numerals or in naming pictures bilinguals take longer to switch into their more dominant language. One possible interpretation here is that there is competition to name and that to produce the name in the less dominant language, the more dominant one must be suppressed (e.g., Green, 1998).

These findings are not under dispute but their interpretation is. There is consensus that access to concepts is a non-selective process (see Dijkstra & van Heuven, 1998, 2002; French & Jacquet, 2004 for a review). A semantically-related distractor in the non-target language (i.e., words not in the language required for naming) will therefore activate lexical nodes or lemmas in both languages. However only those in the target language (i.e., the language required for naming) may create the interference (Costa & Caramazza, 1999). In Roelofs' computational model (2003) there is a production rule that has production in the target language (e.g., L2) as its goal. No lemma can enter the competition if that goal is not met. This account has the merit of parsimony—only a single level of control external to the bilingual lexicon is required to achieve successful production. Perhaps in normal circumstances, there is no competition between languages. The intention to name an object in one language is specified in a preverbal message and this ensures that words in the correct language are more activated than those in another (La Heij, 2005).

One result seems to count decisively against the idea of between-language competition. Naming responses are speeded when the semantic distractor is the direct translation of the target (e.g., the Italian word "cane" (= dog) with the picture of a dog to be named in English). Arguably, such a distractor is the strongest competitor to the target word and so should produce even greater interference than a semantically-related word. However, there are likely to be opposing effects here: a translation equivalent also primes the lexical concept and so speeds object recognition (Green, 2002; Hermans, 1998). The benefit of such priming for speeding naming may outweigh the cost of resolving competition (see Hermans, 2004 for evidence and further argument that the between-language identity effect can be explained by either a model assuming between-language competition or one that does not.

Yet another possibility is that alternative names (phonological forms) enter a speech output buffer and the non-target phonological form is either inhibited (e.g., Green, 1986) or is blocked from production in some other fashion (e.g., Finkbeiner, Almeida, Janssen, & Caramazza, 2006; Finkbeiner, Gollan, & Caramazza, 2006). Suppose there is no competition, then the speed of selecting the correct item, may depend on how rapidly the non-target item enters the buffer and can be blocked or eliminated. A translation equivalent can be entered quickly and so can be eliminated quickly. Finkbeiner, Gollan, et al. (2006) further suppose that the mechanism may use information about the language of the word form. But it is unclear how the elimination process works. In particular,

knowing the language of the non-target item may simply help to inhibit it. Further, response selection could in fact be achieved by reactively suppressing the word's lemma so this alternative may not be so easily distinguished from the IC model until it is further specificied.

A second important source of information derives from research on language switching. When individuals are asked to switch between naming a digit in one language compared to another there is a switch cost (Jackson, Swainson, Cunnington, & Jackson, 2001; Meuter & Allport, 1999). Further, it can take longer to switch into the more dominant language, for example, the first language, L1, compared to the less dominant language, for example, the second language, L2 (Meuter & Allport, 1999). One possible explanation is that the lemmas associated with the non-target language are actively inhibited, and that such inhibition is severe in the case of the more dominant language (Green, 1998).

The precise circumstances in which this type of asymmetry arises has not been established. The requirement that stimuli must be named in two languages is not a sufficient condition because as Costa and Santesteban (2004) showed asymmetry does not exist when bilinguals are equally proficient in their two languages and is substantially reduced even for unbalanced bilinguals after practise (Meuter & Allport, 1999, see also Verhoef, Roelofs, & Chwilla, 2006 for other relevant factors). Explicitly naming a given picture in two languages is unlikely to be necessary for the effect because it exist on first naming a picture in one language rather than another (Wodniecka, Bobb, Kroll, & Green, 2005).

Finkbeiner, Almeida, et al. (2006) sought explicit evidence of a boundary condition. They asked individuals (Experiment 1) to name numerals (1–9) and a small set of pictures. In the case of numerals, individuals named the numerals in response to a colour cue either in L1 or in L2. In contrast, they always named the pictures in L1. They replicated the asymmetry in switching costs for the numerals, i.e., slower to switch into L1 having named a numeral in L2. In contrast, they found that pictures were named equally quickly whether the prior numeral naming trial was in L1 or in L2. They argued that such data count against the idea of language suppression because no asymmetry is observed when a stimulus type is named in just one language. But in this study (see also their Experiment 2) individuals are switching between tasks when they come to name a picture in their L1: they are switching between the task of naming numerals in L1 or L2 and the task of naming pictures in L1 only. The critical data are therefore potentially confounded. According to the IC model individuals must resolve competition between language task schemas and the time course of such an effect may exceed that attributable to the suppression imposed either on the language as a whole or the reactive inhibition of a lexical item.

There are further subtleties. Highly-proficient bilinguals show no asymmetry when switching between L1 and a less proficient third language, L3 (Costa & Santesteban, 2004) or between L2 and L3 (Costa, Santesteban, & Ivanaova, 2006). However, they do show an asymmetry when switching between L3 and L4 (Costa et al., 2006)! Costa and colleagues argue that a different mechanism comes into place when the linkage between concepts and word forms is sufficiently strong. In such circumstances, bilinguals select the relevant language without competition from the other language. However, highly-proficient bilinguals who show symmetry in switching are nonetheless slower to name a picture in one language if they have named it previously just once in their other language (Wodniecka et al., 2005). It is not clear then that a different selection mechanism is involved.

Other behavioural data may be marshaled for and against a particular theoretical position but currently no model accounts transparently for the full range of behavioural data. Empirically, there may be no single locus at which language selection occurs (see Kroll et al., 2006) and, if so, different cognitive and neural mechanisms will be involved in managing and in resolving competition. We take up this idea in the next section.

1.2. Representation and control and the role of neuroimaging data

An account of bilingual speech production must cover the representations involved and their control. Such an approach chimes well with the importance of these notions for developing an account of cognitive change across the life span (Craik & Bialystok, 2006). Broadly conceived, control helps in the construction of representations (e.g., the decision to acquire and use a language). In turn, a representational change (e.g., learning new vocabulary in L2) creates new issues of control (e.g., the management of competition) and afford new communicative possibilities (e.g., the ability to converse on a wider range of topics). The exercise and practise of specific skills (e.g., simultaneous translation) will also impact on how linguistic information is represented and connected. The neural regions and networks in representing and controlling language may themselves constrain change and the control that can be exercised. As individuals age, for instance, it may become more difficult to alter automatised routines for production. We take as our point of departure the idea that there is a correspondence between the mechanisms used to control language and select lexical items and the control and selection of actions in the face of competing cues. We use the term level when considering the cognitive description of control. When identifying levels of control with the neural substrate we refer to neural structures, sites or regions and when referring to the linkage of these structures or regions we use the term networks or circuit.

Individuals can perform different actions on the same stimulus. For instance, a bilingual can name a presented word in L1 or translate it into L2. Individuals must maintain the task goal in the face of conflicting goals and co-ordinate the various actions required to perform the task (e.g., retrieve or compute the word's phonology from its spelling or retrieve the meaning of the word and select its translation). Once a given task is established however (e.g., speaking in L2), competition with alternative possible tasks (speaking in L1) may be resolved more automatically—a process that Norman and Shallice (1986) termed contention scheduling. Where individuals wish to alter their goal (for example, to switch from speaking in one language to speaking another), they must disengage from the current goal and switch to the new goal (see Green (1986, 1998) and Monsell (2003) for extensive consideration of task switching in other contexts). Lexical concepts matching the intended message must be selected and output. A behavioural response is the outcome of many different processes and facilitating effects in one process may be outweighed by opposing effects in another.

Functional neuroimaging techniques offer an important tool to understand details of the mechanisms of representation and control and to complement behavioural explorations. It can challenge the sufficiency of existing cognitive accounts leading to their development by showing more clearly the full nature of the neural mechanisms involved. It can also reveal individual differences (e.g., in control processes) where the behavioural response may not differ (see, for example, Bialystok et al. (2005) for differences between bilinguals and monolingualsin the Simon task revealed by MEG but not by behavioural response).

Prior to the adoption of these techniques, studies of bilingual aphasics provided evidence that different languages may be neurofunctionally distinct (e.g., Paradis, 1998; Paradis, Goldblum, & Abidi, 1982). Such data help identify which brain regions are necessary for a given task (e.g., speaking one language rather than another) but they cannot tell us whether that component is localised to a particular neural region at the lesion site or whether the lesion interrupts a network of anatomically distinct regions required in using a language (Abutalebi, Cappa, & Perani, 2001, 2005; Green & Price, 2001; Vaid & Hull, 2002). Functional neuroimaging offers an opportunity to draw inferences about representation and use from the pattern of activation within the normal brain. We suggest that in combination with bilingual aphasia data they reveal the subtlety of control processes and provoke further questions that can be explored in both behavioural and neuroimaging work.

