



Research Report

Activation of the language control network in bilingual visual word recognition

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ABSTRACT

Research into bilingual language production has identified a language control network that subserves control operations when bilinguals produce speech. Here we explore which brain areas are recruited for control purposes in bilingual language comprehension. In two experimental fMRI sessions, Dutch-English unbalanced bilinguals read words that differed in cross-linguistic form and meaning overlap across their two languages. The need for control operations was further manipulated by varying stimulus list composition across the two experimental sessions. We observed activation of the language control network in bilingual language comprehension as a function of both cross-linguistic form and meaning overlap and stimulus list composition. These findings suggest that the language control network is shared across bilingual language production and comprehension. We argue that activation of the language control network in language comprehension allows bilinguals to quickly and efficiently grasp the context-relevant meaning of words.

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1. Introduction

People who master more than one language inevitably need to exert control over the activation of their languages as a function of the specific context they are in. When speaking, for instance, bilinguals need to make sure to select words from memory that belong to the language in which they would like to express themselves, suppress interference from competing

words belonging to the non-target language, and continuously monitor their language output for potential cross-linguistic errors. The network of brain regions supporting such language control operations has been termed the language control network (Abutalebi & Green, 2008, 2016; Green & Abutalebi, 2013). It includes, among other regions, prefrontal areas such as left and right inferior frontal gyrus (IFG), dorsal anterior cingulate cortex (ACC) and the pre-supplementary motor area (pre-SMA), the inferior parietal lobules (IPL), and

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subcortical structures such as the left caudate and thalamus. Identification of the language control network was almost exclusively based on neuroimaging studies investigating bilingual language production (see [Abutalebi & Green, 2016](#)).

Studies investigating the neural infrastructure supporting control processes in bilingual language comprehension are scarce. Recent evidence from a study investigating bilingual language switching suggests that control operations during language comprehension are not supported by the full language control network, but rather by left ACC only ([Blanco-Elorrieta & Pykkänen, 2016](#)). This finding is surprising in the light of several behavioral studies that have concluded that bilingual language control mechanisms must be shared between comprehension and production ([Gambi & Hartsuiker, 2016](#); cf.; [Peeters, Runnqvist, Bertrand, & Grainger, 2014](#); [Van Heuven & Dijkstra, 2010](#)). Furthermore, control operations in language comprehension need not only take place when bilinguals encounter explicit language switches, as in [Blanco-Elorrieta and Pykkänen \(2016\)](#), but also when bilinguals perceive words with cross-linguistic form and/or meaning overlap, both in pure and mixed language environments (e.g., [Cop, Dirix, Van Assche, Drieghe, & Duyck, 2017](#); [Dijkstra, Miwa, Brummelhuis, Sappelli, & Baayen, 2010](#); [Dijkstra & Van Heuven, 2002](#); [Peeters, Dijkstra, & Grainger, 2013](#)). Using functional magnetic resonance imaging (fMRI), here we test whether also in such situations specifically left ACC is recruited as a function of language control demands during language comprehension. The alternative is that, just like in language production, the full language control network subserves language control in the comprehension domain.

To investigate the neural architecture underlying language control in bilingual language comprehension using neuroimaging, we opted for the use of a task and stimuli that have shown well-replicated and robust effects in the behavioral and event-related potential (ERP) literature. Specifically, we capitalized on the use of word stimuli with cross-linguistic overlap in form and/or meaning. Previous research has consistently shown that words that show overlap in both orthographic form and meaning across a bilingual's two languages (i.e., *cognates*) are processed more quickly than matched control words that occur in only one of a bilingual's languages. Such cognate facilitation has been reflected by faster reading times and reduced N400 amplitude in ERPs when bilinguals read cognate words (e.g., [Caramazza & Brones, 1979](#); [Cop et al., 2017](#); [Cristoffanini, Kirsner, & Milech, 1986](#); [Dijkstra et al., 2010](#); [Midgley, Holcomb, & Grainger, 2011](#); [Peeters et al., 2013](#)). These facilitation effects have been observed in task settings in which activation of the non-target reading of cognates does not lead to cross-linguistic conflict. Therefore, recruitment of control areas during bilingual processing of cognate stimuli is not expected for task settings that yield cognate facilitation.

