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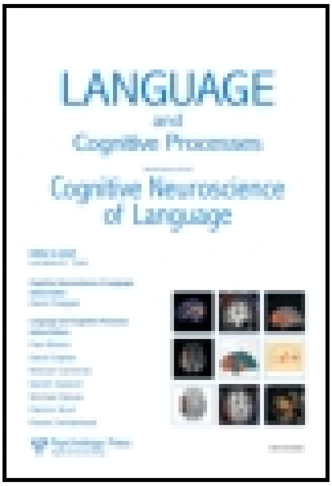

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Control mechanisms in bilingual language production: Neural evidence from language switching studies

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Control mechanisms in bilingual language production: Neural evidence from language switching studies

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A key question in bilingual language production research is how bilingual individuals control the use of their two languages. The psycholinguistic literature concerning language control is unresolved. It is a matter of controversy whether (a) issues to do with control are central to understanding bilingual language processing; and (b) if they are, what is the site or sites of control; and (c) whether language control in bilinguals relies upon inhibitory mechanisms.

One way to deepen our understanding of language control is to consider the implications from research on functional neuroimaging. In the present paper, we illustrate that neuroimaging research shows that bilinguals engage cognitive control networks for achieving tasks such as language switching. The neural evidence points to multiple neural regions of control that may rely upon an inhibitory mechanism. These 'brain data' may, in turn, stimulate the development of neurocognitive accounts of bilingual language processing.

A key question in bilingual research is how bilingual individuals control the use of their two languages. They can speak in one language rather than another. But how do they do so? Recent evidence indicates that even for fluent speakers of a second language (L2) there is activation of lexical representations in the first language (L1) and yet they do not obviously show dysfluency. Such findings suggest that bilinguals must possess an effective

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means to select the intended language. Bilinguals can also switch between languages on demand or translate between them. How bilinguals perform such tasks can help reveal the nature of the cognitive architecture that supports language use.

Behavioural evidence suggests that the practice of selecting one language may improve skills in selective attention (e.g., Craik & Bialystok, 2006) and lead to benefits even in a non-verbal task. Bilinguals, for instance, show less interference in a flanker task (Costa, Hernandez, & Sebastian-Galles, 2007). Such findings suggest that bilinguals, at least those in environments where two languages are regularly spoken, have to manage competition between their languages. But even granted such an inference, the precise site or sites at which such competition is resolved is open to debate.

Consider the simple case of naming a depicted object: a speaker must identify it (access a conceptual representation of it), understand its meaning (access a semantic and syntactic representation for it, its lemma) and map this meaning onto a suitable word (access a suitable word form) and specify its phonology. For bilingual speakers, at least for concrete objects, a conceptual representation will be linked to two different words, i.e., different lexico-semantic representations (Francis, 1999; Gollan & Kroll, 2001; Kroll & Stewart, 1994). A number of models assume that in planning to name an object in one language rather than another, individuals specify the language goal as a cue that is part of the conceptual representation of the intended utterance (de Bot & Schreuder, 2003; Green, 1986, 1998; Hermans, 2000; La Heij, 2005; Poulisse & Bongaerts, 1994). The purpose of the cue is to direct activation to lexical representations in the target language but, as indicated above, there is good evidence that alternative lexico-semantic representations in both languages are active at least briefly (e.g., Colomé, 2001; Costa & Caramaza, 1999; Costa, Miozzo, & Caramazza, 1999). Debate currently concerns how the bilingual system handles such unintended activation.

Three broad possibilities have been considered in the literature. One model (La Heij, 2005) supposes that the intention to speak one language rather than another, expressed in terms of a language cue in a preverbal specification of the utterance, is sufficient to differentiate words in the intended language. A second model (Costa, 2005; Costa et al., 1999) supposes that although lexical candidates in both languages are active during the planning of an utterance, the intention to speak in one language rather than another effectively restricts selection to words in the target language. Competition on this view only occurs within the target language (see Finkbeiner, Gollan, & Caramazza, 2006 for a threshold version of this account). An alternative, third, possibility is that active lexical representations in both languages compete for selection and that such competition is in part managed by mechanisms external to the lexicon (e.g., Green, 1998). The language cue on this account can bias the activation of representations in the target language but does not necessarily prevent candidates in the non-target language competing for selection.

Competition may arise between the goal of speaking in the first language (L1) and the goal of speaking in the second language (L2) (cf. de Bot & Schreuder, 1993; Green, 1998; Roelofs, 2003); between lemmas in different languages (Green, 1998) or between word forms or their response (Finkbeiner et al., 2006) or at more than one site (Green, 1986, 1998; Kroll, Bobb, & Wodniecka, 2006).

Current behavioural evidence provides no adjudication.

One area where one might have expected behavioural data to show consensus is in the case where individuals must switch between one language and another. Typically, in a production task, such as a digit naming or picture naming, there is a reaction time cost in switching from one language to another. The mere fact of such a cost is not of specific interest in behavioural terms because individuals must replace one language goal with another. What is of interest is that this cost can be asymmetric such that it takes longer to switch back into a more dominant language (Meuter & Allport, 1999). One interpretation of such data is that lexical representations in the more dominant language, typically L1, must be actively suppressed in order to produce words in the less dominant language (e.g., Green, 1998). Such an interpretation is consistent with the everyday observation that it can be effortful to speak in a second language but asymmetry in the cost of switching is not always present (see Costa & Santesteban, 2004). The exploration of an asymmetric cost in language switching is important because it provides a way to determine what is involved in the intentional control of language and the impact of factors such as proficiency that is often correlated with the age at which a language is acquired and the frequency of a language's current usage.