1.3. Structure of the paper

In this paper we argue that neuroimaging data, in combination with aphasia data provide strong evidence, at least at the lexical-semantic level, in favour of the following claims about speech production in bilingual speakers: (i) the neural representation of L2 (i.e., the brain structures implicated in its representation) converges with the neural representation of that language in native speakers—in other words, there is common neural network subserving L1 and L2, and (ii) both cortical and subcortical structures are involved in the control of language and in lexical selection. Additionally, the imaging data are compatible with the view that (iii) there is competition to control output in L2 vs L1, i.e., to achieve language selection and lexical selection, and this competition exists at cortical and subcortical sites and that (iv) on the basis of brain data we suggest that inhibition is a key mechanism in language control and lexical selection.

The paper is organised as follows: We begin (Section 2) by discussing research on the neural basis of the more general aspects of cognitive control and the key role of inhibition since these data may be crucial for the interpretation of brain activity patterns found in neuroimaging studies investigating L2 production in bilinguals. Our premise is that language selection and control is an aspect of processes associated with the control of action in general. In the following section (Section 3), we present a dynamic view of representation and control in bilinguals and in the penultimate section (Section 4) we review our claims and propose further lines of work that address a number of outstanding questions.

2. The neural basis of cognitive control

With the advent of functional neuroimaging the neural underpinnings of cognitive control have been relatively well investigated (see for extensive reviews Botvinick, Braver, Barch, Carter, & Cohen, 2001; Collette & Van der Linden, 2002; Duncan & Owen, 2000; Elliot, 2003; Gruber & Goschke, 2004). The following is a brief description of the brain areas involved in cognitive control.

A number of lines of evidence indicate that a complex function such as cognitive control is not attributable to a single unitary brain system, but rather emerges from the interaction of separable systems, which are responsible for complementary control functions (Gruber & Goschke, 2004). For instance, among the multiple components of cognitive control are

the ability to filter out irrelevant information in the environment (interference suppression) and the ability to inhibit inappropriate but prepotent response tendencies (response inhibition), see Bunge, Dudukovic, Thomason, Vaidya, and Gabrieli (2002). Here we will mainly focus on the mechanisms involved in maintaining goals in the face of conflict, switching between tasks and selecting amongst different responses because these aspects are involved in bilingual language processing.

Functional neuroimaging studies investigating these aspects of cognitive control confirm that cognitive control emerges from the integration of separable neural systems (Botvinick, Nystrom, Fissell, Carter, & Cohen, 1999; Carter, et al., 1998; MacDonald, Cohen, Stenger, & Carter, 2000; Petrides, Alivisatos, Meyer, & Evans, 1993). These systems include prefrontal, inferior parietal cortex and, anterior cingulate cortex (Braver, Barch, Gray, Molfese, & Avraham, 2001; Bunge, Hazeltine, Scanlon, Rosen, & Gabrieli, 2002; de Zubicaray, Andrew, Zelaya, Williams, & Dumanoir, 2000). Likewise, also the basal ganglia with their multiple parallel excitatory and inhibitory cortical connections are believed to be crucially involved in cognitive control and information processing (Graybiel, 1997; Middleton & Strick, 2000). Fig. 1 represents a schematic model of the areas involved in cognitive control.

The chief neural component subserving cognitive control is the prefrontal cortex. This brain region may be considered an interconnected set of neocortical areas having a unique pattern of connectivity with virtually all sensory, motor, and associative neocortical systems and a wide range of subcortical structures (Miller, 1999). This pattern of connectivity provides an ideal architecture for the orchestration of a diverse range of information needed for cognitive control. From an anatomical view, the various areas of the prefrontal cortex are thought to contribute to specific and separable cognitive functions. In humans, on the basis of clinical syndromes as well as neuroimaging studies, it has been suggested that whereas the ventromedial prefrontal cortex is involved in decision-making processes, the lateral portion has a role in working memory, planning and sequencing of behaviour, response inhibition, language and attention. However, exactly how discrete prefrontal regions and their differential connections contribute to the executive role of the prefrontal cortex remains still an open field (see Elliot, 2003 for extensive review). Nevertheless, processes such as attention, working memory and response inhibition can be viewed as key components of a general capacity for effecting appropriate behaviour.

Models of cognitive control conceptualise prefrontal cortex functions as top-down bias mechanisms that facilitate the processing of task-relevant representations even in the presence of prepotent, irrelevant ones (Dehaene & Changeux, 1991; Desimone & Duncan, 1995; Miller & Cohen, 2001). In the bilingual case, such a situation could ideally be when a bilingual has to produce words in a weaker L2 and, hence, to block potential prepotent responses from the stronger L1.

Indeed, due to its widespread projections to many systems the prefrontal cortex can exert a 'top-down' influence on a wide range of brain processes. Petrides (1998) has advanced the idea of a two-stage hierarchical organisation of prefrontal cortex according to which in humans the midfrontal areas 9 and 46 carry out sequential processing and self-monitoring functions while the inferior prefrontal areas 45 and 47 are engaged in a lower-level function entailing comparison between stimuli in short-term memory as well as the active organisation of sequences of responses based on conscious explicit retrieval of information from posterior cortical association systems (Petrides, 1998). Moreover, the
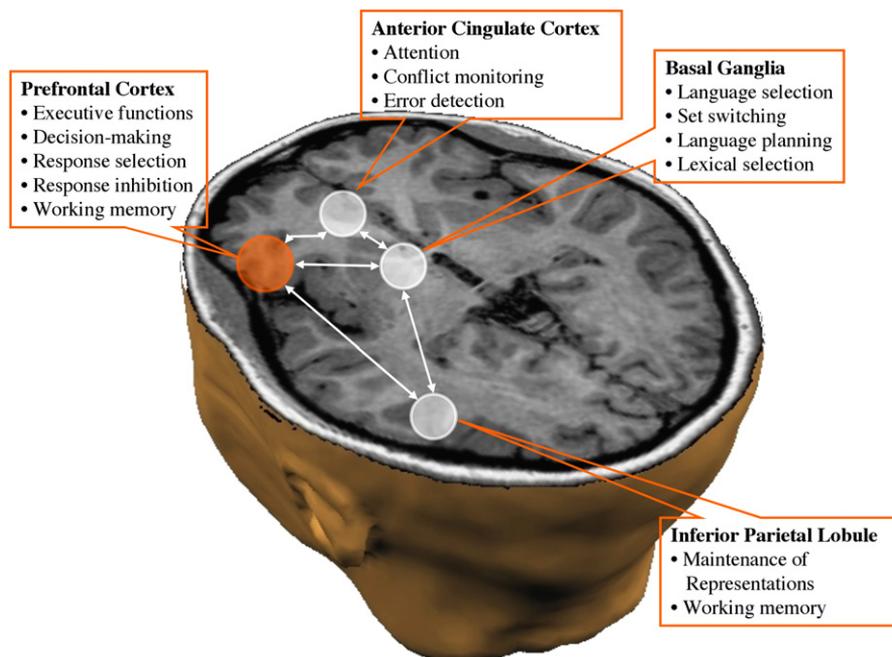
Fig. 1. Multiple levels of cognitive control and bilingual language production. The figure schematically illustrates the neural devices responsible for cognitive control (see text for details) as displayed on a BrainVoyager template. Cognitive control emerges from the integration of separable neural systems including the anterior cingulated cortex, the basal ganglia, the inferior parietal lobule and most prominently the prefrontal cortex (for illustration's sake these areas are represented on the same axial brain slice). Each of these systems is responsible for distinct aspects of cogntive control as outlined in the "callout" boxes of the figure. In the domain of language, cognitive control refers to processes not directly concerned with the representation of language (i.e., lexical items), but rather with the selection and temporal sequencing of such representations. During bilingual word production, cognitive control may be at work in order to achieve the correct selection of the lexical item in the target language and to keep it free from non-target language interferences. This is achieved through the normal interplay of the mentioned neural devices: the left basal-ganglia and the anterior cingulate cortex will modulate activity in the left prefrontal cortex providing a normal modulatory influence on the systems mediating word production (left prefrontal cortex and inferior parietal cortex).

two-level hypothesis makes a distinction between active-controlled (strategic) retrieval, which requires the engagement of the inferior prefrontal cortex, and automatic retrieval that does not (Petrides, 1998). Active retrieval implies conscious effort to retrieve a specific information (i.e., a word to be produced) guided by the subject's intention and plans. This attempt at retrieval may be self-generated or set up by the instructions given to the subject.

The distinction between active-controlled vs. automatic retrieval may have strong implications also for word production in bilinguals. A so-called 'non-automatic' language, such as an L2 not mastered to a high degree of proficiency, may require the engagement of the inferior prefrontal cortex because retrieval of L2 words is processed in a controlled manner. On the other hand, word production in L1 or in a well-mastered L2 would not require the prefrontal cortex because retrieval is more automatic except in certain contexts, for example, in translation.

