

Language Conflict in the Bilingual Brain

Walter J.B. van Heuven^{1,2}, Herbert Schriefers¹, Ton Dijkstra¹
and Peter Hagoort^{1,2}

¹Nijmegen Institute for Cognition and Information, Radboud University Nijmegen, Montessorilaan 3, 6525 HR, Nijmegen, The Netherlands and ²F.C. Donders Centre for Cognitive Neuroimaging, Kapittelweg 29, 6525 EN Nijmegen, The Netherlands

The large majority of humankind is more or less fluent in 2 or even more languages. This raises the fundamental question how the language network in the brain is organized such that the correct target language is selected at a particular occasion. Here we present behavioral and functional magnetic resonance imaging data showing that bilingual processing leads to language conflict in the bilingual brain even when the bilinguals' task only required target language knowledge. This finding demonstrates that the bilingual brain cannot avoid language conflict, because words from the target and nontarget languages become automatically activated during reading. Importantly, stimulus-based language conflict was found in brain regions in the LIPC associated with phonological and semantic processing, whereas response-based language conflict was only found in the pre-supplementary motor area/anterior cingulate cortex when language conflict leads to response conflicts.

Keywords: event-related functional magnetic resonance imaging, interlingual homographs, lexical decision, pre-supplementary motor area and anterior cingulate, response conflict

Introduction

Despite the presence of 2 languages in memory, a proficient bilingual person is able to speak in one language at a time. To accomplish this, his/her language system must select words from the target language, whereas those from the nontarget language should be ignored. In most situations, bilinguals are successful in selecting the intended language, but sometimes a word of the nontarget language intrudes and a cross-language speech error arises. This common observation indicates that in the bilingual brain words from the different languages compete with each other. Such interference between languages can be characterized as *language conflict*.

Bilinguals could handle a potential language conflict in 2 ways. First, words of both languages become activated, and an effective mechanism then selects words from the target language out of the set of activated target and nontarget language representations. Second, there might be a mechanism that blocks the nontarget language completely, such that normally nontarget language representations do not become activated at all. Electrophysiological and neuroimaging data have been interpreted in favor of the latter option (Rodríguez-Fornells et al. 2002). A completely blocked nontarget language assumption is indistinguishable from the idea of language-specific lexical access. One of the first behavioral studies that supported the language selective access hypothesis is the study from Gerard and Scarborough (1989). However, recent behavioral studies indicate that words are stored in a common lexicon and are accessed nonselectively and suggest that blocking of the nontarget language is not possible (e.g., Dijkstra et al. 1998,

2000; van Heuven et al. 1998; de Groot et al. 2000; van Hell and Dijkstra 2002; von Studnitz and Green 2002). For instance, data from Dutch-English bilinguals show that the recognition of words from one language is affected by the existence of similarly spelled words in the other language (van Heuven et al. 1998). It has been found that the recognition speed of a written English word like BLUE is slowed down by the existence of similarly spelled Dutch words like BLUT (meaning “broke”). Thus, whether or not bilinguals have a mechanism that can block nontarget language representations in order to prevent language conflict is still a matter of debate.

Activation of the first (L1) and second (L2) language in bilinguals and the occurrence of language conflict might depend on specific language combinations, proficiency of the bilinguals, the language context (purely L1 or L2, or mixed), input/output modality, task demands, and/or instructions. For example, in language switching tasks language interference does occur (Hernandez et al. 2000, 2001), because both languages are required for the task. Also, a picture naming study with bilinguals (Rodríguez-Fornells et al. 2005) revealed nontarget language interference, but again both languages were required for the task, because picture naming alternated between L1 and L2. However, more compelling evidence that language conflict cannot be avoided would be to observe language conflict in tasks and context that require only one language so that bilinguals could potentially block the other language. Behavioral studies, however, have shown that the nontarget language is activated and that cross-language effects appear even in situations and tasks that are purely monolingual. For example, in unbalanced bilinguals cross-language effects of L2 on L1 were found in a purely L1 context (van Hell and Dijkstra 2002; van Wijnendaele and Brysbaert 2002). Thus, these data also suggest that bilinguals are not able to block a nontarget language.

The occurrence of language conflict is predicted by models of word processing that assume parallel activation of words from different languages in an integrated lexicon that contains words from all these languages (van Heuven et al. 1998; Dijkstra and van Heuven 2002). According to one such model (Dijkstra and van Heuven 2002), a distinction should be made between a word identification system with access to a fully integrated multilingual lexicon, and a decision system that regulates control and the selection for action. According to this model, in a bilingual person a visual letter string activates semantic, orthographic, and phonological representations of both languages in parallel, and these representations compete with each other in the word identification system. Accordingly, a stimulus-based language conflict can arise in the word identification system, because of competition between activated representations from the 2 languages.

A possible second source of language conflict arises at the level of the decision system where a response is selected based on the activated representations in the word identification system. For example, when one has to decide whether a word belongs to one language and not the other, a response conflict can arise when words of both the target and nontarget language are activated and are connected to different responses (e.g., respond “Yes” to target language words, and “No” to nontarget language words). There are thus 2 potential sources of language conflict: a stimulus-based conflict, and a response-based conflict in the decision system that guides selection for action.

In the present study, we use functional magnetic resonance imaging (fMRI) and behavioral measurements to investigate stimulus-based and response-based language conflict during visual word recognition in bilinguals. We expect that if language conflict occurs, brain areas involved in executive control need to be recruited to handle the conflict.

The main brain region associated with executive control is the prefrontal cortex (PFC) (Miller and Cohen 2001; Koechlin et al. 2003), although other brain areas are involved with cognitive control as well, such as the medial frontal cortex (Botvinick et al. 2001, 2004; Paus 2001; Ridderinkhof et al. 2004) and the basal ganglia (Middleton and Strick 2000). The PFC is assumed to be involved in a wide variety of cognitive and language related functions, such as working memory (Smith and Jonides 1999), controlled semantic retrieval (Gold and Buckner 2002; Badre et al. 2005; Gold et al. 2006), phonological retrieval (Poldrack et al. 1999; Gold and Buckner 2002), selection of task-relevant information (Thompson-Schill et al. 1997, 1999), grapheme-to-phoneme conversion and lexical search (Heim et al. 2005), hierarchical control (Koechlin and Jubault 2006), and unification for language (Hagoort 2005).