One way to deepen our understanding of the language control is to consider the implications from research on neuroimaging. For the past 15 years, functional neuroimaging studies have played an important role in identifying brain structures associated with various language tasks (Démonet, Thierry, & Cardebat, 2005; Price, 2000). However, a shortcoming of neuroimaging research is that it has too often failed to make contact with theoretical models of language and cognition in general. The domain of bilingualism is not an exception to this generality, because many neuroimaging findings in this area have been only interpreted in the context of a localisationist view following which a given language is represented in brain area 'A' and the other language is represented in brain area 'B' (see for details Paradis, 2004). Little effort has been spent to yield a mapping between neural substrates and proposed cognitive processes. On the other hand, also theoretical cognitive accounts of bilingual language processing seldom take into consideration the results of functional neuroimaging studies. If properly interpreted, these brain data may be very informative for models of bilingual language processing. Regarding the key question of language control and selection, neuroimaging research may not only provide crucial insight but also an indication of the nature of the mechanisms involved in control. Thus, the main aim of this paper is not to discuss the validity of the various cognitive accounts dealing with bilingual language processing, but to stimulate researchers to consider data from functional neuroimaging.

First, we briefly review psycholinguistic data on language switching and control. Next, since language switching is an instance of task switching, we outline the neural basis of task switching. This network involves frontal, parietal, and subcortical regions. Next, we show how bilinguals, when switching among languages, engage the same cognitive control network. We then discuss ideas for future experiments.

PSYCHOLINGUISTIC STUDIES OF LANGUAGE SWITCHING IN PRODUCTION

One of the strongest sources of information about language switching comes from production studies in bilinguals. For instance, when individuals are asked to switch between naming a digit in one language compared with another there is a ‘switch cost’ (Costa & Santesteban, 2004; Jackson, Swainson, Cunnington, & Jackson, 2001; Macnamara, Krauthammer, & Bolgar, 1968; Meuter & Allport, 1999; Philipp, Gade, & Koch, 2007). Such a cost has been observed both when the sequence of trials follows an alternating pattern of two trials in one language followed by two trials in the other, where the first trial of each pair is a switch trial and the second a non-switch trial (Hernandez, Dapretto, Mazziotta, & Bookheimer, 2001; Hernandez, Martinez, & Kohnert, 2000; Wodniecka, Bobb, Kroll, & Green, 2005; see Rogers & Monsell, 1995 for the original paradigm) or, more typically, in an unpredictable pattern (e.g., Costa & Santesteban, 2004; Meuter & Allport, 1999; Philipp et al., 2007) and when they name objects (e.g., Costa & Santesteban, 2004) or digits (e.g., Jackson et al., 2001; Meuter & Allport, 1999). As noted above, 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 (Costa & Santesteban, 2004; Jackson et al., 2001; Meuter & Allport, 1999; Philipp et al., 2007). One explanation derives from the proposal that the selection of a language involves the inhibition of the unintended language (e.g., Green, 1998) and that the switch cost reflects, in part, persisting inhibition of the previously irrelevant language. Asymmetry in switch cost is also explicable in terms of the notion of persisting inhibition. In order to name an object in L2 or a digit in L2 the more dominant L1 has to be strongly inhibited resulting in an increase in persisting inhibition.

The pattern of asymmetry observed between L1 and L2 is also observed between L1 and L3 and L2 and L3 (Philipp et al., 2007). The idea that the extent of inhibition reflects the relative dominance of the two languages predicts that any asymmetry should vary with the extent of difference between two languages. It should disappear as proficiency and use of the two languages becomes more balanced. And this seems to be the case (Costa & Santesteban, 2004) but the precise effects of relative dominance remain unclear (see Philipp et al., 2007). Intriguingly, for speakers highly proficient in L1 and L2, there was no asymmetry when these speakers switched between L1 and L3 or between L2 and L3 (Costa, Santesteban, & Ivanova, 2006) consistent with a distinct mechanism of selection. However, they do take longer to switch back into L3 than in L4 (Costa et al., 2006).

Costa and Santesteban (2004) proposed that the nature of control may change with proficiency. So, for example, as individuals are able to access lexical concepts in L2 without L1 mediation (see Kroll & Stewart, 1994) then the language cue may become sufficient to ensure correct selection. However, there was still a switch cost so persisting inhibition could still be important even for highly proficient bilinguals (see Philipp et al., 2007, p. 397) and, as Costa and Santesteban (2004) acknowledged, even their proficient bilinguals took longer to name in L1 suggesting that L1 in the context of L2 was under a degree of suppression (see also Verhoef, Roelofs, & Chwilla, 2006 for other relevant factors).