The prefrontal cortex is not the sole area involved in cognitive control. As mentioned above a complex function such as cognitive control is likely carried out through a network of brain areas, each contributing with specific complementary control functions. For instance, the prefrontal cortex interconnects strongly with the parietal cortex (Petrides & Pandya, 1984; Schwartz & Goldman-Rakic, 1984) and this circuit may be implicated in the selection of competing responses. For instance, Bunge and coworkers (2002) investigated the neural correlates of selection among multiple alternatives and found an interesting dissociation between the left parietal cortex and the prefrontal cortex. Whereas the former was activated only for *maintaining* a representation among possible responses, the prefrontal cortex was recruited when there was a need to *select* between competing responses. We consider other functions of the parietal cortex in the context of task switching.

Badre and Wagner (2004) showed that the selection process might be further dissociated with specific contributions from the prefrontal cortex and the anterior cingulate cortex (ACC). The prefrontal cortex guides response selection under conditions of response conflict or refreshes recently active representations within working memory. In contrast, the ACC modulates cognitive control (see Bush, Luu, & Posner, 2000; Cabeza & Nyberg, 1997). Functional neuroimaging studies have shown ACC activity during tasks that engage selective attention, working memory, language generation, and controlled information processing (Cabeza & Nyberg, 1997). One of its most prominent roles is detecting and signaling the occurrence of conflicts in information processing (Botvinick et al., 1999; Carter et al., 1998). The emerging view is that ACC activation (specifically, within the caudal portion) is directly related to the degree of response conflict present in a given cognitive task (Botvinick et al., 2001; Carter et al., 1998). Response conflict arises because of either physical or task-induced constraints on response generation. For example, it is not possible for certain responses to occur simultaneously. For instance, during a naming task it is not possible to say the word "cat" while at the same time saying the L2 word "gatto". Conflict can be thought of as the simultaneous co-activation of incompatible responses, such as trying to name the ink color of the word "red" written in green ink in the classic Stroop task. A further nice example for cognitive conflict comes from the study of the tip-of-the-tongue phenomena (TOT). The TOT state refers to a temporary inaccessibility of information that one is sure exists in long-term memory and is on the verge of recovering. During a TOT state, cognitive control mechanisms may be recruited in attempts to resolve the conflict between the subjective conviction of knowing the word and the retrieval failure that characterise this state. Maril, Wagner, and Schacter (2001) showed in an fMRI experiment that retrieval failures (i.e., TOTs) were characterised by the co-activation of the left prefrontal cortex and the AAC.

The left prefrontal cortex and the AAC are co-activated in a variety of cognitive tasks, including the Stroop task, sequence learning, and working memory (Duncan & Owen, 2000). Activation of these regions by such diverse cognitive demands suggests that they have a straightforward role in domain-general computations (D'Esposito et al., 1995; Smith & Jonides, 1999). Recent work to isolate these computations suggests that the ACC and the prefrontal cortex have distinct roles. According to one view, the ACC detects conflict between competing responses and signals a need for greater control to the prefrontal cortex. The prefrontal cortex, in turn, implements control via top-down modulation of posterior cortex or the basal ganglia (MacDonald et al., 2000), a possibility that is supported by recent neuroimaging studies (Knight, Staines, Swick, & Chao, 1999).

Consider how this complex network may be at work during bilingual language processing. As an example we choose that of language switching in which cognitive control is involved (e.g., Green, 1998).

Switching between tasks (such as between two languages) involves two distinct steps: individuals must withhold a response to the current task (i.e., language A) and must initiate a response to the now relevant task (i.e., language B). A more anterior part of the ACC may be involved in the former case but a more posterior part in the latter (Swainson et al., 2003). The details of the circuits involved have yet to be determined but the parietal cortex is likely to play a key role. Indeed the right and left posterior parietal cortices may play complementary roles. Generalizing the findings and interpretation of Mvorach, Humphreys, and Shalev (2006), we suggest that the left posterior parietal cortex may bias selection away from the previous task whereas the right parietal cortex may bias selection towards the current task.

Precisely how switching is signalled is also likely to be important. The predictability of a switching sequence (e.g., as in the Rogers and Monsell (1995) paradigm) speeds responses when the current task is repeated. In contrast a visual precue speeds a switch in task. Swainson, Jackson, and Jackson (2006) have identified possible ERP markers of these effects. Knowing that a following trial will involve the same task may lead individuals to maintain the current schema—an action associated with a centro-parietal ERP response. Alternatively, the mechanism may maintain the automatic priming of the task currently used—a priming that is modified when the sequence of switches in unpredictable (Monsell, Sumner, & Waters, 2003). Precued switch trials in contrast elicit a late positive parietal response (somewhat lateralised to the right) that precedes the target. Conceivably, such a response reflects a shift from processing involving executive control as in standard switch trials without a precue to one resolved more automatically by competition between task schemas (contention scheduling in the Norman and Shallice (1986) model).

The basal ganglia are traditionally associated with motor control, probably because of the dramatic, often devastating effects of dysfunction on movement. Although an array of corollary functions such as motor learning and automatisation were long suspected, only recently have these subcortical structures been recognised as indispensably involved in cognitive control. One critical function is cognitive sequence planning (Graybiel, 1997, 2000).

With respect to language production, the basal ganglia may subserve language planning (Fabbro, Peru, & Skrap, 1997) through a left basal ganglia-left prefrontal cortex circuitry. They may also be involved in selecting the most appropriate lexical alternative. In Wallesch's lexical-decision model (1985) it was hypothesised that multiple lexical alternatives (for instance, response alternatives during lexical retrieval) are produced and released in the posterior perisylvian cortex, then carried in parallel to the anterior perisylvian cortex and the basal ganglia. Damage to the basal ganglia may disrupt late integrational language processes such as the suppression of competing alternatives (Friederici, Kotz, Werheid, Hein, & von Cramon, 2003; Longworth, Keenan, Barker, Marslen-Wilson, & Tyler, 2005).

More specifically, intraoperative direct electrical stimulation carried out in monolinguals indicates two distinct basal ganglia systems specific to language use: one related to the motor control aspect of language in the putamen and another related to language control in the head of caudate (Robles, Gastignol, Capelle, Mitchell, & Duffau, 2005). Stimulation of the head of caudate led to perseveration in picture naming, whereas stimulation of the

putamen led to dysarthria or to anarthria. In the next session we will also outline how lesions to the head of the left caudate may lead to impaired language control in bilinguals.

In summary, we have discussed the key neural regions involved in the control of action. In the context of lexical retrieval our argument is that any activated representation will, unless actively prevented, affect all other representations to which it is connected, whether or not that influence is relevant to current goals and actions (see for instances, the recent fMRI study by de Zubicaray, McMahon, Eastburn, & Pringle, 2006). In the next section we argue for a dynamic view of speech production in bilinguals involving cortical and subcortical structures.

3. A dynamic view of bilingual speech production

In this section we argue for the notion that there is a single network mediating the representation of a person's L1 and L2 and that this network is modulated by the control structure identified in Fig. 1. We first of all consider the grounds for the single network hypothesis (Section 3.1) and then address the evidence for it (Section 3.1.1). We argue that the manner in which this network operates depends on a person's proficiency in L2. At a minimum, as noted in the previous section, an increase in proficiency is accompanied by a shift from controlled to automatic processing and this will be accompanied by a reduction in prefrontal activity. It follows that in order to interpret neuroimaging data correctly we need to take proficiency into account if we are to assess the validity of the single network hypothesis. A prefrontal effect is consistent with a number of sources of difficulty and in Section 3.1.2 we explore imaging studies that address the issue of lexical competition between languages. There are few such studies and so we propose relevant ones in a later section (Section 4). In Sections 3.2, we examine tasks specific to bilinguals (language switching in picture naming and a specific type of language switching -translation) with a view to identifying the role of the various control structures in Fig. 1. Section 3.3 discusses data from aphasia that provide further support for the involvement of such structures.

3.1. The single network hypothesis

Consider a word generation task. A native English speaking person who has learned Italian in high school and is invited to generate L2 Italian words related to 'gatto' (cat). Will she use the same neural devices for correctly accomplishing this task, as she would do in English? And how will these devices be controlled?

Having acquired L1 during childhood, the second language learner[2] comes to the task of learning an L2 with an already well-organised neurolinguistic system with its computational devices. Conceivably then a different system is used compared to that of native speakers of that language (e.g., Albert & Obler, 1978; Ullman, 2001, 2004). Ullman (2001, 2004) argued that L2 grammatical knowledge is acquired explicitly and is represented declaratively in a left temporal area along with L1 and L2 vocabulary. In contrast, grammatical knowledge for L1 is acquired implicitly and is mediated by a frontal-basal ganglia circuit. A difference in the way information is represented will have consequences for the way control is exercised. Production in L2 compared to L1 will be mediated by

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[2]If not further specified, second language learner refers to subjects learning L2 after puberty.

explicit, metalinguistic knowledge rather than by implicit grammatical competence that is procedurally represented (Paradis, 1994, 2004; Ullman, 2001, 2004).