Language conflict could therefore lead to activations within the PFC. For example, selection or retrieval difficulties might occur when semantic and phonological representations of 2 languages are activated and the correct ones have to be selected or retrieved for the task at hand. The medial frontal cortex could be activated, because, for example, the anterior cingulate cortex (ACC) is assumed to monitor conflicts in information processing (Carter et al. 1998; Barch et al. 2001; Botvinick et al. 2001, 2004; Yeung et al. 2004) or is involved in selection for action (Holroyd and Coles 2002). A number of neuroimaging studies with bilinguals have investigated language control in language switching, translation, and naming tasks. All these tasks require language control in order to select the pronunciation of the correct language. Price et al. (1999) found that word translation activated the ACC, putamen and head of caudate, whereas language switching activated the anterior insula, cerebellum, and the pre-supplementary motor area (pre-SMA). In a study by Crinion et al. (2006), bilinguals made semantic decisions to words preceded by semantically related or unrelated primes. The language of the target and prime was either the same or different. Activation in the left caudate was only reduced when the prime and target were semantically related and written in the same language. Crinion et al. (2006) concluded, based on their data and several neuropsychological studies of monolingual and bilingual patients (e.g., Abutalebi et al. 2000), that the left caudate plays an important role in language control.

Rodriguez-Fornells et al. (2002) conducted a go/no-go vowel-consonant discrimination task in which bilinguals had to ignore pseudowords and words of the nontarget language. The authors argued that the activation in the left inferior PFC (LIPC)

observed for nontarget words and pseudowords was associated with inhibition processes to reduce response conflict. Also, activation was found in the ACC. Rodriguez-Fornells et al. (2005) used a go/no-go task with monolinguals and bilinguals and explicitly manipulated language interference. Their imaging data revealed, in the contrast between bilinguals and monolinguals, activation in the pre-SMA and the middle frontal gyrus. Recently, Abutalebi et al. (2007) concluded that the ACC and the left caudate are involved in keeping 2 languages active in tasks that require both languages. Thus, brain areas associated in particular with executive control processes in bilingual language processing are the left caudate, the ACC, and the pre-SMA. However, the tasks used in the neuroimaging studies mentioned above (Price et al. 1999; Rodriguez-Fornells et al. 2002, 2005; Crinion et al. 2006; Abutalebi et al. 2007) involved presentation of words from both languages of the bilinguals and/or focused on language production.

The present study focuses on language comprehension and was designed to investigate the effects of stimulus and response-based language conflicts in the bilingual brain when bilinguals perform a task that involves and requires only one of their languages. We studied language conflict in single word processing, an experimentally well-controllable domain. Language conflicts were induced in Dutch-English bilinguals using a special set of words that exist in both Dutch and English. These words are spelled identically in both languages but they have a different meaning and pronunciation in each language. For example, the Dutch-English word KIND means “child” in Dutch. These so-called *interlingual homographs* are an ideal tool to investigate language conflict in the bilingual brain.

We selected a set of Dutch-English interlingual homographs and a set of matched English control words that have no counterparts in Dutch. Recognition of interlingual homographs will suffer from a stimulus-based language conflict, because 1) they belong to 2 languages; 2) they are semantically ambiguous; and 3) their pronunciation is different for each language (Fig. 1A). Thus, interlingual homographs might activate representations from both languages in the word identification system, resulting in a potential language conflict within the word identification system, whereas the matched English control words will not induce such a conflict.

Two tasks were chosen that, for interlingual homographs, both generate conflict at the stimulus level, but only one of which generates conflict at the response level. In the English lexical decision (ELD) task, participants were required to press a “Yes” button when a presented letter string is an English word, and a “No” button when the letter string is not an English word. When Dutch-English bilinguals read interlingual homographs in an ELD task as English words, they must respond with “Yes,” because interlingual homographs are correct English words. However, these words might also evoke a tendency to respond with “No,” because they are also existing Dutch words (Fig. 1B). As a consequence, in this task a response-based language conflict will arise for interlingual homographs.

In the generalized lexical decision (GLD) task, participants were required to press a “Yes” button when a presented letter string is a word, irrespective of the language to which it belongs, and a “No” button when the string is not a word in any of the languages involved. Thus, when interlingual homographs are presented in a GLD task, response conflict should not occur, because for both Dutch and English the homograph converges on the same response (Fig. 1B). However, language

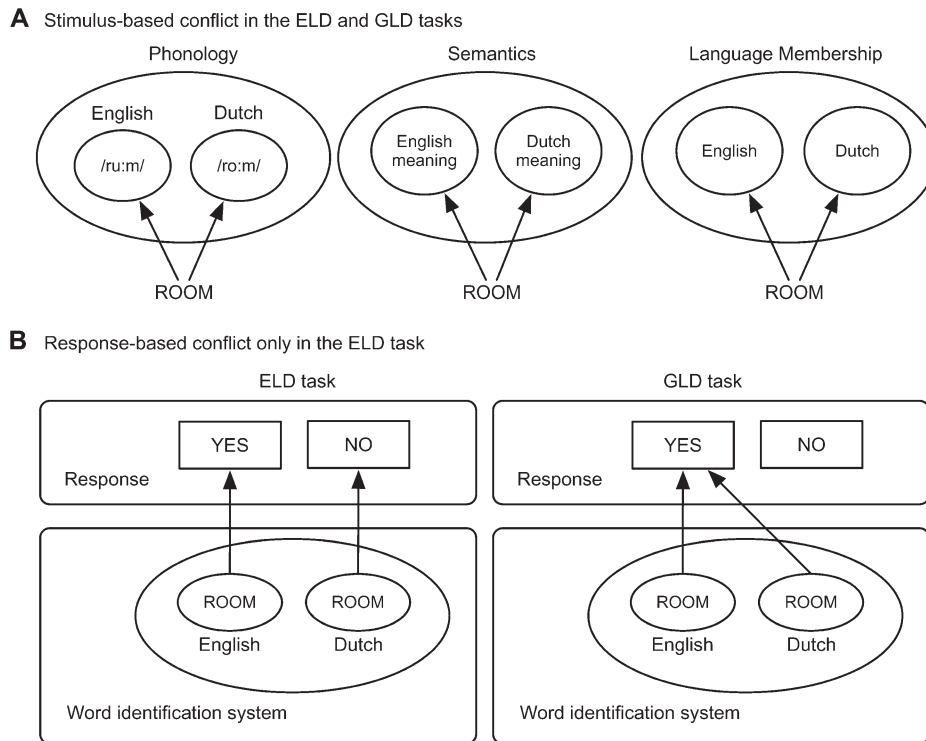


Figure 1. Sources of stimulus-based and response-based language conflicts for interlingual homographs in the ELD task and the GLD task. (A) For Dutch–English bilinguals a stimulus-based language conflict is present in both tasks at the level of phonology (e.g., phonology of ROOM in English is /ru:m/, and in Dutch /ro:m/), semantics (ROOM has different meanings in Dutch (meaning “cream”) and English), and different language memberships (ROOM is both a Dutch and an English word). (B) For Dutch–English bilinguals a response-based language conflict is present for interlingual homographs (e.g., ROOM) in the ELD task, because they can be interpreted as an English word (requiring a “Yes” response), and as a Dutch word (requiring a “No” response). In contrast, in a GLD task both interpretations of the homograph require a “Yes” response and therefore no response-based language conflict arises in this task.

conflict will be present for bilinguals in both tasks when these are stimulus-based. By contrast, if bilinguals are able to block in the ELD task the nontarget language to avoid interference, no language conflict will occur.