Finkbeiner, Almeida, Janssen, and Caramazza (2006) sought explicit evidence of a boundary condition for the asymmetric cost of language switching. 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 (i.e., Inhibitory Control model, Green 1998) 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. Asymmetry in switching may reflect persisting inhibition but it could also reflect the need to strongly activate the weaker of the two languages. In an interesting extension of the language switching literature, Philipp et al. (Experiment 2) assessed the reaction time cost of switching back into a language (e.g., L1) after first switching away from it (i.e., as in a naming sequence involving just two languages, e.g., L1-L2-L1) compared with switching into it without first switching away from it (i.e., as in a naming sequence involving three languages, e.g., L3-L2-L1). They found that naming in L1 on the third trial in the two language condition took longer than in the three language condition. In the two language condition the same language task is performed two trials back and so this phenomenon is known as an 'n-2 repetition' cost and has been shown in other task-switching experiments (see p. 408 of their paper). This n-2 repetition cost is consistent with inhibition amongst the set of responses. Such a cost was indeed greater for L1 than for L2 and for L3. However, the cost for L3 was greater than for L2. Overall, then the findings are consistent with a role for inhibition in the selection of a language though the extent to which inhibition is related to dominance or some other factor is unclear.

Currently no model accounts transparently for the full range of behavioural data. Empirically, there may be no single site 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. As underlined by Paradis (1994, 2004), bilinguals may initially use deliberate control and monitoring in production tasks. Changes in proficiency may increase the linkage between concepts and lemma items (cf. Kroll & Stewart, 1994) within a language and mediate the feeling of 'thinking in a language' and so increase the efficiency of language cue in selecting the appropriate response. At the neural level, different brain regions are engaged in the context of language selection and functional imaging data suggest that the precise nature of any conflict may alter with proficiency (Abutalebi & Green, 2007) consistent with a change from controlled to automatic L2 processing. Neuroimaging studies also indicate that a number of neural regions are indeed involved in switching between languages. In the next section we discuss the neural network identified in switching between tasks as a precursor to discussing neuroimaging work on language switching itself.

THE NEURAL CORRELATES OF CONTROL AND TASK SWITCHING: A FRONTAL, PARIETAL, AND SUBCORTICAL NETWORK

Regions implicated in control

Language switching is an instance of task switching as it involves, at a minimum, a switch between different stimulus-response sets. Apart from taking time to invoke new stimulus-response mappings according to a new goal and choosing which attributes to attend to, changing tasks might require the inhibition of competing stimulus–response mappings specified by the now inappropriate task, or even the inhibition of the entire task (Monsell, 2003; Rogers & Monsell, 1995). Task switching then involves a number of processes of control.

Such control processes are unlikely to be carried out by a single unitary brain system but rather emerge from the interaction of separate systems contributing complementary functions (Gruber & Goschke, 2004). Indeed, functional neuroimaging studies suggest that dorsolateral prefrontal and inferior parietal cortex and, medially, anterior cingulate cortex (ACC) are implicated in cognitive control (Botvinick, Nystrom, Fissell, Carter, & Cohen, 1999; Botvinick, Braver, Barch, Carter & Cohen, 2001; Braver, Barch, Gray, Miller, & Cohen, 2001; Molfese, & Avraham, 2001; Bunge, Hazeltine, Scanlon, Rosen, & Gabrieli, 2002; Duncan & Owen; 2000; Kerns, Cohen, MacDonald III, Cho, Stenger, Aizenstein, & Carter, 2004).

Likewise, the basal ganglia with their multiple parallel excitatory and inhibitory connections are implicated in complementary cognitive control functions (Graybiel, 1997; Middleton & Strick, 2000). The same frontal, cortical, and subcortical networks also mediate task switching and so we give a brief characterisation derived from a range of different studies.

In Abutalebi and Green (2007), we characterised the functions of the network as follows: the prefrontal cortex is involved in executive functions, decision-making, response selection and inhibition, and working memory, and together with the anterior cingulate, that detects response conflict, constitutes a control loop in which the identification of conflict triggers a top-down signal from the prefrontal cortex to modulate the non-target representation (see Kerns et al., 2004). Parietal cortex is involved in working memory and in the maintenance and implementation of representations. Task representations have to be held on-line for the control process which may be achieved through parallel networks, one directly linking the posterior parietal cortex to the prefrontal cortex, and one passing through the caudate nucleus, a subcortical brain structure belonging to the basal ganglia. Traditionally, the caudate nucleus, and the basal ganglia in general, have been associated with motor control, probably because of the dramatic, often devastating effects of dysfunction on movement such as Parkinson's disease and Huntington disease. Only recently have these subcortical structures been recognised as indispensably involved in cognitive control such as cognitive sequence planning (Graybiel, 1997, 2000). Work carried out to disentangle the role of the basal ganglia from that of the prefrontal cortex suggests that prefrontal cortex is involved in maintaining representations in the face of competing interference while the basal ganglia has a more direct role in the inhibition of inappropriate behaviours (Casey, Durston, & Fossella, 2001).

Interestingly, and related to language, 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). Taken together, the network described here consisting of the prefrontal cortex, the anterior cingulate cortex, the posterior parietal cortex, and the basal ganglia, constitute a powerful brain network underlying cognitive control. As outlined above, each brain area may contribute distinct functions to achieve cognitive control. In the next section we will underline that the same network is engaged when subjects have to switch between tasks since task switching relies heavily on cognitive control (Monsell, 2003).