An alternative possibility is convergence (Green, 2003). Consider the computational grounds for convergence. The different devices required to represent words and grammar, for example, have different computational requirements and so involve a different neural substrate. Specialisation to perform the kinds of computation may arise because of innate specification, as has been argued in the case of grammar (e.g., Pinker, 1994), or perhaps because of slight differences in computational efficiency or resource. Once a localised brain region or network has begun to process signals of a certain type it will be less effective at processing other types of signal. It follows that the acquisition of an L2 will involve the use of the devices that perform the same computation as in the person's L1. That is, the processing of L2 will use the same network and control circuits deployed by monolingual speakers. Convergence predicts that the neural regions mediating meaning, syntax and phonology (see Indefrey & Levelt, 2004) will be identical to those used to represent L1. With respect to grammatical processing, in particular, the regions subserving grammar in L2 speakers should be identical to those subserving a speaker's L1 even if L2 is acquired late. Differentiation of the L1 network may also occur as in the case of learning a tone language where pitch changes carry lexical effects.

Further, and this is a separable claim, assuming that there is a commonality across individuals in the initial sensitivity of different brain regions, the representation and processing of L2 will converge with that of native speakers of that language as individuals gain proficiency in the language. This is not to claim that the processing profile will be identical. On the contrary, because bilinguals have to learn to manage distinct syntactic, phonological and prosodic patterns, the common network will have to adapt and this entails that a bilingual speaker of an L2 will not process this L2 identically to that of a monolingual speaker of that language. Nor will bilingual speakers process their original L1 in quite the same way as monolingual speakers of their L1.

One view might seem to rule decisively against the notion of convergence and the idea of a single network and that is the idea that there is a critical period for language acquisition. The evidence for a critical period relies on the view that late learners of a language (e.g., post-puberty) rarely attain native-like proficiency and that the level of proficiency achieved shows evidence of a discontinuity such that, for example, it can be high if L2 is learned within the critical period and low when L2 is acquired after that critical period. Birdsong (2006) provides an insightful overview and critique. He notes that the age of acquisition of L2 in the sense of immersion in the L2 linguistic environment correlates negatively with the end state of L2 proficiency in terms of morphosyntax errors in production and nonnative accent but that these age effects persist across the span of age of acquisition surveyed and so are not restricted to a limited period (see Hakuta, Bialystok, & Wiley, 2003). There are in any case a number of factors that may generally militate against the achievement of native-like proficiency that have nothing to do with the constraints of a critical period but everything to do with the fact that the network has to adapt to the acquisition of a new language (see MacWhinney, 2005) and that ageing places various constraints on the ability to acquire new skills. In any case, more rigorous empirical work shows that nativelikeness in the acquired L2 although not typical is not rare with rates ranging from 0% to 46%. Some of the relevant factors are the language pairings in the case of morphosyntax, amount of practice and in the case of pronunciation, a person's motivation to sound native. Clearly some of these factors highlight the more general importance of considering

control matters when thinking about representational change whether at the cognitive or the neural level (see Section 1.2 above).

We consider the evidence in support of convergence and in particular the single network hypothesis in the next section. We defer consideration of the consequence of acquiring a second language for a person's L1 till Section 4.

3.1.1. Evidence in favour of convergence and the single network hypothesis

The data we suggest strongly support convergence subject to recognising effects of proficiency (see also Perani & Abutalebi, 2005). Note that the idea that the neural representation of an L2 converges with that of an L1 does not deny that in certain cases, the reverse will apply. For instance, when individuals learn to read in L2 first, the substrate for reading L1 will converge with that of L2 (see Abutalebi, Keim, et al., 2006). Nor does it deny that there may be language-specific neuronal sites within common regions or sites sensitive to language change. Studies using cortical stimulation mapping (e.g., Lucas, McKhann, & Ojemann, 2004) identify sites at which naming is selectively disrupted for one language but not for another. Such disruption may alternatively reflect differences in the difficulty of producing a particular word. Convergence will have both structural and functional consequences. We focus on the acquisition of new vocabulary but note that there is good evidence, even for late learners, that grammar is mediated by the same left frontal areas as native grammar (e.g., Sakai, Miura, Narafu, and Muraishi (2004) for a study of Japanese–English adolescent twins acquiring regular and irregular verb forms in English; see also Wartenburger et al. (2003) for the first fMRI study investigating grammatical and semantic judgments in groups of bilinguals with different ages of L2 acquisition and different levels of proficiency).

One set of consequences arises from the fact that the process of acquisition involves competition for neural representation. As a result, brain structures may need to adapt to deal with increased demands in representing new vocabulary. We discuss one example of this. Functional consequences will arise because use of L2 will reflect various sources of difficulty. Structurally, a given region or network representing vocabulary must increase its capacity to represent relevant information or it must reorganise to do so. So we should expect either a broad structural effect such as an expansion of the relevant neural region (i.e., increasing the number of units for coding input and output) or an increase in functional capacity by other means such as increasing the connectivity among the units or by increasing their density in a given region.

Consistent with this expectation, work in the area of memory shows plastic changes in regions such as the hippocampus as a function of task demands (Maguire et al., 2000). More specifically, recent work using a whole-brain mapping technique (Lee et al., submitted) identifies a region of the inferior parietal cortex (the posterior supramarginal gyrus) that shows an increase in grey matter density with vocabulary growth in English adolescents irrespective of verbal or nonverbal IQ or verbal fluency abilities. The parietal region (see Lee et al., submitted) is well placed to register new words given its anatomical connections to regions mediating meaning and sound. Additionally, and consistent with convergence, the same region shows increased grey matter density for Italian–English bilinguals compared to matched monolingual English speakers (Mechelli et al., 2004). Functionally, establishing evidence of convergence requires that we consider proficiency. At low levels of proficiency, individuals will struggle to produce the correct name for a picture or to name a word and such difficulty may have a number of sources. The neural

connections between the concept, lemma and word form may be weaker. Lexical retrieval takes more time for a low proficient L2 (Kroll & Stewart, 1994; Snodgrass, 1993). Such differences in relative strength offer one reason to expect a difference in prefrontal activation and a change with proficiency. A second potential source of difficulty is interference from a prepotent concept name. The low proficient L2 speaker must inhibit unwanted L1 lexical items during L2 word production. On this view, any "prefrontal effect" will also reflect between language competition involving the controlled, rather than the automatic processing of L2. Certainly, once a speaker achieves higher levels of proficiency in L2, overt intrusions (Poulisse & Bongaerts, 1994) become infrequent. A decrease in interference is to be expected to the extent the system underlying the use of L2 is differentiated from that of L1 (see for recent discussion Hernandez, Li, & MacWhinney, 2005). Third, the actual process of producing a name will be more practised and so demand less effort. We expect then that with growing proficiency, the bilingual speaker may be less in need of controlled processing in normal language use except in the context of recent use of the L1 or in circumstances involving overt language switching. Competition can be resolved more automatically (contention scheduling) or the resolution of lexical competition may become internal to the lexico-semantic system (see Section 4.3).

At the neural level, to be less dependent on the control mechanism is indexed by a decrease in prefrontal activity. Expressed differently, we should expect that the patterns of activation will differ substantially from native speakers at low levels of proficiency. The implication is that it would be false to infer that L2 is differentially represented from L1 on the basis of neuroimaging data that ignore proficiency. Consider an analogy to the monolingual case: you have to choose between lexical alternatives during a verbal task. If subjects are well trained in the task (i.e., after multiple task-specific training sessions as compared to a non-trained session) functional neuroimaging reveals reduced involvement of left prefrontal structures (Brodman areas, 9, 46, 47; see Thompson-Schill, D'Esposito, Aguirre, & Farah, 1997; Thompson-Schill, D'Esposito, & Kan, 1999). It is unlikely that the neural representation of lexical items has changed in these monolingual subjects. Indeed, the interpretation put forward to explain these plastic changes was that cognitive effort is reduced for a well mastered task and this occasions less prefrontal activity (Thompson-Schill et al., 1997, 1999). Hence, the deactivation of the left prefrontal cortex may be linked to the decrease of computational demands inherent to the task rather than any change in neural representation of lexical items in that region. Retrieval, correct selection and maintenance of lexical items will become more tuned and more automatic because subjects are familiar with the task. Table 1 summarises a range of neuroimaging studies bearing on the issue of representation and control in bilingual speakers. They confirm the absence of the 'left prefrontal effect' for L2 as proficiency increases.

Inspection of Table 1 shows that bilinguals use identical brain areas for achieving identical tasks for their two languages and these results are independent of the age of L2 acquisition. For instance, during lexical retrieval L2 related brain activations were found in identical left frontal and temporo-parietal brain areas (Chee, Tan, & Thiel, 1999; De Bleser et al., 2003; Hernandez, Dapretto, Mazziotta, & Bookheimer, 2001; Hernandez, Martinez, & Kohnert 2000; Perani et al., 2003; Yetkin, Yetkin, Haughton, & Cox, 1996) that are engaged when monolinguals perform the same task. These L2-related neural networks also overlapped with those underlying L1 lexical retrieval in the same subjects underlining the fact that a bilingual can utilise the same neural device to perform identical tasks for both languages. However, there are differences in the activations of L1 and L2.