One should note that no purely Dutch words were included in the stimulus materials. Thus, bilinguals did not need to use any Dutch to perform the task. In this context, participants could simply block their Dutch language to avoid interference. Thus, observing language conflict in these circumstances indicates that blocking a language is not possible and therefore representations of both languages are automatically activated.

The stimulus materials were presented in 3 event-related fMRI experiments: 2 experiments with high-proficiency Dutch–English bilinguals, and one experiment with English monolinguals. One group of Dutch–English bilinguals performed an ELD task, the other group performed a GLD task. English monolinguals provide the baseline for the bilinguals. For English monolinguals responses to interlingual homographs should not differ from those to English control words, because interlingual homographs are not represented as Dutch words in their word identification system. For these monolinguals, the task is always necessarily an ELD task. Hence, no neuronal activation differences are expected to arise for this control group.

Materials and Methods

Participants

Twenty-four Dutch–English bilinguals were recruited from the Radboud University Nijmegen (the Netherlands) for the fMRI study (ELD: 12 participants, 6 female, age 19–30, mean 24.1; GLD: 12 participants, 9

females, age 18–24, mean 21.2). The language questionnaire administered after the experiment revealed that all bilinguals had acquired English at school from the age of 10–12 onwards. The mean starting age for bilinguals in the ELD task was 11.2 and for bilinguals in the GLD task this was 10.9 (group difference not significant, $P = 0.58$). The average number of years experience with English was for the bilinguals in the ELD 13.2 year and for those in the GLD task 12.1 year (group difference not significant, $P = 0.53$). In the language questionnaire the bilinguals also rated on a 7-point scale their experience/skills in English reading, writing, and speaking. The bilinguals in the ELD task rated their experience (1 = hardly no experience, 7 = a lot of experience) with English reading 6.3, writing 5.2, and speaking 5.3, whereas bilinguals in the GLD rated their skills in these respectively 5.8, 5.2, and 5.5 (1 = very bad, 7 = very good). The information from the language questionnaire as well as the results of an off-line ELD task indicated for both groups of bilinguals a high English proficiency and a regular use of English.

Twelve English monolingual foreign students were recruited from the Radboud University Nijmegen (the Netherlands) (9 females, age 19–42, mean 24.6). These monolinguals participated in the first weeks or months after their arrival in the Netherlands. A language questionnaire indicated no or minimal knowledge of Dutch. This was confirmed by an off-line Dutch proficiency test (Dutch lexical decision task) in which accuracy was at chance level.

All participants were right-handed, and all had normal or corrected-to-normal vision. None of the participants had any neurological impairment. All participants gave written informed consent.

Stimuli

Interlingual homographs ($n = 36$) and English control words ($n = 36$) were matched as closely as possible on word frequency in English (both 28 occurrences per million, Baayen et al. 1995), word length (3.9 vs. 4.3 letters), number of phonemes (3.5 vs. 3.5 phonemes), and first phoneme. In addition, interlingual homographs and English control words all had consistent English spelling-to-sound mappings. The mean frequency of the Dutch reading of the interlingual homographs was 55 occurrences

per million (Baayen et al. 1995). A group of 72 English filler words were also included. These were matched with the interlingual homographs and control words in word frequency and length. All English filler words had inconsistent English spelling-to-sound mappings. The complete list of stimulus words is presented in Appendix A of the Supplementary Material.

The stimulus materials were pretested in 2 behavioral tasks (word naming and an ELD task) outside the MRI scanner with English monolinguals, who were recruited from Duke University (Durham, USA). The results revealed that English monolinguals processed Dutch-English interlingual homographs at the same speed as matched English control words in word naming, $F_{1,17} < 1$ (homographs 432 ms, English control words 436 ms), and in the ELD task $F_{1,17} < 1$ (homographs 514 ms, English control words 510 ms).

Design and Procedure

In first-order counterbalanced lists, 144 monosyllabic English words, 144 monosyllabic pseudowords (constructed by concatenating English legal onset, nucleus, and coda letter clusters), and 144 null-events (no letter string) were presented. Each letter string was presented for 500 ms. Average trial duration was 4 s (range 3–5 s in 9 intervals). A small line just above and below the central fixation point remained on screen during the experiment. One-fourth of the English words were Dutch-English interlingual homographs. Task instructions were written in English. Note that participants in the ELD task were not informed about the presence of interlingual homographs in the stimulus list. In the generalized lexical decision (GLD) task, however, bilinguals were informed that some words might be correct words in Dutch and English, because the language of the item is irrelevant in the GLD task they were instructed to press the “Yes” button to those words. Twelve English monolinguals and 12 bilinguals performed an ELD task, whereas 12 other bilinguals performed a GLD task. For the fMRI experiments, oral communication with the bilingual participants was conducted in Dutch so that these bilinguals fully understood the MRI procedures. With the English monolinguals oral communication was conducted in English.

Image Acquisition and Analysis

Imaging data were collected with a 1.5-Tesla Siemens Sonata magnetic resonance (MR) scanner. Multislice single shot gradient echo-planar imaging (EPI) (25 slices, time echo = 40 ms, time repetition = 2 s, field of view = $256 \times 256 \text{ mm}^2$, 64×64 pixel matrix and $3.75 \times 3.75 \times 5 \text{ mm}$ voxels) was applied. The fMRI experiment consisted of a single session of 29 min in which 868 whole-brain volumes were acquired. The first 4 volumes were discarded because of T_2^* saturation. High-resolution T_1 images were acquired for coregistration of the functional images. Functional images were realigned, corrected for slice timing, corrected for movement artifacts, spatially normalized to the Montreal Neurological Institute (MNI) EPI template, resampled to $2 \times 2 \times 2 \text{ mm}$ voxels, and spatially smoothed using a Gaussian filter of 8 mm.

Statistical analyses were conducted with SPM5 (www.fil.ion.ucl.ac.uk/spm/). The event-related design matrix including all conditions of interest was specified using the canonical hemodynamic response function and its temporal derivative. Furthermore, 6 motion parameters were included in the model. A high-pass filter was used to remove low-frequency drifts. Random-effects analyses that included only imaging data of correct responses (percent discarded incorrect trials: Bilinguals ELD 9.5%, GLD 12%, monolinguals ELD 5%) were conducted, and the resulting statistical parameter maps were thresholded at $P < 0.001$ uncorrected at the voxel level unless reported otherwise. Only clusters with a spatial extent threshold of $P < 0.05$ corrected for multiple comparisons are reported. All coordinates are reported in Talairach coordinates (Talairach and Tournoux 1988). MNI coordinates were converted to Talairach coordinates using the nonlinear transformation procedure described by Matthew Brett (imaging.mrc-cbu.cam.ac.uk/imaging/MniTalairach). The MarsBaR tool for SPM (marsbar.sourceforge.net) was used for region of interest analyses.