Neural correlates of task switching

Within cognitive neuroscience, investigators have only recently become interested in the neural mechanisms of task switching. We focus on the three basic elements of task switching: shifting, updating, and inhibition, and the brain regions involved. Indeed, while shifting (i.e., to shift from one task to a different one) may be considered the core element of switching, it is nonetheless related to other executive processes such as inhibition (i.e., inhibiting the previous task or a prepotent response) and updating (i.e., updating within working memory resources for holding on-line information concerning the new task) (Miyake, Friedman, Emerson, Witzki, Howerter, & Wager, 2000). Consider, as an example, a rule switching task. If the task is to press button A when you see an X, and button B when you see a Y, a rule switch would involve reversing the mappings: button B for X, and button A for Y. The reassignment of different responses to the stimuli may be considered as the 'shifting' component, maintaining these new rules on-line may be considered the 'updating' component and blocking potential prepotent responses (i.e., those who were necessary to perform the previous task (button A for X, and button B for Y) may be considered the 'inhibitory' component.

In a recent meta-analysis, Wager, Jonides, and Reading (2004) demonstrated that multiple regions were reliably activated across a series of studies of attention shifting of various types (e.g., location shifts, rule switching, object switching, task switching, and switching between response sets). These regions included both anterior areas (including the prefrontal cortex and anterior cingulate cortex, ACC) and posterior (parietal) areas (Collette et al., 2005). Some studies also reported more systematic activation of parietal than prefrontal areas in various shifting tasks (for a review, see Collette & Van der Linden, 2002) suggesting that parietal areas may play a more basic functional role in switching processes than prefrontal areas. Sohn, Ursu, Anderson, Stenger, and Carter (2000) attributed the activations of the superior and posterior parietal cortex to endogenous goal-directed preparation for specific subtasks during shifting, whereas the inferior parietal cortex may be responsible for stimulus-driven completion during a different subtask. It is worth underlining that some studies have demonstrated increased activity in the superior parietal cortex during visual and verbal alternating tasks (such as alternating between the processing of letters and digits or alternately producing words belonging to different semantic categories; Dove, Pollmann, Schubert, Wiggins, & von Cramon, 2000; Gurd et al., 2002) as well as during various attentional tasks that require feature integration (i.e., shifting between shape and colour information of objects presented; Corbetta, Shulman, Miezin, & Petersen, 1995; Le, Pardo, & Hu et al., 1998).

Still, following Collette et al. (2005), the left parietal cortex is associated specifically with shifting processes abilities as compared to inhibition processes and to updating processes, while the left frontal lobe is associated more specifically with updating than with other executive functions involved in task switching. More specifically, the more anterior aspects of the prefrontal cortex were found to be associated with information evaluation and selection processes (Christoff & Gabrielli, 2000). This is a key process for updating, because subjects must continuously compare new information with items already encoded so that they can keep in working memory only a specific set of the last items presented. Regarding updating processes, it was proposed that one function of the prefrontal cortex could be temporal coding of representations to be processed (Smith, Marshuetz, & Geva, 2002; Wager & Smith, 2003). Indeed, tasks that require the reordering of a temporal sequence or maintaining memory for temporal order routinely activate this region. Along similar lines, Fuster (2001) and Koechlin, Ody, & Kouneiher (2003) suggested that the prefrontal cortex has a general role in monitoring or temporal organisation of cognitive processes necessary to carry out the ongoing task. Consequently, the prefrontal cortex would be involved in the temporal organisation necessary to select and initiate the function to be carried out in accordance with the task rules and goals, whereas parietal areas would be involved, as discussed previously, in the enactment of attentional sets responsible for the shifting process. During the updating process also the anterior cingulate cortex is involved since monitoring and error-detection processes may be at work while task switching (Collette & Van der Linden, 2002).

Finally, apart from updating and shifting, inhibition constitutes a main feature of task switching. Ideal candidates for carrying out this specific component are the basal ganglia because of their forward and backwards connections to the prefrontal cortex (Alexander & Crutcher, 1990). Specifically, the engagement of striatal neurons by top-down signals would allow the striatum to enhance and suppress particular sets of representations through prefrontal-basal ganglia loops in terms of the well-known direct and indirect pathways (Alexander & Crutcher, 1990; Mink, 1996). Thus, prefrontal-basal ganglia loops seem to work as a top-down 'biased control' system in favour of a selected set of representations that effect action and cognition in a particular context. When a salient external event occurs, particularly in a behavioural context in which the event is not predictable or is contrary to what is expected (such as unpredictable task switch), the event strongly activates striatal neurons.

In summary, task switching is carried out by the engagement of multiple brain areas (i.e., a frontal-parietal-subcortical network) and this may be attributable to the different types of cognitive control necessary to achieve task switching (i.e., updating, shifting, and inhibition). What implications does this research have for language switching in bilinguals? It suggests that multiple sites of control may also mediate language switching. If sites associated with inhibitory processing are activated then neuroimaging data can speak directly to the nature of the control exercised by bilingual speakers.

LANGUAGE SWITCHING IN BILINGUALS

An overview of functional neuroimaging studies investigating language switching

We have discussed the neural regions involved in task switching. In bilinguals, the engagement of the above illustrated brain structures should be most obvious when performing tasks that are similarly in need of mental coordination such as switching between languages and translating between languages. The cognitive mechanism supporting translation may bear similarities to language switching in that both actions involve moving from one distinct cognitive set (i.e., speaking in L2) to another cognitive set (i.e., speaking in L1). In the following, we comment on the available evidence provided by functional neuroimaging studies and link brain-imaging data to the bilingual aphasia literature in order to underline the strong convergence of these two research traditions.