Table 1
The table provides an overview of the functional neuroimaging studies available in the literature and reviewed in the current paper

Authors	Task and methods	Subjects	Main findings
A. Studies reporting converging L2 representations			
Klein et al. (1994)	PET scanning during word repetition	Twelve late but high proficient bilinguals (French–English)	Convergent brain activity pattern mainly located in the left frontal lobe
Klein et al. (1995)	PET scanning during word generation and word translation	Twelve late but high proficient bilinguals (French–English)	Convergent brain activity pattern mainly located in the left frontal lobe
Kim et al. (1997)	fMRI investigation during sentence generation task	Heterogeneous group of six early bilinguals with different pairs of L1 and L2	Convergent brain activity observed in Broca's area
Chee et al. (1999)	fMRI scanning during cued word generation	Fifteen early bilinguals and nine late but high proficient bilinguals (Mandarin–English)	Convergent L1 and L2 representations for both groups of bilinguals
Illes et al. (1999)	fMRI investigation of semantic and non-semantic decisions	Eight late but high proficient bilinguals (Spanish–English)	Overlapping brain activity for L1 and L2 during the semantic task
Klein et al. (1999)	PET scanning during verb generation and word repetition	Seven late but high proficient bilinguals (Chinese–English)	Converging brain activity for L1 and L2
Hernandez et al. (2000)	fMRI investigation of picture naming in L1 and L2	Six early high proficient bilinguals (Spanish–English), more dominant in their L2 (English)	No differences between L1 and L2
Hernandez et al. (2001)	fMRI investigation of picture naming in L1 and L2	A different group of six early high proficient bilinguals (Spanish–English), more dominant in their L2 (English)	Overlapping brain areas when naming either in L1 and L2
Pu et al. (2001)	Event-related fMRI study on word generation	Six late but high proficient bilinguals (Chinese–English)	Same hemodynamic profile in left inferior to middle frontal gyrus
Wartenburger et al. (2003)	fMRI investigation of grammatical and semantic judgment	Three groups of bilinguals divided on the basis of age of L2 acquisition and proficiency (i.e., early acquisition and high proficiency, late acquisition and high proficiency, and late acquisition and low proficiency)	Convergent representations for grammar only in early bilinguals; Convergent representations for semantics only in high proficient bilinguals
B. Studies reporting divergent L2 representations			
Yetkin et al. (1996)	fMRI study of word generation in L1, L2 and L3	Five multilinguals fluent in L2 but non in L3	Activations were more extended in the left frontal lobe for the languages in which subjects were least fluent
Kim et al. (1997)	fMRI during sentence generation in L1 and L2	Heterogeneous group of six late bilinguals	Divergent brain activity observed in Broca's area

Table 1 (*continued*)

Authors	Task and methods	Subjects	Main findings
Chee et al. (2001)	fMRI during semantic judgments	low and high proficiency bilinguals (Mandarin–English)	Reduced brain activity mainly in left prefrontal areas for high proficient bilinguals as compared to low proficient bilinguals
De Bleser et al. (2003)	Cognates and non-cognates naming in L1 and L2 investigated with PET	Eleven late bilinguals (Dutch/French) with good but non L1-like proficiency for L2	Divergent L2 representation for non-cognate naming
Perani et al. (2003)	fMRI during word generation	Group of early and high proficient bilinguals but exposed differentially to L2	More extensive brain activity for the language to which subjects are less exposed
Pillai et al. (2003)	fMRI during semantic and phonological decision tasks	Eight late bilinguals with a low-moderate degree of L2 proficiency	More extended engagement of the left prefrontal cortex for L2, especially for the semantic task
Wartenburger et al. (2003)	fMRI investigation of grammatical and semantic judgment in bilinguals	Three groups of bilinguals divided on the basis of age of L2 acquisition and proficiency (i.e., early acquisition and high proficiency, late acquisition and high proficiency, and late acquisition and low proficiency)	Divergent L2 representation for grammar in late bilinguals; Divergent L2 representation for semantics in low proficient bilinguals
Briellmann et al. (2004)	fMRI during noun-verb generation	Six heterogeneous quadrilinguals	More extended left-sited brain activity (including the anterior cingulate cortex) for languages with lower proficiency
Rueschemeyer et al. (2005)	fMRI during grammatical and semantic judgment	14 late Russian-German bilinguals	Specific engagement of the left inferior frontal gyrus, superior temporal gyrus and basal ganglia when processing the non-native language
Tatsuno and Sakai (2005)	fMRI during past tense word processing	29 English learners from Japan divided into two groups on the basis of years of schooling in English	Less activity within the left inferior frontal gyrus corresponding to a higher proficiency state

C. neuroimaging studies of language selection, switching, and translating

Price et al. (1999)	PET scanning during written word translation	six late bilinguals (German–English)	Activation of the anterior cingulate and bilateral subcortical structures while translating
Hernandez et al. (2000)	fMRI investigation of picture naming and language switching	Six early bilinguals (Spanish–English), more dominant in their L2 (English)	Specific switching related activity in the left prefrontal cortex
Hernandez et al. (2001)		A different group of early bilinguals (Spanish–English),	

Table 1 (*continued*)

Authors	Task and methods	Subjects	Main findings
	fMRI during picture naming and language switching	more dominant in their L2 (English)	Increasing brain activity in the left frontal lobe only when switching
Rodriguez-Fornells et al. (2002)	fMRI study of language selection between visually presented words	Seven early bilinguals compared to a group of seven monolinguals	Selective activation of a prefrontal area present only in bilinguals
Chee et al. (2003)	fMRI study of word repetition within and across languages	Twelve early and high proficient English–Chinese bilinguals	More extended left prefrontal activity for the 'across language' switching condition
Lehtonen et al. (2005)	fMRI during sentence translation	Eleven late Finnish–Norwegian bilinguals	Selective activation of the left inferior frontal gyrus and left basal ganglia during translation
Rodriguez-Fornells et al. (2005)	fMRI study during a go/no-go tacit picture naming task	A group of 18 fluent German-Spanish bilinguals as compared to a group of 14 German monolinguals	Selective activation of a left middle prefrontal cortex present only in bilinguals
Crinion et al. (2006)	PET and fMRI study of semantic decisions on target words preceded by prime words related or unrelated in meaning and either in the same language or in a different language	PET eleven late German–English bilinguals fMRI fourteen late German–English bilinguals fMRI nine late Japanese–English bilinguals	Reduced activation (neuronal adaptation) in the ventral surface of left anterior temporal lobe for semantically-related target-prime pairs regardless of language; increased activation in left head of caudate for target-primes pairs unrelated in meaning or related in meaning but differing in language

Only studies that addressed production paradigms, judgment paradigms, language selection and language switching paradigms were considered. Part A shows those studies reporting a convergent L2 representation to that of L1 whereas part B shows studies where divergent representations for L1 and L2 were found. Finally, part C enlists studies investigating language selection, switching and translation in bilinguals. The table outlines that whether word production, word completion, or sentence production were used, most neuroimaging studies find that bilinguals, independently of the age of L2 acquisition, activate common brain areas in the left hemisphere when the degree of L2 proficiency is comparable to L1 (e.g., Chee et al., 1999, 2001; Hernandez et al., 2000, 2001; Klein et al., 1994, 1995,1999; Kim et al., 1997; Pu et al., 2001) and this happened irrespective of the differences in orthography, phonology and syntax between the two languages (Chee et al., 1999). On the other hand, bilinguals

There are, as expected, more extended activations for L2 when it is mastered with a low degree of proficiency or with a lower exposure. Noteworthy, these activations (such as the left prefrontal activity along the inferior and middle frontal gyri, BA 9, 46, 47) are found outside areas classically related to language representation but in areas related to cognitive control.

Anatomical differences, mainly within the left prefrontal cortex, are also found in studies that did not directly address lexical retrieval but employed judgment tasks in bilinguals (for example, lexical decision: Illes et al., 1999; semantic judgement: Chee, Hon, Ling Lee, and Soon, 2001; lexical and phonological decision tasks: Pillai et al., 2003;

grammatical and semantic judgments: Wartenburger et al., 2003, Rueschemeyer, Fiebach, Kempe, & Friederici, 2005; past tense processing of words: Tatsuno & Sakai, 2005). In short, the neuroimaging data provide support for convergence and the single network hypothesis.

3.1.2. The prefrontal effect

We have focused in this appraisal on the role of prefrontal structures. An open question remains whether the 'prefrontal effect' is specific to the bilingual case. Recent reviews of language production in monolinguals (Démonet, Thierry, & Cardebat, 2005) do not report such extensive brain activity in areas located anteriorily to the language areas of the frontal lobe such as those reported in Table 1. An exception to this may be studies in monolinguals investigating competition during lexical selection, a task where cognitive control may be required. However, following Kan and Thomson-Schill (2004), functional neuroimaging studies have so far shown an inconsistency for the specific engagement of the left prefrontal cortex during lexical competition. The explanation put forward by the authors is that the presence of prefrontal activity may reflect low name agreement of the pictures to be named. Only studies using low agreement stimuli elicit left prefrontal activity since correct lexical retrieval may be considered more effortful whereas studies using high agreement stimuli lacked the prefrontal activity possibly because lexical selection is restricted and hence more automatic (Kan & Thomson-Schill, 2004).