Results

Behavioral Results Obtained in the MRI Scanner

The behavioral data of the bilingual subjects obtained in the MRI scanner showed that correct response times to interlin-

gual homographs in the ELD task were significantly slower (94 ms) than to English control words, $F_{1,11} = 10.0$, $P < 0.01$ (Fig. 2). In contrast, no reaction time difference was observed between homographs and English control words in the GLD task, $F_{1,11} < 1$. A between-group analysis of the bilingual data revealed a significant interaction between task (ELD vs. GLD) and word type (homographs vs. English control words), $F_{1,22} = 7.54$, $P < 0.05$ (Fig. 2). As expected, the behavioral results of English monolinguals showed no response time difference between homographs and English control words (Interlingual homographs 966 ms, English control words 958 ms), $F_{1,11} = 1.17$, $P = 0.30$. Reaction times of the monolinguals in the ELD task did not differ significantly from those of the bilinguals in the ELD task, $F_{1,22} = 2.59$, $P = 0.12$, but subject group (monolingual vs. bilingual) interacted significantly with word type (homographs vs. controls), $F_{1,22} = 8.00$, $P < 0.05$ (Fig. 2).

The error data of the bilinguals revealed a significant interaction between task and word type, $F_{1,22} = 7.42$, $P < 0.05$, because no significant difference was found between homographs and controls in the ELD task (homographs: 12.3%, controls 10.9%; $F_{1,11} < 1$), whereas in the GLD task error rates were lower for homographs than for English control words (homographs: 6.9%, control words 12.3%; $F_{1,11} = 23.18$, $P < 0.01$). For the English monolinguals, no error rate differences were observed between homographs and control words (homographs 5.6%, controls 3.7%, $F_{1,11} = 2.38$, $P = 0.15$).

Imaging Results

The imaging data of bilinguals obtained in the ELD task showed greater activations particularly in the LIPC and the medial part of the superior frontal gyrus for homographs relative to English control words (Fig. 3A and Table S1 in Supplementary Material). The activated region in the medial and superior frontal gyrus covers the pre-SMA and the ACC. Peak activations were found in the pre-SMA (Brodmann area [BA] 6: 2, 1, 55), the superior frontal gyrus (BA 8: 8, 35, 46) and at the border of the superior frontal gyrus and the ACC (BA 8/32) (2, 20, 43). The largest brain region activated in the LIPC covers the inferior frontal gyrus (IFG) and extends to the precentral gyrus and the middle frontal gyrus. Peak activations in this region were found in the left pars triangularis and pars opercularis portions of the IFG (BA 44, 45, 46). Smaller clusters in the same region of the right

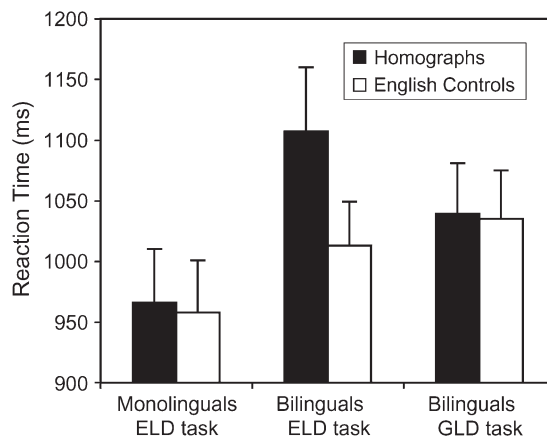


Figure 2. Behavioral results of English monolinguals in the ELD task, and Dutch-English bilinguals in the ELD task and the GLD task. Error bars indicate standard error of the mean.