Regarding the left prefrontal cortex, a key mediator of cognitive control, two functional neuroimaging studies indeed found the selective engagement of this brain region specific to language-switching tasks in bilinguals. In a series of fMRI studies carried out (Hernandez et al., 2000, 2001) in different groups of Spanish-English early and, supposedly high-proficient, bilinguals language switching was addressed by a mixed naming paradigm. Subjects named objects in one language or switched between languages on the basis of a pre-stimulus cue indicating the language to use. It is noteworthy that the authors reported increasing activity in dorsolateral prefrontal cortex for the switching condition relative to the non-switching conditions, suggesting that left dorsolateral prefrontal is implicated in the mechanism of language switching and language selection. Unfortunately, the whole switching condition was pooled together so that we do not know whether there are differences when switching from L1 to L2 or rather from L2 to L1. Similar findings were reported by Chee, Soon, and Ling Lee (2003) in English-Chinese bilinguals during a word repetition paradigm within and across languages.

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 also activate the language goal to name in the current language, any effects of lexical competition between-languages are indirect.

Wang, Xue, Chen, Xue, and Donga (2007) did investigate the cost of switching into L1 versus L2 in a sample of Chinese speakers learning English. They confirmed a reaction time cost of switching between Chinese and English and an asymmetry in such a cost: their English learners showed a greater cost of switching into Chinese compared with English. Language switching, relative to non-switching, increased activation in areas associated with executive control (e.g., bilateral frontal cortex, bilateral ACC) and also right caudate. The involvement of the right caudate is somewhat unexpected given the results of Crinion et al. (2006) who found increased activation in left caudate during a language switch (see also Abutalebi, Brambati, Annoni, Moro, Cappa & Perani, 2007, discussed below). The notion that there is competition between languages, predicts that increased executive resources are required in order to speak L2 compared with L1. In line with this expectation, Wang et al. (2007) reported significantly increased activation in regions associated with executive control (bilateral frontal cortices and left ACC) when switching into L2. They also found increased activation in the supplementary motor area (SMA) consistent with the role of this region in inhibiting incorrect response and selecting a less automatic response. Overall, their data are consistent with the notion that the asymmetry in reaction time cost is a product of persisting suppression of L1.

The role of left prefrontal cortex was also characterised by the studies of Rodriguez-Fornells et al. (Rodriguez-Fornells, Rotte, Heinze, Noesselt, & Muente, 2002; Rodriguez-Fornells, van der Lugt, Rotte, Britti, Heinze, & Muente, 2005) with groups of bilinguals as compared with monolinguals. Although the two studies of Rodriguez-Fornells et al. (2002, 2005) did not directly address language switching or translation but rather language selection, they may be very informative since language switching and selection have in common an important cognitive component: a current task must be inhibited (i.e., speaking in language A) in favour of the new task (speaking in language B) in the case of switching and withholding a potential prepotent response (i.e., from a non-target dominant language) when selecting items of a weaker language in the case of language selection. The first study by Rodriguez-Fornells et al. (2002) aimed 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 with 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. 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 with the monolinguals. Similar findings were reported by Abutalebi et al. (2007) who investigated the neural correlates of language selection processes in German-French bilingual subjects during picture naming in different monolingual and bilingual selection contexts. Abutalebi et al. (2007) reported that naming in L1 in the bilingual context (where subjects had to select L1 or L2 nouns following a cue) compared with monolingual contexts (where subjects had to select L1 nouns or L1 verbs following a cue) increased activation in the left prefrontal cortex and engaged specifically the left caudate and anterior cingulate cortex. Strikingly, this pattern of activity was absent for the same L1 nouns when the same subjects were placed in a monolingual mode.

A study by Price, Green, and von Studnitz (1999) investigated language switching and translation. Their subjects were native German speakers (L1 = German) who became fluent in their second language L2 (English) late, after infancy. Subjects were studied with PET while reading or translating written words presented one at a time. In distinct blocks, the words were presented only in German, only in English, or in alternation between the two languages. During the language switching the authors reported activation of Broca's area and the supramarginal gyrus. In contrast, translating, when compared with 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 the fMRI study of Lehtonen, Laine, Niemi, Thomson, Vorobyev, and Hughdal (2005) during sentence translation in a group of Finnish-Norwegian bilinguals. Such results provide good evidence for the involvement of subcortical structures in tasks special to bilinguals.

How might the role of the basal ganglia be characterised? Based on their intraoperative electrical stimulation data in monolinguals, Robles, Gastignol, Capelle, Mitchell, and Duffau (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.

The above-mentioned studies investigated language production, and except for the study of Lehtonen et al. (2005), investigated production only at the single word level. It is therefore remarkable that in a recent study focusing on the auditory perception of language switches during comprehension of narratives (Abutalebi et al., 2007) a neural network consisting of the ACC and the left caudate was reported when subjects perceived a switch into the weaker language. In general, a language comprehension paradigm is thought to be a more passive and automatic task than language production (Abutalebi, Cappa, & Perani, 2001). The fact that even during auditory perception of a switch a cognitive control network is engaged strongly emphasises the importance of control in bilingual processing. The activation of the brain areas specifically reported during switching, translation and selection may thus constitute the neural counterpart of the so-called 'switch-cost' reported in many behavioural studies (see above).