However, relevant for the current study is that cognates have also elicited strong interference effects in specific contexts. By adding words from the bilingual's first language (L1) to the stimulus list in a lexical decision task performed in their second language (L2), we recently observed that words identical in orthographic form and similar in meaning across a bilingual's two languages (henceforth: identical cognates) yielded significantly slower response times than matched

control words that exist only in a bilingual's L2 ([Vanlangendonck, Peeters, Rueschemeyer, & Dijkstra, under review](#); see also [Brenders, van Hell, & Dijkstra, 2011](#)). Adding L1 words to the stimulus list in an L2 lexical decision task leads to the establishment of a link between L1 word forms and a no-response. Because for unbalanced bilinguals the subjective frequency of the L1 reading of cognates is higher than their subjective frequency of the L2 reading, it is likely that the L1 reading will be activated first. Hence the subsequent need to selectively inhibit the no-response in an L2 lexical decision task should elicit activation of control-related areas in bilingual language comprehension. Furthermore, we test whether such activation is higher for identical cognates (e.g., Dutch-English TENT) compared to non-identical cognates (e.g., English TOMATO with translation equivalent TOMAAT in Dutch), as non-identical cognates do not show this interference effect at a behavioral level ([Vanlangendonck et al., under review](#)). In sum, on the basis of previous behavioral work, we predicted the recruitment of control areas for cognates in mixed language settings, but not in pure L2 settings. This recruitment should be stronger for identical than for non-identical cognates.

Also for words that overlap in form across languages but differ in meaning (i.e., *interlingual homographs* such as the Dutch-English word form RAMP meaning 'disaster' in Dutch), slower response times have sometimes been observed compared to matched control words that exist in only one of a bilingual's languages ([Dijkstra, Van Jaarsveld, & Ten Brinke, 1998](#); [Hsieh, Jeong, Dos Santos Kawata, Sasaki, Lee, et al., 2017](#); [Van Heuven, Schriefers, Dijkstra, & Hagoort, 2008](#); [Vanlangendonck et al., under review](#); [Von Studnitz & Green, 2002](#)). The fact that the same orthographic word form is linked to different meaning representations in a bilingual's two languages requires them to suppress activation of the link between the perceived orthographic representation and its non-target meaning in order to successfully grasp the intended, context-relevant meaning. Previous studies suggest involvement of different parts of the language control network in bilinguals' comprehension of interlingual homographs ([Grant, Fang, & Li, 2015](#); [Hsieh et al., 2017](#); [Van Heuven et al., 2008](#)). Here we seek to find further evidence for this involvement and test whether it is modulated by the composition of the stimulus list as a proxy for the broader language context.

Exploiting the fact that both cross-linguistic form overlap and stimulus list composition thus require bilinguals to implement control processes, the current study presented unbalanced Dutch-English bilinguals with cognates, interlingual homographs, matched L2 control words, and pseudowords in the MRI scanner in two experiments that differed in stimulus list composition. First, participants performed a regular L2 lexical decision task including these different types of stimulus. We will refer to this block as the *L2 task setting*. Second, they performed another L2 lexical decision task in which half of the pseudowords were replaced with words from their L1 Dutch. This latter setting will be referred to as the *mixed language setting*. As such, the need for control operations to take place should be relatively stable across the two task settings with regards to interlingual homographs, but vary for cognate stimuli.