Kan, Kable, Van Scoyoc, Chatterjee, and Thompson-Schill (2006) recently identified the left frontal operculum as the anatomical site of lexical competition in monolinguals. Unfortunately, few studies directly compare bilinguals to monolinguals. However, two such crucial studies were performed by Rodriguez-Fornells Rotte, Heinze, Noesselt, and Muente (2002) and Rodriguez-Fornells et al. (2005) who, indeed, reported the specificity of the 'prefrontal effect' in bilinguals as compared to monolinguals (see Section 3.2 below for a description of their investigations).

Likewise, Abutalebi, Annoni, et al. (2006) have reported that bilinguals when placed in different language contexts (i.e., single language vs. two language context) show differences in the pattern of brain activity for L1 naming. When placed in a two language context (where a cue in the picture naming task indicates whether to generate an L1 or an L2 noun) compared to a single language context (where a cue indicates whether to generate a noun or a verb) the same subjects when selecting the same L1 nouns, activate more extensively, the left prefrontal cortex, the ACC and selectively the left caudate nucleus. The specificity of the left caudate for language control in bilinguals was also recently described by Crinion et al. (2006) who suggested a universal role of the left caudate in monitoring and controlling the language in use. In the next section we consider further evidence observed during tasks specific to bilinguals such as translation and switching that implicate prefrontal structures together with other components of the control structure identified in Fig. 1.

3.2. Studies of language switching and translation

Involvement of the structures identified in Fig. 1 should be most obvious in tasks particular to bilinguals such as switching between languages in receptive processing or in naming or in translation. We consider pertinent data from normal bilinguals and bilingual aphasics.

Hernandez et al. (2001) performed an fMRI study with early Spanish–English bilinguals who had to name objects in one language or switch between languages. Increased activity was found in the left dorsolateral prefrontal cortex for the switching condition relative to the non-switching condition. Similar findings were reported by Chee, Soon, and Ling Lee (2003). Although differences in the relative difficulty of naming between L1 and L2 can help explain activation differences when bilinguals name pictures over a block of trials either in L1 or in L2 such differences cannot explain increased prefrontal activation in the switching condition. Such an increase is consistent with the requirement to switch between language goals (i.e., to handle goal competition). In the sense that currently active lexical concepts in the current language activate the language goal to name in the current language, any effects of lexical competition between-languages are indirect.

Interestingly, rTMS (repetitive transcranial magnetic stimulation) applied over the left prefrontal cortex of two bilingual subjects as treatment for major depression induced language switching (Holtzheimer, Fawaz, Wilson, & Avery, 2005), though we cannot tell whether rTMS directly stimulated language switching (by shifting the language goal) or disrupted inhibition of the non-target language. More direct evidence of between-language competition comes from the study by Rodriguez-Fornells et al. (2002).

As mentioned above, Rodriguez-Fornells et al. (2002) investigated the neural correlates of language selection. They recruited a group of early bilinguals (Catalan–Spanish) reporting a high degree of language proficiency for both languages. The main aim of their study was to determine how bilinguals inhibit the non-target language (Catalan in that study) during lexical access of visually presented words in the target language (Spanish in the study). They addressed this question by using event-related potentials (ERPs) and fMRI. The results were compared to a group of Spanish monolinguals selecting visually presented real Spanish words intermixed with pseudowords. Interestingly, activation of a left anterior prefrontal region (Brodmann areas 45 and 9) was only observed in the group of bilinguals. Aside from emphasizing this selective effect for bilinguals, we stress that this study confirms that even highly proficient bilinguals need inhibition mechanisms. Indeed, this finding may add crucial evidence to the debate whether language control in bilinguals is limited only to low proficient bilinguals. As to the anatomical details of their findings (Ba 45 and 9), the prefrontal area related to language control is located more anterior to that described by Kan et al. (2006) during lexical competition in monolinguals (see above).

A further intriguing finding of Rodriguez-Fornells et al.'s study (2002) was that ERPs showed a typical sensitivity to word frequency only for words in the target language and not for words in the non-target language. It may be hypothesised that words from the non-target language are not accessed through a direct 'lexical route', but rather they are discarded through a 'sublexical' route. In their second study, Rodriguez-Fornells et al. (2005) confirmed their finding of the specificity of the left middle prefrontal activity in bilinguals as compared to monolinguals during a go/no-go tacit picture-naming task (i.e., subjects were asked to respond when the name of the picture began with a consonant and to withhold a response for words starting with a vowel, see Colomé (2001), for an earlier behavioural study). Apart from the differential activity of the left prefrontal cortex, a further interesting finding of their study was that bilinguals made more errors and their response latencies were longer as compared to the monolinguals.

Jackson et al. (2001) examined ERPs associated with language switching in a digit naming task. They used an ingenious procedure to avoid movement artifacts: individuals named the digit in the target language at offset and the offset occurred either after a short

interval (250 ms) or after a long interval (1000 ms). ERPs were analysed only for the latter trials. The N2 component, recorded over the left frontocentral region and typically associated with response inhibition, was much more negative when individuals switched from naming in L1 (the habitual language) to naming in L2. Such data are consistent with the notion that the more dominant language requires more active suppression (see also Verhoef et al. (2006) for evidence that attentional engagement as evidence by N2 amplitude is at the root of different switch cost patterns).

Jackson et al. (2001) also examined the effects of switching on activity in the parietal cortices. Price, Green, and von Studnitz (1999) had previously shown in a PET study that switching between languages increased activation bilaterally in the supramarginal gyri of the parietal cortex—regions associated with phonological processing. Jackson et al. found that switching induced a sustained increase over the parietal cortices in an ERP component (the late positive complex) associated with increased demands on response selection as in Stroop interference. Taken together, these data indicate that language switching induces increased frontal and parietal activity consistent with the requirement to inhibit ongoing activity and select a relevant response in the face of competition. These structures are activated in order to bring about the response switch and their activation, Jackson et al. speculate, may reflect different types of inhibitory process: one associated with executive control (the N2 component) and the other associated with reconfiguring stimulus–response linkage, i.e., contention scheduling (Jackson et al., 2001, p. 177).

Price et al. (1999) reported that translating, when compared to reading in different languages, activated mainly the anterior cingulate and bilateral subcortical structures (the striatum specifically, the putamen and head of caudate). Price and colleagues (1999) attributed this to the need for greater coordination of mental operations for translation, during which the direct cerebral pathways for naming words must be inhibited, in favour of less automated circuits. The involvement of subcortical structures along with activity in the left prefrontal cortex was also reported by Lehtonen et al. (2005) during sentence translation. Such results provide good evidence for the involvement of subcortical structures in tasks special to bilinguals.

3.3. Bilingual aphasia

Data from bilingual aphasics corroborate the importance of the above areas for language control. Note though that selective vascular lesions to the anterior cingulate cortex are seldom reported mainly because of the existence of collateral arteries that protect this area from ischemia. The prefrontal cortex, the inferior parietal cortex and especially the basal ganglia are relatively more susceptible to stroke, and thus more patient reports exist. It is noteworthy that these latter areas were each separately advocated by different researchers to explain two sets of recovery patterns in bilingual aphasia that are directly linked to language selection and control mechanisms: pathological switching and mixing on the one hand, and selective recovery on the other hand. For instance, pathological switching was found either after left prefrontal lobe lesions (Fabbro, Skrap, & Aglioti, 2000; Stengel & Zelmanowicz, 1933; Zatorre, 1989) or after left inferior parietal damage (Herschmann & Pötzl, 1920; Leischner, 1948; Pötzl, 1925, 1930). In the latter case it was also argued that the left inferior parietal lobule is the site of the so-called "language switch talent" whereby subjects are able to translate and switch among languages (Pötzl, 1930).

Lesions to the left subcortical structures, the head of the caudate in particular, were reported for both, pathological fixation (selective recovery) on a language (Aglioti, Beltramello, Girardi, & Fabbro, 1996; Aglioti & Fabbro, 1993) and pathological switching among languages (Abutalebi, Miozzo, & Cappa, 2000; Mariën, Abutalebi, Engelborghs, & De Deyn, 2005) which led Abutalebi et al. (2000) to theorise that the bilinguals' lexical representations may be selectively accessed under the control of a left basal ganglia—left prefrontal loop. A strong analogy to basal ganglia motor dysfunctions such as inhibition of activity (i.e., Parkinson's Disease) and decreased inhibition of activity (i.e., Huntington's Disease) may be drawn with these cases of pathological language switching and mixing and those with pathological fixation on one language (i.e., so-called selective recovery). Indeed, the former may be thought as a model of decreased inhibition while the latter may be thought of as a model of inhibition of activity.