Bilingual aphasia data and the fronto-parietal-subcortical network in language switching

Neuroimaging data indicate the involvement of certain regions in language switching. They do not establish the necessity of such regions. The aphasia literature provides converging evidence that the left prefrontal cortex is directly involved in language switching. Bilinguals with prefrontal lesions were often reported to suffer pathological language switching (Fabbro, Skrap, & Aglioti, 2000; Zatorre, 1989). 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 and 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.[1]

Again, in the classical aphasiological literature there is good evidence for the role of posterior parietal cortex. Both Pötzl (1925, 1930) and Leischner (1948) had suggested, on the basis of defective switching performance by patients with supramarginal lesions, a central role for this region in language switching. Following their observations, this region was then referred to as the 'language talent' area (Leischner, 1943). While in the aphasia literature, the parietal region has been linked to the ability to speak multiple languages, it is likely that it plays a role in a number of different functions. One function that seems reasonably established is its role in the representation of vocabulary. Voxel-based morphometry shows that bilinguals compared with monolinguals have increased grey-matter density in one region of parietal cortex, the posterior supramarginal gyrus (Mechelli, Crinion, Noppeney, O'Doherty, Ashburner, Frackowiak, & Price, 2004; see Green, Crinion & Price, 2007 for an extension to Chinese-speaking bilinguals). One possibility is that the increase reflects the increased vocabulary of bilinguals compared with monolinguals. One source of support for this interpretation is that grey-matter density in this region is strongly associated with vocabulary knowledge. In monolingual adolescents, it shows a correlation with vocabulary knowledge but not with other aspects of verbal IQ (Lee et al.,

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[1] At a first view, it may seem counterintuitive that a lesion to the left prefrontal cortex may lead to unintentional language switching, since as shown above, this region is involved in language switching. However, as outlined by Abutalebi et al. (2001), Mariën et al. (2005) and Abutalebi and Green (2007), the prefrontal cortex is part of a larger network underlying language control in bilinguals. As such, a lesion may interfere with control of languages rather than with language switching per se, producing two distinctive features of deficits: on the one hand, impaired control may lead to pathological and unintentional switching; and on the other, it may lead to pathological fixation on a given language (i.e., in the sense that the control system is unable to activate a given language).

2007). Further, connectivity analysis found that this region is well placed to mediate the connection between the sound and meaning of words.

Finally, lesion studies in bilinguals have indicated that damage to subcortical structures may interfere with the complex mechanism implicated in the selection of languages. Aglioti and coworkers described the case of a bilingual suffering left subcortical damage (capsulo-putaminal lesion), that inhibited language changes when speaking (Aglioti & Fabbro, 1993; Aglioti, Beltramello, Girardi, & Fabbro, 1996).

Abutalebi, Miozzo, and Cappa (2000) and Mariën, Abutalebi, Engelborghs, and De Deyn (2005) reported cases of bilinguals who showed pathological language switching, due to lesions located in the head of the left caudate nucleus. In monolinguals, lesions to the caudate may result in naming difficulties (Cappa & Abutalebi, 1999) consistent with a role in limiting interference. In bilinguals it may monitor and control the language in use in order to prevent interferences from the language not in use (Crinion et al., 2006). It has thus been theorised that the bilinguals' lexical representations may be selectively accessed under the control of neural routes involving a cortical-subcortical circuit (Abutalebi & Green, 2007).

How does the control network work in bilinguals?

In Figure 1 we have summarised the neural findings related to the functional neuroimaging studies focusing on switching, translation, and selecting languages. How may this complex network be at work during language selection (see Figure 2)? The prefrontal cortex is linked to the ACC, and particularly to the anterior part of the ACC (McCormick et al., 2006). Apart from working memory resources (i.e., updating and keeping on-line the now relevant language) it may work together with the ACC and the basal ganglia for response inhibition (i.e., to inhibit interferences from the non-target language). The ACC would signal to the prefrontal cortex potential response conflict or errors (i.e., in the case that an erroneous language was chosen) and the prefrontal cortex would bias against incorrect selection. A more anterior part of the ACC may be involved in withholding a response to the current language and a more posterior part may be involved in initiating a response to the now relevant language (Swainson, Cunnington, Jackson, Rorden, Peters, Morris, & Jackson, 2003).

Left and right posterior parietal cortex may play complementary roles in the switching process. Using a non-spatial selection task, Mvorach, Humphreys, and Shalev (2006) showed that rTMS (repetititive transcranial magnetic stimulation) applied over left and right posterior parietal cortex exerted different effects in response to conflicting stimuli. They proposed that right posterior parietal cortex was necessary to bias selection towards