In general, we thus reasoned that control operations were necessary to resolve cross-linguistic interference for interlingual homographs in both settings and for cognates in the mixed language setting only. On the basis of previous behavioral findings (see Table 3), this latter involvement was predicted to be stronger for identical cognates than for non-identical cognates (cf. Dijkstra et al., 2010; Vanlangendonck et al., under review). Three theoretical positions were contrasted. First, if indeed bilinguals specifically recruit only left ACC for inhibitory language control purposes in language comprehension (Blanco-Elorrieta & Pykkänen, 2016), we should see activation of this area for interlingual homographs in both task settings and for identical cognates in the mixed language setting. Second, however, if language control mechanisms are shared between comprehension and production (e.g., Gambi & Hartsuiker, 2016), different or additional nodes of the larger language control network might be involved. Both for interlingual homographs and for cognates in the mixed language setting right IFG might be recruited, as a region of the language control network that has been particularly implicated in response inhibition (Abutalebi & Green, 2016; Aron, Fletcher, Bullmore, Sahakian, & Robbins, 2003; Chikazoe, Konishi, Asari, Jimura, & Miyashita, 2007; Luk, Anderson, Craik, Grady, & Bialystok, 2010). Control over interference of irrelevant information and response selection, on the other hand, might be reflected by activation of the left IFG (Abutalebi & Green, 2016; Aron, Behrens, Smith, Frank, & Poldrack, 2007; Branzi, Della Rosa, Canini, Costa, & Abutalebi, 2016). Response inhibition and selection might furthermore be supported by activation of subcortical structures such as the thalamus, implicated in the selection of relevant semantic and lexical representations (Abutalebi & Green, 2016), and the left caudate, implicated in language control in suppressing task-irrelevant words (Ali, Green, Kherif, Devlin, & Price, 2010; see also; Crinion, Turner, Grogan, Hanakawa, Noppeney, et al., 2006; Lehtonen, Laine, Niemi, Thomson, Vorobyev, & Hughdal, 2005) and language-based conflict in general (Van Heuven et al., 2008). A final possibility is that the language control network will not show any enhanced activation during bilingual language comprehension (see Blanco-Elorrieta & Pykkänen, 2017).

2. Method

2.1. Participants

Nineteen Dutch-English unbalanced bilinguals participated in the experiment. Data from one participant was excluded from the analyses due to chance-level performance on the pseudoword condition. The remaining participants were nine men and nine women with a mean age of 23.9 years (SD 2.3). All participants were right-handed and had normal or corrected-to-normal vision. They gave written informed consent before the start of the experiment and received 20 euros or course credit for participating. None of the participants reported any neurological impairment. The number of participants was established prior to the start of data collection, and considered to be at the higher end of fMRI studies into bilingual language

processing (e.g., Lehtonen et al., 2005; Luk et al., 2010) at the time of data collection.

Participants' language background and English proficiency were assessed by means of a self-rating questionnaire. All participants were native speakers of Dutch who on average came into contact with English at the age of 10.3 (SD 2.7). They rated their English reading experience as 6.1 (SD 1.0) on a scale from 1 (*very little experience*) to 7 (*very much experience*). We know from other recent experiments (Peeters & Dijkstra, 2017), which used several samples from the same bilingual population, that these participants score an average of 75/100 on the English version of the LexTale proficiency test (Lemhöfer & Broersma, 2012). In line with the current self-reports, this population is thus best qualified as unbalanced bilinguals with a relatively high L2 English proficiency. This is confirmed by the high L2 task accuracy in the behavioural equivalent of the current study (Vanlangendonck et al., under review) that used another participant sample from the same population (see below).

2.2. Materials

The total stimulus set consisted of 300 English words, 30 Dutch words, and 90 pseudowords. All words were nouns or adjectives consisting of one or two syllables and four to six letters. The English words comprised 60 English-Dutch interlingual homographs, 60 English-Dutch identical cognates, 120 English-Dutch non-identical cognates, and 60 English control words. Levenshtein distance (LD) was used to quantify the degree of cross-linguistic orthographic overlap between the non-identical cognates and their Dutch translation equivalents. Levenshtein distance refers to the number of characters that have to be replaced, added, or deleted to transform one string of characters into another string. Half of the non-identical cognates ($n = 60$) had a Levenshtein distance of 1 (LD1). The other half of the non-identical cognates ($n = 60$) had a Levenshtein distance of 2 (LD2). The interlingual homographs had a Levenshtein distance of at least three to their Dutch translation equivalents.

The English words were matched item-by-item across conditions based on their length and English word form frequency, as available from the SUBTLEX-US database (Brysbaert & New, 2009). The pseudowords were created by replacing one letter in existing English words. The Dutch words were low-frequency words with a Dutch word form frequency between 2 and 10 occurrences per million, as available from the SUBTLEX-NL database (Keuleers, Brysbaert, & New, 2010). The Dutch words did not include any interlingual homographs or cognates. The pseudowords and Dutch words were matched item-by-item with the English words for length. Table 1 contains examples of the matched stimuli used in the two tasks.