How might the role of the basal ganglia be characterised? Based on their intraoperative electrical stimulation data in monolinguals, Robles et al. (2005) suggested that stimulation of the head of caudate blocked its normal role in inhibiting a previously active representation allowing reactivation of the neural circuit underlying the naming of the previous picture mediated by the putamen. In other words, the head of caudate, in line with our inference from the lesion data, is involved in the selection and inhibition of alternatives. In monolinguals, lesions to the caudate may result in naming difficulties (Cappa & Abutalebi, 1999) whereas in bilinguals such lesions may result in difficulties in language control (Abutalebi et al., 2000). We suggest therefore that in monolinguals this region may mediate the selection of words while in bilinguals it mediates the selection of words in one language rather than another or, in the words of Crinion et al. (2006), "monitoring and controlling the language in use".

3.4. Summary

During the course of acquiring an L2, whether early or late, we argue that the same network is involved as used in L1. Recent data indicates that this view is also true for the acquisition of syntax (see above). How then do we reconcile the single network hypothesis with neuroimaging evidence indicating more extensive prefrontal activation? Evidence for this claim requires that we take account of the consequences of differences in proficiency that will affect the degree of left prefrontal activation. These consequences may be explained by Petrides' two-level hypothesis (1998, see above) that distinguishes automatic vs controlled retrieval processes within the prefrontal cortex. The non-automatic language (generally L2 when not mastered to a high degree of proficiency) engages more extended portions of the left prefrontal cortex whereas the more automatic language does not. Controlled processing for an L2 would be conscious, effortful and would entail cognitive control processes (Favreau & Segalowitz, 1983; Segalowitz & Hulstijn, 2005).

Together, lesion data and functional neuroimaging results allow us to postulate how brain areas subserving control work together in the bilingual case. In the normal case (i.e., healthy subjects) there is a functional integration of different areas and hence, the basal ganglia and the anterior cingulate cortex will modulate activity in the prefrontal cortex normally. This circuit will provide a modulatory influence on the network mediating word production. The neural evidence implicates multiple structures of control and so cognitive accounts that focus on a single level of control (e.g., competition between goals) may be insufficient to explain the nature of lexical retrieval in bilinguals.

The proposal that multiple languages are mediated by a single network regardless of the age of acquisition is parsimonious. We also expect that a single network will mediate the comprehension and production of sign language and speech. Recent research suggests substantial overlap in left perisylvian areas (posterior temporal and inferior frontal regions) with differences attributable to the nature of the visuo-spatial input (MacSweeney et al., 2006). The parsimony of the single network claim may seem to contrast with the relative complexity of the control system. Of course, the network itself comprises many functional systems (see Démonet et al., 2005; Indefrey & Levelt, 2004). But what we do wish to emphasise is that any control system must be no more complex than is required. Anything more complex will demand greater energy and lose out in competition with a less resource-demanding solution. One challenge then is to demonstrate in detail how the control system works and to show that any proposed control system is the simplest one possible compatible with the representations that must be manipulated under real constraints of time and energy.

4. Future work on the dynamics of representation and control in bilinguals

Work considered in the previous section supports the single network hypothesis and the view that language control in bilinguals involves multiple structures. Language control involves not only cortical structures (the prefrontal cortex, the anterior cingulate and parietal regions) but also subcortical structures such as the basal ganglia. Changes in prefrontal activation as a function of changes in proficiency are compatible with the view that at lower levels of proficiency lexical production is more effortful. It may be so for a number of different reasons. For instance, it may simply be more difficult to retrieve the phonological form of a newly acquired word as well as being more difficult to articulate such words. Such data, we suggest, also reflect competition between languages but direct support for this claim is currently limited. In the next Section (4.1), we consider the kinds of experiment required to provide more direct support for this key question. The studies we have reviewed despite their concern with proficiency have largely been cross-sectional and so in following Section (4.2) we urge longitudinal designs that can examine how details of performance change especially in the context of acquiring specialised skills (e.g., simultaneous interpreting). Understanding the workings of the bilingual production system requires research on how the different regions work together. We have discussed evidence indicating the modulatory role of the anterior cingulate cortex on prefrontal structures but future work needs to address issues of connectivity more widely (4.3). Critically, future work needs to address precisely how control is implemented in terms of neural resources. In Section 4.4 we discuss brain data supporting the importance of inhibitory neurons in the control circuits of both cortical and subcortical structures.

4.1. Direct evidence for lexical competition between languages

More direct evidence could be obtained in a number of ways. One method is to use a competitor priming task (e.g., Wheeldon & Monsell, 1994) in which participants name pictures on target trials having produced the name of semantically-related concept (e.g., whale) in response to a definition several trials earlier. In such circumstances, Moss et al. (2005), showed increased activation in the left inferior gyrus (left pars triangularis) for the competitor condition relative to a repetition condition (in which the prior definition

referred to the target noun) and to an unrelated control condition. This finding is consistent with earlier work by Kan and Thompson-Schill (2004). Such data suggest that there is increased competition for selection in the competitor condition.

Recent work by de Zubicary et al. (2006: on-line) suggests the prospect of a more fine-grained analysis. Using the same paradigm in a more powerful machine, they showed that competitor priming relative to an unrelated control condition, increased activation in a region mediating lemma selection (middle temporal gyrus) and in regions mediating word form retrieval (Wernicke's area). This suggests that competition occurs in both regions: i.e., alternative lemmas and their word forms are jointly activated. In addition, to these regions, they found enhanced activation in regions associated with control: the same region as Moss et al. (2005) together with activation in the anterior cingulate and regions involved in the suppression of stimulus–response mappings (the pars orbitalis and pars opercularis). In short, work by de Zubicary et al. provides strong evidence that distinct regions are active in selecting between lexical competitors and that lexical competition arises both at the level of lemmas and of word forms. In principle then the competitor priming paradigm permits an exploration of lexical competition between languages.

Behavioural work (Lee & Williams, 2001) has confirmed a competitor-priming effect between languages (i.e., when the competitor was named in one language in response to the definition but a different language is used to name the picture on the target trial). We predict that the de Zubicary et al. findings will be replicated when the semantically-related targets are named in different languages. Interestingly, Lee and Williams (2001) showed that the competitor priming effect was eliminated when there was a change of language between the definition trial and picture naming trial. Such a result implies that active lemmas, and not simply word forms, can be suppressed once they do not meet the current language goal. Neuroimaging offers a way to see if there are any residual costs (i.e., continued activation in control regions) that do not in fact give rise to differences in overt response times. Data from a neuroimaging study of this type could be usefully contrasted with data from the results of another type of competitor priming study (see Wodniecka et al., 2005). Here individuals first of all name a picture in L1 (say) and are then required to name it in L2. We predict the prefrontal effects even for proficient bilinguals when they have to resolve competition with competitor-primed pictures. It will be of interest to know whether word form regions also show increased activation. We have focused on the production of bare nouns. The notion that lexical items in different languages compete for selection leads us to predict that there will be effects of a syntactic property such as gender. In languages that specify the gender of a noun, requiring individuals to describe a picture in terms of an adjective noun sequence (e.g., large/small X) takes longer in the presence of an auditorily-presented distractor noun if this noun has a different syntactic gender (e.g., La Heij, Mak, Sander, & Willeboordse, 1998; Schriefers, 1993; Schriefers & Teruel, 2000) at least in non-Romance languages (e.g., Dutch and German but not Italian, see Costa, Kovacic, Franck, & Caramazza, 2003) that allow the form of a determiner to be specified independently of the onset of the noun (see Miozzo & Caramazza, 1999). Salamoura and Williams (accepted for publication) report a gender-congruency effect when translating bare Greek nouns into a German adjective nounphrase (e.g, klein/gross + noun X). Translation takes longer when the syntactic gender of the Greek noun is incongruent with that of the German noun (e.g., the former is feminine and the latter masculine). Such a result indicates between-language competition in the specification of syntactic gender and should yield, relative to the gender congruent case, increased activation in left middle

temporal gyrus but not in Wernicke's area if the selection is indeed completed before the adjective is specified phonologically. In addition, incongruency should increase activation in regions associated with control, for example, the anterior cingulate cortex.

4.2. Longitudinal changes

The research work we have considered primarily concerns probing a system that has already acquired a particular level of proficiency. We have focused too on the way in which structures external to the lexico-semantic system exert control. It is conceivable that the system alters its internal structure. A change in representation will have an effect on the process of control. Kroll and Stewart (1994) argued convincingly that as acquisition proceeds producing a response in L2 may be driven more directly by conceptual input rather than by a linkage to an existing L1 word form. Conceivably, inhibitory connections are established between items that regularly compete for selection. Relations between the lemmas of translation equivalents, for instance, may become mutually inhibitory (see also Gollan, Montoya, & Werner, 2002). If such changes occur, then this would have implications for our account of the way in which control is exercised. Some aspects of the process of selecting a lexical item in the face of competitor from another language would become internal to the system. In order to examine such internalisation of control, we need techniques that can detect competitive effects in the absence of any overt competition.