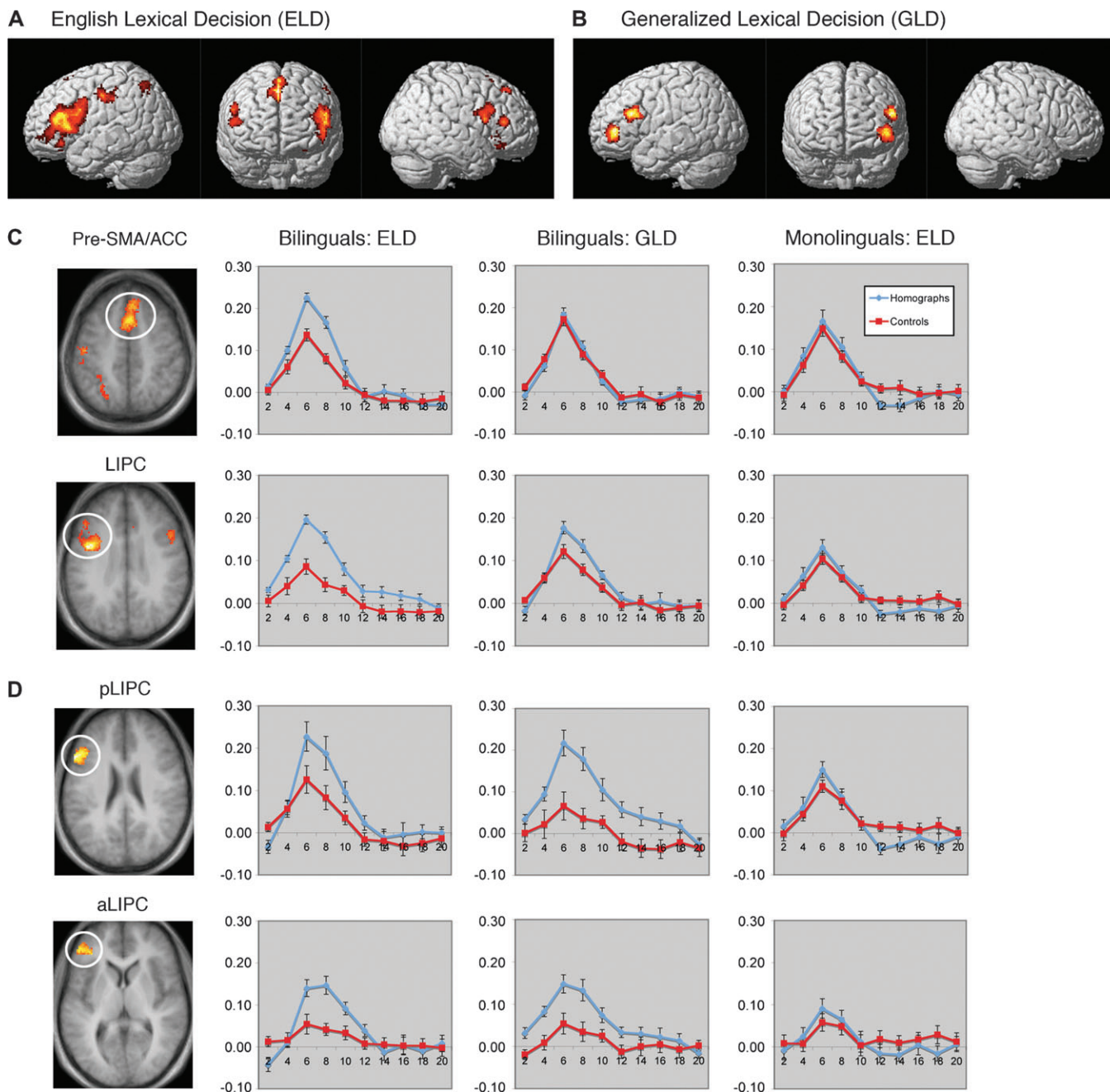


Figure 3. Dutch-English bilingual brain activations showing greater activations for interlingual homographs than for English control words in (A) ELD task (Table S1), and (B), the GLD task (Table S2). Brain activations projected on averaged anatomical axial slices, and the BOLD response for Dutch-English homographs and English controls words of the monolinguals and bilinguals in (C) 2 clusters activated by bilinguals in the ELD task: the pre-SMA/ACC (peaks at 2, 20, 43; Z score = 4.45; 2, 1, 55; Z score = 4.38; 8, 35, 46; Z score = 4.20) and the LIPC (peaks at $-42, 5, 27$; Z score = 4.93; $-48, 18, 6$; Z score = 4.61; $-40, 36, 11$; Z score = 4.50), and (D), in 2 clusters activated by bilinguals in the GLD task in the posterior/superior LIPC (pLIPC with peaks at $-55, 22, 21$; Z score = 4.60; $-44, 26, 21$; Z score = 4.08; $-44, 14, 18$; Z score = 3.52) and the more anterior part of the LIPC (aLIPC with peaks at $-50, 41, 2$; Z score = 4.11; $-38, 41, 3$; Z score = 3.95; $-42, 45, -4$; Z score = 3.94). Error bars indicate standard error of the mean.

hemisphere were also found with peak activations in BA 44 and BA 45. Activation was also found bilaterally in the pars orbitalis of the IFG (BA 47) and in the left insula. Furthermore, a cluster with peaks in left precentral (BA 4) and postcentral gyrus (BA 2) was also observed. Posterior brain areas that were activated more strongly by homographs than control words lie in the left inferior parietal lobule (BA 40) and left precuneus (BA 7). Finally, subcortical activations were found in the left caudate and in the thalamus.

In contrast, brain activation differences between homographs and English control words in the GLD task were only found in 2 clusters in the LIPC (Fig. 3B and Table S2 in Supplementary Material). One of these clusters lies in a more anterior region (peaks in BA 45, 45/46, 47) of the LIPC, whereas the other lies in a more posterior and superior region of the LIPC (peaks in BA 44, 45). Importantly, no brain areas in the GLD task were activated in or near the medial and superior frontal gyrus (pre-SMA and ACC). Thus, this cortical brain

region in bilinguals was only activated in the ELD task (Fig. 3C). Brain activation differences between interlingual homographs and English control words in the English monolingual imaging data were, as expected, not found (Table S3 in Supplementary Material), because for English monolinguals interlingual homographs cannot be interpreted as Dutch words.

Differences between the activated brain regions of bilinguals in the ELD and GLD tasks were tested statistically by comparing the contrasts between homographs and English control words of both experiments. As expected, a significant cortical cluster with peak activations in the pre-SMA (BA 6) and the ACC (BA 8/32) survived this between-task comparison (Fig. 4A and Table S4 in Supplementary Material). In addition, this contrast revealed stronger activation in a cluster with peaks in the insula/putamen, and left caudate head, and in a cluster with peaks in the right cerebellum and posterior cingulate. The difference between the ELD and GLD tasks is that response-based language conflicts only appear in the ELD task. Thus, activation in the pre-SMA/ACC and in the left caudate must reflect response-based language conflict and its resolution.

In addition to this response-based language conflict, which is only present in the ELD task, the imaging data of the bilinguals also revealed for the ELD and GLD tasks that interlingual homographs showed greater activations than English control words in the LIPC, which suggests that this region is sensitive to stimulus-based language conflict. In the ELD task a large cluster was activated in the LIPC, whereas in the same region 2 smaller clusters were activated in the GLD task. The large cluster found in the ELD task overlapped with the 2 clusters found in the GLD task (center of mass: $-49, 28, 17$; cluster size: 2824 mm^3). To investigate whether the 3 clusters in the LIPC were in both tasks sensitive to a stimulus-based language conflict a series of ROI analyses were conducted to investigate whether the 3 regions showed larger responses for homographs than control words in both tasks.

First, a ROI was defined using the homographs versus control words contrast of the ELD task. This ROI is a cluster (2409

voxels) in the LIPC with its peak coordinates at $-42, 5, 27$. For the ROI analysis we used the imaging data of the GLD task and we looked at the contrast between homographs and controls. This analysis revealed stronger activations for homographs than for English control words ($t = 4.32, P < 0.001$). In addition, an analysis of variance with the percent signal change for homographs and controls in the ELD and GLD tasks revealed in this ROI ($-42, 5, 27$) a significant difference between homographs and controls in both tasks ($F_{1,22} = 64.24, P < 0.001$), no difference between the tasks ($F_{1,22} < 1$), and an interaction between task and condition ($F_{1,22} = 4.56, P < 0.05$), because the percentage signal change difference was larger in the ELD (0.09) than in the GLD (0.05) task.

Next, we took the 2 ROIs found in the homographs versus control contrast of the GLD task and tested the contrast between homographs and controls in these ROIs using the data of the ELD task. These analyses revealed also significantly stronger activations for homographs than control words in both ROIs (ROI with its peak at $-55, 22, 21$; 350 voxels: $t = 3.73, P < 0.01$, ROI with its peak at $-50, 41, 2$; 351 voxels: $t = 5.64, P < 0.0001$). Again, the analysis of variance using the percent signal change for homographs and controls in both tasks produced the same results. In both ROIs significant effects were found for Condition (homographs vs. controls) ($-55, 22, 21: F_{1,22} = 45.76, P < 0.001$; $-50, 41, 2: F_{1,22} = 49.89, P < 0.001$), no differences between the tasks (ELD vs. GLD) (both ROIs: $F_{1,22} < 1$), and no interactions between task and condition ($-55, 22, 21: F_{1,22} = 2.09, P = 0.16$; $-50, 41, 2: F_{1,22} < 1$). Thus, all 3 regions in the LIPC are sensitive to stimulus-based language conflicts that occurred in both tasks (see also Fig. 3C, D).