The 300 English words were allocated to two lists, which were matched for English word form frequency and word length (Table 2). Half of the participants were presented with the first list in the L2 task setting; the other half saw it in the mixed language setting. In the L2 task setting, 60 pseudowords were included in the experiment. In the mixed language setting, 30 pseudowords and 30 Dutch words were included in the experiment in addition to the English words. As a result, the stimulus lists for each lexical decision task consisted of

Table 1 – Examples of stimuli used in the two lexical decision tasks. For interlingual homographs, the Dutch meaning of the word is provided in English in parentheses. For cognates, Dutch translation equivalents are provided within parentheses. For Dutch words, the meanings are provided in English.

Interlingual homographs	Identical cognates	NI cognates LD1	NI cognates LD2	English controls	Pseudowords	Dutch words
brave (righteous)	alarm (alarm)	ocean (ocean)	wheel (wiel)	shape (vorm)	jorce	pruik (wig)
ramp (disaster)	duel (duel)	calf (kalf)	cork (kurk)	cone (kegel)	mift	bijl (axe)
vast (solid)	echo (echo)	crab (krab)	bean (boon)	leap (sprong)	tond	geel (yellow)
mode (fashion)	yoga (yoga)	mint (munt)	text (tekst)	leaf (blad)	mipe	boef (crook)

Table 2 – Average English word form frequency per million and number of letters per condition. Interlingual homographs, cognates, and English control words were matched item-by-item for length and English word form frequency. Dutch words (occurring only in the second task) and pseudowords were matched with the other items for length.

	FF	Id. cognates	NI cognates LD1	NI cognates LD2	English controls	Pseudowords	Dutch words
English WF frequency	53.78	52.17	51.61	47.44	51.67		
Number of letters	4.43	4.43	4.47	4.50	4.43	4.42	4.47

Table 3 – Mean reaction times with standard deviations and proportion correct for interlingual homographs, cognates, and control words in the L2 task setting and the mixed language setting, taken from Vanlangendonck et al. (under review).

Condition	L2 Task Setting	Mixed Language Setting
Interlingual Homograph	641 (188, .94)	644 (199, .92)
Identical Cognate	609 (178, .97)	628 (188, .96)
Non-identical Cognate LD1	628 (168, .96)	605 (157, .97)
Non-identical Cognate LD2	627 (165, .96)	604 (162, .95)
English Control	634 (171, .96)	608 (163, .96)

210 stimuli, 150 of which were existing English words. Each stimulus was presented once to each participant over the course of the two task settings. The stimuli were pseudorandomised to create a different list for each participant. Each pseudorandomised list contained no more than four English words in a row and stimuli were never succeeded by an item from the same condition. In addition to the stimuli, 30 null events were included in the design for each task setting.

We recently carried out a behavioural lexical decision task study using the same materials and participants from the same participant pool of unbalanced bilinguals (Vanlangendonck et al., under review). The procedures used in these two studies were kept as similar as possible. The reaction time results from the behavioural study are provided in Table 3. In the current study's mixed language setting, participants correctly identified the non-cognate Dutch words as non-English words with an accuracy of 96.9%, similar to the 94.4% correct score for this condition in the behavioural study.

2.3. Procedure

Participants received written instructions before the start of the experiment. They were instructed to press a button when a presented letter string was not an existing English word. All

responses were given with the right index finger. Because reaction time data on these stimuli in different participants from the same participant pool were recorded in a separate behavioural study (see Table 3) in which participants performed traditional lexical decision tasks (i.e., a 2-button yes/no setup), in the two fMRI sessions responses were only required for non-English words to avoid motor artifacts on critical trials. The inclusion of null events in both studies ensured that on all trials participants made a go/no-go decision, allowing for a generalization of the behavioural findings to the MRI environment. Participants were informed of the presence of words existing in both Dutch and English in the stimulus list. The same instructions were used for both task settings.

Participants completed a series of 14 practice trials outside the scanner before the start of each task. The practice trials contained the same proportion of stimuli from each condition as the actual experiment. The two tasks were run using Presentation software. Stimuli were presented in white 20-point Arial font on a black screen. Each trial started with a variable jitter of 0, 500, 1000 or 1500 msec to improve the temporal resolution of the fMRI signal. Then a fixation cross was presented in the centre of the screen for 400 msec. The fixation cross was immediately followed by the presentation of the stimulus in the centre of the screen. The stimulus remained visible until the participant pressed the button or until the maximum response time of 2000 msec was reached. A blank screen then appeared for a variable period of time so that each trial lasted 8 sec. In total, participants spent approximately 45 min in the scanner per session.