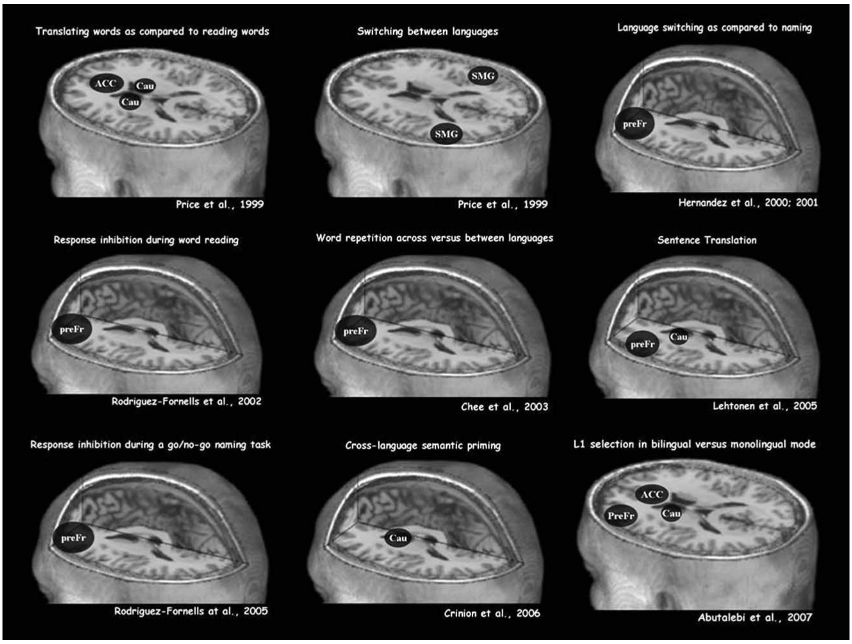

Figure 1. The figure reports a summary of neuroimaging studies investigating language switching, translation and selection in bilinguals. The neuroanatomical findings of these studies are illustrated on a standard brain template.

the current object of attention whereas left posterior parietal cortex was necessary to bias away from the salient dimension and reduce conflict. In the case of unpredictable language switching, we suggest that the left posterior parietal cortex may bias selection away from the previous language whereas the right parietal cortex may bias selection towards the current language. Finally, the basal ganglia may subserve language planning through a left basal ganglia-left prefrontal cortex circuitry or may act along with the SMA to inhibit a prepotent response (see Sumner et al., 2007).

The precise way in which the network operates will depend on the language task. One aspect is relevant here. When individuals are required to speak one language rather than another or to translate from one language into another the attentional load is arguably less than when they are required to switch unpredictably between languages. The main neural difference between these two ways to access a language is found in the parietal lobe: parietal activity is absent when subjects have to translate (Lehtonen et al., 2005; Price et al., 1999) or to select a language

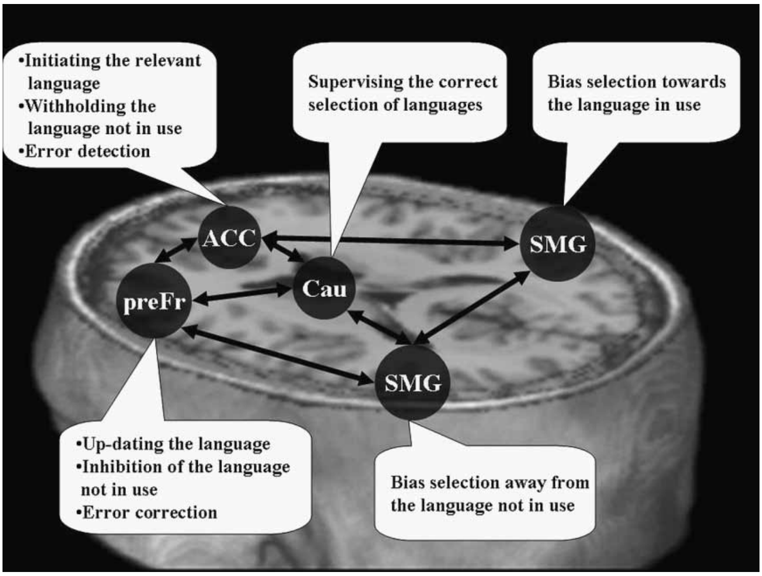

Figure 2. How does a bilingual switch among languages? The figure schematically illustrates the brain system underlying language switching (see text for details) as displayed on a brain template. To switch from one language to the other engages brain areas involved in cognitive control (for illustration's sake, these areas are represented on the same axial brain slice). Each of these subsystems is responsible for distinct aspects of cognitive control that are involved in language switching as outlined in the 'callout' boxes of the figure.

(Rodriguez-Fornells et al., 2002, 2005) while it is present when subjects have to deal with unexpected language switches (Price et al., 1999). This neural difference fits well with the claim that the parietal lobe is more involved when the attentional load for selecting a language is higher such as in the case of unexpected language switches.

TOWARDS NEUROCOGNITIVE MODELS OF BILINGUAL LANGUAGE PROCESSING

Grosjean et al. (2003) urged that psycholinguistic research and neuroscientific research need to work together to understand bilingual performance. In this paper, we have shown that data from neuroscience provide critical information for the development of a cognitive model of bilingual language processing. The neural evidence points to the fact that language selection is achieved through multiple and distinct sites of cognitive control. Cognitive models that focus on a single site of control (e.g., language cues or response competition) are unlikely to be of sufficient power to account for the behavioural data. The ultimate goal of a collaborative approach however is the construction of effective neurocognitive models.