The imaging data of the bilinguals thus revealed that the pre-SMA/ACC is only activated in the ELD task, whereas the LIPC is activated in both tasks. We tested this finding explicitly in an analysis of variance using the percent signal change in the 2 regions for the homographs and controls in the ELD and GLD tasks. This analysis included the within-subject factors Region (pre-SMA/ACC cluster with its peak in $2, 20, 43$ vs. LIPC cluster with its peak in $-42, 5, 27$), Condition (homographs vs. controls) and the between-subject factor Task (ELD vs. GLD). This analysis showed, as expected, an interaction between Region, Condition, and Task ($F_{1,22} = 5.27, P < 0.05$). Condition and Task interacted in the pre-SMA/ACC ($F_{1,22} = 14.19, P < 0.01$) and in the LIPC ($F_{1,22} = 4.56, P < 0.05$). However, the nature of the interaction was different for these 2 regions. In the pre-SMA/ACC an effect of Condition appeared in the ELD task ($F_{1,11} = 32.78, P < 0.001$) but not in the GLD task ($F_{1,11} < 1$), whereas in the LIPC an effect of Condition was found for both tasks, although the effect was stronger in the ELD task (percent signal change difference = $0.09, F_{1,11} = 44.46, P < 0.001$) than in the GLD task (percent signal change difference = $0.05, F_{1,11} = 19.78, P < 0.01$).

Bilinguals versus Monolinguals

The brain regions that are sensitive to language conflict should also appear in a direct contrast between imaging data of the bilinguals and English monolinguals. We therefore compared the contrasts between homographs and control words of the bilinguals (ELD task) and English monolinguals, and found, as expected, activation in the LIPC, but no activation of the medial superior frontal gyrus. To increase the sensitivity of the analysis, we used a more liberal statistical height threshold

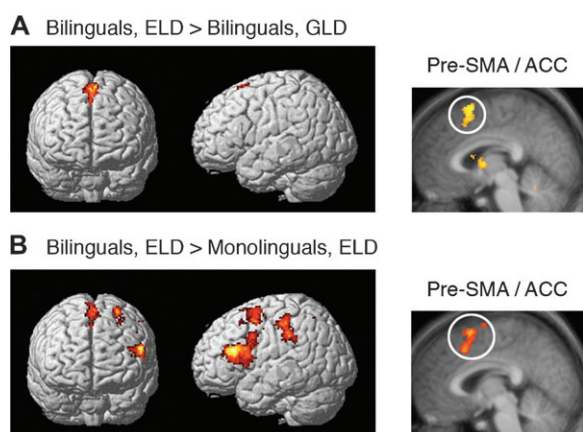


Figure 4. (A) Bilingual brain activations showing greater activations in the ELD task than the GLD task for the contrast between interlingual homographs and English control words (Table S4). Brain activation projected on an averaged anatomical sagittal slice. Cluster with peak coordinates in the pre-SMA ($-2, 16, 54$; Z score = 3.83 ; $-4, 14, 49$; Z score = 3.66) and the ACC ($2, 21, 41$; Z score = 3.61). (B) Brain activations showing greater activations for bilinguals than monolinguals in the ELD task for the contrast between interlingual homographs and English control words (Table S5). Cluster with peak coordinates in the pre-SMA ($-2, 15, 58$; Z score = 3.51 ; $-4, 16, 49$; Z score = 3.16) and the ACC ($-4, 21, 39$; Z score = 3.39).

($P < 0.01$), which resulted in greater activations for bilinguals than monolinguals in the LIPC (BA 44, 6), the pre-SMA (BA 6) and ACC (BA 32), and the left inferior parietal lobule (BA 40) (Fig. 4B and Table S5 in Supplementary Material). As expected, a cluster was now activated in the pre-SMA/ACC. Its peak activation was very similar to the peak activation of the contrast between ELD and GLD tasks of the bilinguals (2, 16, 54 vs. -2, 15, 58) (Fig. 4A,B). Furthermore, the peak activation in the LIPC (-40, 7, 27) is also very close to the peak activation in the cluster activated in the contrast between homographs and controls in the bilingual ELD data (-42, 5, 27). Interestingly, the contrast between bilinguals and monolinguals also activated a cluster in the parietal lobule (BA 40). The coordinates of the peak activity in this cluster (-32, -35, 39) are the same as in the contrast between homographs and controls in the ELD task for the bilinguals, which suggests that this region is also sensitive to language conflicts.

Words versus Pseudowords

Lexicality effects in the bilingual and monolingual data were investigated by contrasting brain responses to English words with those to pseudowords. For bilinguals in the ELD task, the contrast resulted in stronger activation for words bilaterally in the LIPC (BA 45, 47), the medial frontal gyrus (BA 8) and the ACC (BA 32), and the left lingual gyrus (BA 17). Furthermore, stronger responses were also found in the left caudate (Fig. 5A; Table S6 in Supplementary Material). Pseudowords in the ELD task were activated more strongly than words the SMA (BA 6) and the pre- and postcentral gyri (BA 3, 4, 6) (Table S6 in Supplementary Material). Lexicality effects in the GLD task were found in regions in LIPC (BA 45, 45/46, 47), the left parietal lobule (BA 40) and the left angular gyrus (BA 39), and the left middle temporal gyrus (BA 21, 21/37) (Fig. 5A; Table S7). For the monolingual participants, stronger activations for words than pseudowords were observed in the left anterior middle frontal gyrus (BA 21), the left supramarginal gyrus (BA 40), and the left superior temporal gyrus (BA 22). In the right hemisphere stronger activations were found in the IFG (BA 47) and the right middle and superior temporal gyri (BA 21, 22) (Fig. 5A; Table S8). No brain regions were more strongly activated for pseudowords than for words in the monolinguals

and in the bilinguals that participated in the GLD task (Tables S7, S8 in Supplementary Material).

Lexicality effects in the left posterior middle temporal gyrus have been observed before (Hagoort et al. 1999; Fiebach et al. 2002). At first sight, this region seems to be activated only in the GLD task. However, ROI analyses using the cluster activated in the GLD task (158 voxels; peak activations in -51, -28, -7; -57, -43, -5; and -55, -51, -3) revealed significantly stronger activations for words than pseudowords both for the bilinguals in the ELD task ($t = 2.78$, $P < 0.01$) and for the monolinguals ($t = 2.52$, $P < 0.05$). A direct comparison between bilingual and monolingual data revealed no lexicality differences in the left temporal gyrus. Only for bilinguals in the ELD task we found the left IFG (BA 45, 47) to be more strongly activated than in the monolinguals (Fig. 5B; Table S9 in Supplementary Material). Lexicality effects in monolinguals were found to be stronger in the right superior temporal gyrus compared with the bilinguals (Fig. 5C,D; Table S9 in Supplementary Material).