Each participant completed both tasks. The two tasks were scheduled on different days. Order of tasks was kept constant (L2 task setting before mixed language setting) in line with previous behavioural work (Vanlangendonck et al., under review) and to allow for fair comparison of the L2 task setting to the majority of previous L2 studies on the processing of cognates and interlingual homographs, in which commonly no pure L1 words are included as pseudowords. After the first experiment, participants filled out a written questionnaire assessing their language background and English proficiency.

Apart from this, experimental procedures were identical during both sessions.

2.4. Image acquisition and analysis

fMRI data were acquired on a Siemens 3T MAGNETOM Trio MRI scanner using a single-shot FID-EPI sequence (TR = 2000 msec, TE = 30 msec, flip angle = 90°, 31 axial slices in ascending order, voxel size = 3.5 × 3.5 × 3 mm). Structural images were acquired using a MPRAGE sequence (TR = 2300 msec, TE = 3.03 msec, 192 sagittal slices, voxel size = 1 × 1 × 1 mm).

The functional scans were preprocessed and analysed using SPM8 (Statistical Parametric Mapping, www.fil.ion.ucl.ac.uk/spm). The first three volumes per session were discarded to allow for T1 equilibration effects. All volumes were realigned to correct for small head movements and slice timing correction was applied by temporally realigning the time course for each voxel to the 16th slice. The mean functional images per participant were coregistered to their anatomical T1 images and structural images were then segmented into grey and white matter. Functional images were spatially normalised to the MNI template provided by SPM, resampled to 2 × 2 × 2 mm voxels and smoothed using an 8-mm FWHM Gaussian filter kernel.

The resulting fMRI time series were analysed as an event-related design using the general linear model. A design matrix was constructed for each participant and session that contained 6 regressors modelling the presentation of each of the conditions (interlingual homographs, identical cognates, non-identical cognates LD1, non-identical cognates LD2, English control words, and pseudowords/Dutch words) and a regressor modelling the incorrect responses. All regressors were convolved with the haemodynamic response function and its temporal derivative. In addition, 6 movement parameters from the realignment algorithm were included in the model as effects of no interest.

Contrast images of the main effects of the conditions of interest (interlingual homographs, identical cognates, non-identical cognates LD1, non-identical cognates LD2, and English control words) were generated per session and participant. In addition, contrast images directly comparing the experimental conditions to the English control word condition were generated. These first-level contrast images were then entered into a second-level random effects analysis per contrast. A one-sample t-test was performed to look whether the differences between conditions at the group level for each task were significantly different from zero. Below, we report only brain regions showing significantly more activation for the conditions of interest in comparison to the English control words. In addition, we created contrast images to test the Task × Condition interaction between interlingual homographs and English control words and between identical cognates and English control words in both settings. A one-sample t-test was then performed to test whether the interaction effects at the group level were significantly different from zero. A Monte Carlo simulation (Slotnick, Moo, Segal, & Hart, 2003) with 1000 iterations was run to correct for multiple comparisons at $p < .05$

with an individual voxel type I error of $p \leq .001$. Based on this procedure, the cluster extent threshold was set at 46 resampled voxels (368 mm³). Only clusters exceeding this threshold are reported. All reported coordinates are Montreal Neurological Institute (MNI) coordinates.

3. Results

Table 4 shows all significant clusters observed in the L2 task setting. Comparisons between the conditions of interest and the English control words in this task yielded only significant differences for the contrast between interlingual homographs and English control words (Fig. 1). We found a large cluster covering the left inferior frontal gyrus, and a left superior medial frontal cluster extending to the pre-SMA. Although a cognate facilitation effect was observed in the behavioural data comparing identical cognates to English control words in the L2 task setting (Vanlangendonck et al., under review), no significant clusters were found in the reverse contrast comparing these two conditions (English control words > identical cognates).

All significant activations obtained in the mixed language setting are listed in Table 5. The contrast between the interlingual homographs and the English control words yielded a large cluster in the left inferior frontal gyrus. In addition, a significant cluster covering the pre-SMA and superior medial frontal cortex was found (Fig. 2). Finally, unlike the L2 task setting, this contrast yielded a cluster in the right inferior frontal gyrus, extending into the insula.