Aside from the need to consider the full scope of the control network any such model needs to consider how control is implemented and how the representations and control processes change with proficiency, that is, any neurocognitive model needs to capture the dynamics of the language system as it evolves over time. With respect to the implementation of control, brain data provide a strong constraint on the nature of the mechanism. They suggest that inhibitory mechanisms are key and so rule out bilingual production models in which inhibition plays no role. In contrast, it is psycholinguistic data that point to the need to consider how the system changes. Current neuroimaging data are largely silent on this score. By considering both issues, we stand a better chance of constructing an effective neurocognitive model. We comment on these two issues in the next few paragraphs.

Inhibitory mechanisms

Evidence derived from the study of the molecular bases of prefrontal and basal ganglia functioning argues for the importance of inhibitory resources. Consider that approximately 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 a neural mechanism for inhibitory control (Marín, Smeets, & González, 1998; Miller, Erickson, & Desimone, 1996). Direct and indirect pathways have been identified with their activity modulated by distinct dopamine receptors. 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 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.

The neuroimaging data focusing on language switching reviewed above show that these prefrontal-basal-ganglia circuits are engaged when bilinguals have to access a given language. It would seem then that a neurocognitive model should postulate inhibition during language selection. In order to advance to a more descriptive and applicable model, it will need to characterise the excitatory and inhibitory neural resources required for control (Green, 1986, 1998; Green & Price, 2001). Such a model will allow clinicians to predict the effects of drugs on performance. Factors that limit inhibitory control such as depletion of dopamine supplied to the prefrontal cortex that occurs in normal ageing (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).

Dynamics of language processing

A weak point of current neuroimaging work on bilingualism is its ‘static’ nature. It is static in two interrelated senses. First, researchers have mostly tended to focus on which particular brain areas are active but an important future goal is to examine how these structures work together in order to reveal the dynamics of the bilingual language system. Second, cross-sectional rather than longitudinal studies are the norm and so we lack neuroimaging data on how the system evolves over time as proficiency, for instance, increases in L2.

Cognitive models such as the Revised Hierarchical Model (Kroll & Stewart, 1994) propose that as proficiency in L2 increases there is a change in the way in which individuals access words in L2. One consequence is that production in L2 may become more automatic rather than controlled. Cross-sectional studies show decreased prefrontal activation (a ‘prefrontal effect’, Abutalebi & Green, 2007) in using L2 as proficiency increases. In Petrides’ two-level hypothesis of prefrontal functioning (Petrides, 1998), a distinction between active-controlled (strategic) retrieval requiring the engagement of the inferior prefrontal cortex is made with automatic retrieval that does not require these inferior prefrontal areas. In monolinguals, the studies of Thompson-Schill and coworkers (Thompson-Schill, D’Esposito, Aguirre, and Farah, 1997; Thompson-Schill, D’Esposito, and

Kan, 1999) have shown that these inferior prefrontal regions (such as pars triangularis of Broca's area[2]) are necessary when subjects have to choose between lexical alternatives during a verbal task. However, if subjects are well trained in the task (i.e., after multiple task-specific training sessions as compared with a non-trained session) functional neuroimaging reveals reduced involvement of left prefrontal structures. Hence, increased automaticity deactivates the prefrontal cortex. Likewise, as reviewed by Abutalebi and Green (2007), bilinguals with increasing L2 proficiency rely less on these structures underlying a switch from controlled to automatic L2 processing.

There may also be a correlated change in the way in which words in the language are selected. Costa and Santesteban (2004) reported symmetric costs in switching between L1 and L2 in proficient speakers of the two languages. Such an outcome is consistent with an inhibitory account but it is also consistent, as they propose, with the notion that the nature of selection changes such that a language cue plays a more prominent role (cf. La Heij, 2005).

In principle, neuroimaging data could distinguish these alternatives by examining changes in the coupling of various regions involved in the control of language. Current techniques such as dynamic causal modelling (see Mechelli, Crinion, Long, Friston, Lambon Ralph, Patterson, McCelland & Price, 2005) permit such exploration. As proficiency increases, lexical selection will become more automatic consistent with the prefrontal effect. If there is a marked change in the way in which control is exercised then the coupling between regions will converge with that of native-speakers. However, to the extent there is competition for selection then regions involved in selecting amongst competing candidates (e.g., pars triangularis) will show increased coupling with regions involved in phonological processing. It follows that there will be a difference in the extent of neuronal coupling between these regions even when highly proficient speakers of L2 are compared with monolingual speakers of that language. Equally bilingual speakers will show enhanced use of that pathway compared with monolingual speakers of their L1.

For this reason, the field of the neural basis of L2 processing may benefit from longitudinal investigations addressing the natural course of L2

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[2] It is worth mentioning that the pars triangularis of the left prefrontal cortex was traditionally associated with language production, but in recent years functional neuroimaging studies have also revealed that the functions pertaining to the pars triangularis and surrounding areas are not only confined to language processing. Indeed, it is engaged also in other domains requiring cognitive control (Koechlin et al., 2003), executive control over hierarchically structured action plans (Koechlin & Jubault, 2006) and working memory (Paulesu, Frith, & Frackowiak, 1993; Smith & Jonides, 1999).

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 are informative (see Opitz and 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 (see Osterhout, McLaughlin, Pitkänen, Frenck-Mestre, and Molinaro, 2006 for pioneering work on the lines we have in mind). Investigating L2 learners twice (i.e., at the beginning of L2 learning and after consolidation of the acquisition process) with fMRI and dynamic causal modelling would allow researchers to better document the evolution of representational change and control processes.

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