Discussion

Our findings indicate that stimulus-based and response-based language conflicts occur in the bilingual brain when bilinguals have to decide whether interlingual homographs are correct words in their second language. This result supports the view that words of both languages are automatically activated during reading, and that blocking of the first (nontarget) language is not possible. Interestingly, only a response-based language conflict has consequences at the behavioral level, resulting in much slower responses to Dutch-English homographs than to English control words. Such interlingual homograph interference effects in an ELD task have been reported before (von Studnitz and Green 2002). However, other studies involving Dutch-English bilinguals have reported null-effects for homographs relative to English control words in an ELD task (Dijkstra et al. 1998; de Groot et al. 2000) or facilitation effects (Dijkstra et al. 1999; Lemhöfer and Dijkstra 2004).

A comparison of the reaction times and error rates for homographs and control words in the ELD task of the present and other studies shows that the overall response times differ

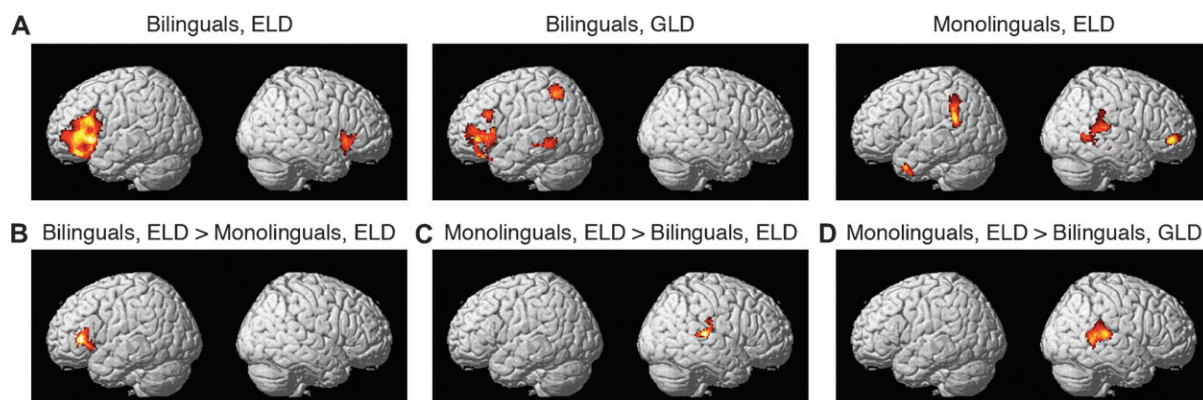


Figure 5. (A) Brain areas that show greater activation for words than for pseudowords in Dutch-English bilinguals performing an ELD task and a GLD task, and English monolinguals performing an ELD task (coordinates in Tables S6, S7, S8). (B) Brain activation differences between Dutch-English bilinguals in the ELD task and English monolinguals for the contrast between words and pseudowords (Table S9). (C) Brain activation differences between English monolinguals and Dutch-English bilinguals in the ELD task for the contrast between words and pseudowords (Table S9). (D) Brain activation differences between English monolinguals and Dutch-English bilinguals in the GLD task for the contrast between words and pseudowords (Table S9).

considerably (Table S10 in Supplementary Material). Bilinguals in the present study and in von Studnitz and Green's (2002) study responded much slower to homographs and control words than the bilinguals in the other studies. Overall error rates did not differ much between the studies. Slower responses time could have resulted in stronger activation of phonological and semantic representations of both languages, so that the behavioral interference effect became stronger. Crucially, only a model of bilingual language processing in which representations of both languages become activated, without the possibility to suppress a nontarget language, can explain the interlingual homograph effects that we observed.

This conclusion is different than that of an earlier neuroimaging study (Rodríguez-Fornells et al. 2002), which concluded that bilinguals are able to block a nontarget language. The event-related brain potentials (ERP) data of this study (Rodríguez-Fornells et al. 2002) revealed no frequency effect for nontarget Catalan words in a task that required Catalan-Spanish bilinguals to decide whether Spanish words start with a vowel or consonant. A subsequent fMRI study (Rodríguez-Fornells et al. 2002) that used the same task, showed no activation difference between nontarget Catalan words and pseudowords. Rodríguez-Fornells et al. (2002) interpreted their data in favor of the view that bilinguals can block a nontarget language. However, the error data of their ERP experiment showed differences between irrelevant (Catalan) low and high frequency words, which cannot be explained if the activation of Catalan words is completely blocked. In fact, in the contrast between the bilinguals and monolinguals, activation was observed in the LIPC for both Catalan words and pseudowords, which, according to the authors, reflects inhibition processes to reduce response conflict. Interestingly, activation was also observed in the ACC, which suggests that response conflict had occurred and that blocking of the nontarget language was not completely possible.

Whereas our fMRI study examined the influence of a nontarget language on the processing of interlingual homographs presented in isolation, Elston-Güttler et al. (2005) investigated the bilingual processing of such items in a nonnative sentence context. They asked German-English bilinguals to perform a semantic priming task, in which German-English homographs were presented as primes at the end of English sentences, followed by targets for lexical decision. They further manipulated the global language context of the items by playing a 20-min silent movie at the beginning of the experiment, accompanied by a narrative in either L1 (German) or L2 (English). Both behavioral and ERP data revealed semantic priming effects only in the first part of the experiment after the bilinguals had seen the German movie. Elston-Güttler et al. (2005) argued that bilinguals who saw the German movie had to zoom in to their L2 (English) by gradually raising decision criteria in order to diminish nontarget language effects of L1 (German) on the target language L2 (English). The results are compatible with the general view that sentence context can affect the activation of representations in the bilingual word identification system (Dijkstra and van Heuven 2002). More precisely, semantically constraining sentences, such as used by Elston-Güttler et al. (2005) are able to eliminate the effects of the nontarget language on item processing (Schwartz and Kroll 2006). At the same time, effects of the nontarget language on target word processing can emerge in low-constraint and neutral sentence context (Schwartz and Kroll 2006; Duyck

et al. 2007). Furthermore, the effects of global language context may be explained by changes in task settings or decision criteria (Dijkstra and van Heuven 2002; Elston-Güttler et al. 2005) without assuming a language blocking mechanism. To conclude, because the bilingual language system is fundamentally nonselective in nature, effects of a nontarget language can arise both for words presented in isolation and for words presented in a sentence context, as long as the sentence context is semantically neutral or of low constraint.