Changes may also arise in the way in which the control structure is organised. For instance, given that production in a language requires that a specific language goal (e.g., speak in Italian) become dominant and be maintained, the requirement to switch regularly into another language (e.g., English) may yield a structure in which these two language goals are in a mutually-inhibitory relationship—activation of one suppresses the other. Such a structure may reduce switching costs and yield symmetrical costs in switching between one language and another. Further, we predict that if a particular task such as simultaneous interpretation requires a specific configuration of control processes then the structures identified in Fig. 1 will also adapt and increase their functional capacity (revealed by an increase in grey matter density) or by an increase in white-matter tracts to the regions they target. For this reason, the field of the neural basis of L2 processing may benefit from longitudinal investigations addressing the natural course of L2 acquisition (i.e., follow-up studies in L2 teaching classrooms).

To date, the course of language acquisition has mainly been documented for specific components (such as grammatical rules or a limited lexicon) using an artificial language where acquisition is generally achieved in a brief time period. Although these studies may be very informative (see Opitz & Friederici, 2004) they do not represent the natural course and environment of L2 acquisition and so may not reveal the exact mechanism of acquiring a real L2. Pioneering work by Osterhout and colleagues (e.g., Osterhout, McLaughlin, Pitkänen, Frenck-Mestre, & Molinaro, 2006) using ERPs to assess on-line comprehension of an L2 in student learners shows that novel semantic and syntactic properties can elicit native-like profiles relatively quickly. Investigating L2 learners twice (i.e. at the early beginning of L2 learning and after consolidation of the acquisition process) with both fMRI and voxel-based morphometry methods would allow researchers to better document eventual changes of structures involved in cognitive control. Such studies would also help document the convergence of neural structures in the same subject.

4.3. System dynamics and bilingual phenotypes

Convergence implies the use of pre-existing systems and networks. Current neuroimaging work on bilingualism has tended to focus on which particular structures are active but an important future goal is to examine how these structures work together. In monolingual speakers, Bokde, Tagamets, Friedman, and Horwitz (2005), in a one-back task, found different couplings of dorsal and inferior frontal areas with occipito-temporal areas for words and pseudo-words. Mechelli et al. (2005) showed, using a silent reading task, that contiguous prefrontal regions covaried in their activity with distinct fusiform areas as a function of word type. For pseudo-words there was increased coupling between the posterior fusiform and the dorsal premotor cortex. For exception words, increased activity in the pars triangularis (a region associated with semantic selection) was associated with increased connectivity with the anterior fusiform, whereas increased activity in the pars opercularis was associated with increased connectivity to the middle fusiform. Such results suggest that it will be possible to examine whether L2 speakers performing a task such as picture naming or word pronunciation modify the coupling of regions in line with native speakers of that language. It will permit researchers to examine the influence of both proficiency and language background. For instance, will Spanish or Italian readers of English as L2 show increased use of the exception route (i.e., the semantic or ventral pathway) as their reading proficiency in English improves. And, returning to the observation made in Section 3.1, will their reading in their L1 change? We predict that it will. Specifically there will be increased use of the semantic/ventral pathway if only because of its importance in handling inconsistent orthographic-phonological mappings in English. Such studies are critical for another reason. There may be different ways in which a given task is performed. Evidence of such differences does not refute convergence given that the variety is present in native speakers of language (Green, Crinion, & Price, 2006). Future studies therefore should aim to explore the variety of performance patterns for a given behavioural output (see Chee, Soon, Lee, and Pallier (2004) for a pioneering example). In addition, if we are really to make use of aphasic data to help establish structure–function relations we need to examine the performance of bilingual and multilingual speakers with deficits in particular regions who can nonetheless perform the task in question.

4.4. Resources and inhibitory control

One further important theoretical and empirical area remains open. Functional capacity can be distinguished from the modulatory and metabolic resources required in order to implement the computation. A more complete neurocognitive model of bilingual speech production will need to characterise the resources required (Green, 1986, 1998; Green & Price, 2001). Evidence derived from the study of the molecular bases of prefrontal and basal ganglia functioning argues for the importance of inhibitory resources. Consider that ~20–25% of the total cell population of the neurons in the cortex are inhibitory interneurons (Gabbot & Somogyi, 1986; Hendry, Schwark, Jones, & Yan, 1987), and their role is to control the explosion of activation that would otherwise result from all the positive interconnectivity among cortical pyramidal neurons. Prefrontal and basal ganglia circuits are mainly equipped with these inhibitory neurons and so they provide the ideal neural mechanism for inhibitory control (Marín, Smeets, & González, 1998; Miller,

Erickson, & Desimone, 1996). These neurons are regulated by dopaminergic and GABAergic systems. Dopamine via D1 receptors increases the excitability of local interneurons and GABAergic inhibitory conductances to sharpen the tuning of pyramidal cells and to focus activity on task-relevant items (Seamans, Gorelova, Durstewitz, & Yang, 2001). In this way, a limited set of representations are focused on and have complete control of prefrontal cortex output. Moreover, Durstewitz, Seamans, and Sejnowski (2000) showed that increases in GABA inhibitory conductances are necessary to prevent uncontrolled, spontaneous switches into high-activity states (i.e., spontaneous activation of task-irrelevant representations). Hence, dopamine might stabilise, by mediating GABA currents, active neural representations in prefrontal cortex circuits during cognitive tasks and render them robust against interfering prepotent stimuli and noise (Durstewitz et al., 2000).

Consider the implications of these ideas for lexical retrieval during bilingual language production. Only a subset of lexical representations are directly relevant to the goal but any activated representation will, unless actively prevented, affect all other representations to which it is connected, whether or not that influence is relevant to current goals and actions. By the above arguments, the only way of controlling the output of cortical systems is by inhibition of pyramidal cell activity. Dopamine is also the neurotransmitter most prominently associated with the basal ganglia, and indeed, it is one of its most conservative traits (Marín et al., 1998). Different subclasses of dopaminergic receptors, D1 and D2 are associated with the so-called direct and indirect basal ganglia pathways, respectively. These pathways classically represented the anatomical basis for understanding motor control and its disorders. They compete with each other to provide net inhibition or excitation of activity, respectively (see Mink's, 1996 "focused selection and inhibition hypothesis," in which, a specific motor program is activated while competing programs are broadly inhibited). Motor activity is based on the outcome of a balance in activity of these pathways, maintained in part by activation of D1 and D2 dopamine receptors. Thus, if the direct pathway is damaged, the indirect predominates, and, as a result, reduced motor activity and rigidity may appear (Parkinson's disease); conversely, motor activity might be excessive, as in Huntington's disease, resulting from a relative inhibition of the indirect pathway (Graybiel, 2000). The precise role of such pathways in modulating the activity of the putamen and head of caudate in language production is not known but it is plausible that modulation involves inhibition.

Finally, we note that the concept of resource provides a means by which a neurocognitive model can incorporate and predict the effects of drugs on particular tasks and the neural mechanisms engaged. It carries implications for treatment in the context of aging and aphasia. Factors that limit inhibitory control such as depletion of dopamine supplied to the prefrontal cortex that occurs in normal aging (see, for example, Braver & Barch, 2002) should lead to problems of language control in the elderly. Juncos-Rabadan and Iglesias (1994) have reported that language deterioration in the elderly is attributable to declines in attentional abilities, and that bilinguals suffer loss in attentional processing in both their languages with increasing occurrence of switching phenomena. Where a performance decrement (inadvertent switching) is attributable to damage to the frontal-basal ganglia circuit then a dopamine agonist may improve performance. Within normal bilinguals, performance decrements, induced by cognitive load, may be overcome by increasing the resources that modulate attention (see also Ullman, 2004).

5. Conclusion

Zatorre (1989, p. 144: 2) urged investigation of the role of structures such as the frontal lobe in language switching and in other behaviours specific to bilingual or multi-lingual speakers such as translation. Pursuing such an investigation still remains key to understanding normal performance. We have argued for a neurocognitive approach to the study that emphasises dynamical questions. Such questions arise when thinking about lexical access during speech production (i.e., immediate processing dynamics) and when thinking about how the system changes as a function of increases in proficiency and patterns of usage (developmental/acquisition dynamics—i.e., plastic changes over time).

A dynamic view leads to a focus on how the system is controlled and on the connectivity of different neural regions during the performance of different language tasks. Our view favours a degree of specialisation in the circuits involved in control precisely because language control is an integral part of language use in bilinguals and the coordination required has distinct properties (representations that are specifically linguistic must be selected). Future longitudinal studies, examining the neurofunctional changes in control are needed to address this question more properly. For instance, modelling changes in the patterns of connectivity among different regions of interest offers the best prospect of understanding plastic changes that may occur during the acquisition of L2. When combined with an understanding of the resources (inhibitory and excitatory) required to perform a given task a dynamic view promises to open a range of interventions to help in the treatment of bilingual aphasia. It should help realise too the goal of a realistic neurocomputational model of bilingualism.

Acknowledgements

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