Response-Based Language Conflict

In our study, the pre-SMA and ACC regions were only activated in the ELD task, but not in the GLD task. These areas, therefore, show cross-language interference in the case of a response-based conflict. Furthermore, in the contrast between the ELD and GLD task a cluster with peaks in the pre-SMA and ACC was also activated. Finally, we contrasted the bilingual and monolingual imaging data in the ELD task, and again found activation in the pre-SMA and ACC. Thus, the pre-SMA and ACC are sensitive to conflict in relation to action (response conflict), but not to a stimulus conflict.

In addition to the activation in the ACC, we observed strong activation of the pre-SMA. The pre-SMA is more related to cognitive functioning than to motor related processes (Picard and Strick 2001). Single neuron recording in the pre-SMA suggests that activity in this region reflects decision processes during action selection (Hernández et al. 2002). In speech production experiments, Alario et al. (2006) found that the anterior portion of the pre-SMA is involved in word selection, whereas the posterior portion of the pre-SMA activation was associated with stimulus length and familiarity. Furthermore, the SMA-proper was found to be active during the motor execution of speech. The peaks in our pre-SMA activations lie mostly in the anterior portion of the pre-SMA, which suggests that in our study this area was involved in selection processes. Furthermore, a recent study of a patient with a rare lesion in the pre-SMA but with an intact SMA showed that the pre-SMA is critically involved in solving response conflict (Nachev et al. 2007). Thus, the activation in the pre-SMA in our study might reflect executive control processes that are recruited to solve response-based language conflict, whereas activation in the ACC signals the response conflict.

Subcortical activations were also observed for bilinguals, in the contrast between homographs and control words in the ELD task and in the direct comparison between the ELD and GLD tasks. In particular, activation was found consistently in the left caudate. The ACC and pre-SMA, as well as the basal ganglia, are part of a cortical-subcortical network (Alexander et al. 1986) that is involved in executive functioning. It has been suggested that the basal ganglia participate in selection and suppression of competing action plans (Mink 1996). The basal ganglia do not only play a role in the control of movement, but also in nonmotor operations, such as language processing (Copland 2003; Crosson et al. 2003). In addition, in bilinguals activation of subcortical structures has been observed during word translation (Price et al. 1999). Basal ganglia activity has also been linked to the selection of a target language in multilinguals (Abutalebi et al. 2000) and especially the left caudate has been associated with language control (Crinion et al. 2006; Abutalebi et al. 2007). Thus, our data are compatible with the view that a network involving the pre-SMA,

ACC, and the basal ganglia plays a critical role in solving response-based language conflicts.

Stimulus-Based Language Conflict

The GLD task involved stimulus-based conflicts only, in particular for the homographs in the bilingual participants. Stimulus-based language conflicts did not lead to behavioral differences between homographs and English control words. However, the fMRI data revealed that stronger activation was present in the LIPC. Interestingly, 2 separate clusters in the LIPC were activated. One of the clusters was located in a more anterior region of the LIPC, whereas the other cluster was located in a posterior/superior region of the LIPC. ROI analyses revealed that both the larger LIPC cluster found in the ELD task and the 2 smaller clusters found in the GLD task showed activation differences between homographs and controls. Thus, these regions are all sensitive to stimulus-based language conflict. The posterior/superior cluster of the LIPC (BA 44) has been associated with processes that select goal-relevant information over irrelevant competing information (Thompson-Schill et al. 1997, 1999; Badre et al. 2005), or with controlled phonological retrieval (Poldrack et al. 1999; Gold and Buckner, 2002). The anterior part of the LIPC has been associated with controlled semantic retrieval (Gold and Buckner 2002; Badre et al. 2005; Gold et al. 2006). Homographs activated the posterior LIPC both in the ELD and GLD tasks and in the contrast between monolinguals and bilinguals. The different theories of the LIPC function can all account for the stimulus-based language conflict observed in the present study. Therefore, we cannot dissociate between them.

Lexicality Effects

In both the ELD and GLD tasks, areas in the IFG were more strongly activated by words than pseudowords. Studies with monolinguals have found that the left IFG is more activated by pseudowords than words (e.g., Fiez et al. 1999; Fiebach et al. 2002). In our study, both English monolinguals and Dutch-English bilinguals activated the IFG (BA 47), although the activation in the monolinguals was in the right IFG. Words also activated the left middle temporal gyrus more strongly than pseudowords in both the bilinguals and monolinguals (as shown by ROI analyses). The left middle temporal gyrus has been associated with the storage of phonological word forms (Hagoort et al. 1999). We note that the peak activation in the middle temporal gyrus (-51, -28, -7) was near the peak (-50, -34, -12) reported in Hagoort et al. (1999). Hagoort et al. (1999) also found activations in the right superior temporal gyrus in the contrast between word and pseudowords. Their PET study was conducted with German native speakers, and their word versus pseudoword contrast included the data of silent and overt naming. In our monolingual data, we also observed activation in the right superior temporal gyrus. Furthermore, words activated only the right superior temporal gyrus (BA 22/42) more strongly in monolinguals than bilinguals. This planum temporale region has been associated with phonological processing (Démonet et al. 1992). This area has been found to be more active for bilinguals than for monolinguals when bilinguals use the sublexical route for lexical access (Rodríguez-Fornells et al. 2002). However, our present data show exactly the opposite pattern; that is, more activation for monolinguals than bilinguals, and activation in the right hemisphere instead of the left

hemisphere. A possible explanation is that for English monolinguals, phonological processing occurs more bilaterally, whereas it is more left lateralized for bilinguals. In the contrast between bilinguals and monolinguals, we observed that words more strongly activated the left IFG in bilinguals than in monolinguals, which is possibly related to a lesser proficiency in English, the second language of the bilinguals in the present study (Chee et al. 2001). Therefore, more mental effort was needed during semantic and phonological processing, which led to stronger activation of the left IFG.

Conclusion

In summary, the present data show that both languages of bilinguals are activated when they read the words from their second language. Importantly, bilinguals are not able to suppress the nontarget language to avoid interference. However, language interference at the behavioral level is only observed when nontarget language information leads to conflicts at the response level. At the neuronal level, stimulus-based language conflict was found in the LIPC due to the activation of phonologically and semantically ambiguous information. Response-based language conflict was found in the pre-SMA, the ACC, and the basal ganglia.

Supplementary Material

Supplementary material can be found at: <http://www.cercor.oxfordjournals.org/>

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Address correspondence to Walter J. B. van Heuven, PhD, School of Psychology, University of Nottingham, University Park, Nottingham NG7 2RD, United Kingdom. Email: wvh@psychology.nottingham.ac.uk

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