Eleven clusters were found when comparing the activation patterns of the identical cognates and the English control words in the mixed language setting (Fig. 3). Identical cognates activated parts of the inferior frontal gyri bilaterally, the medial surface of the frontal lobe, covering the left and right pre-SMA, and subcortical regions including the left and right caudate and the thalamus (see Table 5).

All significant Task × Condition interactions are listed in Table 6. No interaction effect was found when comparing the mixed language setting to the L2 task setting for the contrast between interlingual homographs and English control words. A significant Task × Condition interaction effect was found when comparing the mixed language setting to the L2 task setting for the contrast between identical cognates and English control words in the right inferior frontal gyrus.

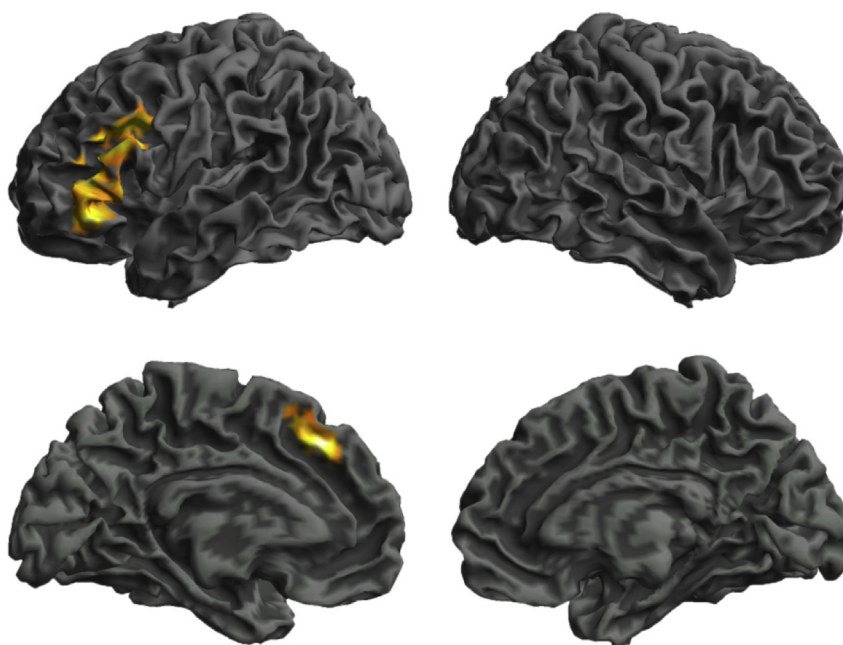
4. Discussion

The current study investigated the neural underpinnings of control in bilingual language comprehension. In two experimental fMRI sessions, the same group of unbalanced Dutch-English bilinguals read words that differed in their degree of cross-linguistic form and meaning overlap. Between the two sessions, stimulus list composition was manipulated to vary the need for specific control operations. We observed enhanced activation in regions that are part of the language control network, which has previously been identified almost

Table 4 – Brain regions showing significantly more activity for the experimental conditions than for the English control word condition in the L2 task setting ($p < .001$, $k > 46$ voxels).

Contrast	k (extent)	Zmax	MNI coordinates			Region/Peak
Interlingual homographs > English control words	2025	5.06	-54	38	6	left inferior frontal gyrus
		4.87	-52	36	16	left inferior frontal gyrus
	339	4.47	-50	20	24	left inferior frontal gyrus
		4.64	-6	30	40	left superior medial frontal gyrus
		3.72	-6	18	50	left supplementary motor area
Identical cognates > English control words	n.s.	–	–	–	–	
Non-identical cognates LD1 > English control words	n.s.	–	–	–	–	
Non-identical cognates LD2 > English control words	n.s.	–	–	–	–	

Abbreviations: n.s., no suprathreshold clusters.

**Fig. 1 – Brain regions showing significantly more activation for interlingual homographs than for English control words in the L2 task setting ($p < .001$, $k > 46$ voxels).**

exclusively on the basis of studies into bilingual language production, as a function of both cross-linguistic form and meaning overlap and stimulus list composition.

Behavioural and ERP studies have consistently shown that bilinguals cannot “switch off” one of their languages when reading (e.g., Cop et al., 2017; Dijkstra & Van Heuven, 2002; Peeters et al., 2013). When encountering the orthographic word form RAMP, for instance, Dutch-English bilinguals will activate both the Dutch meaning (‘disaster’) and the English meaning (‘a sloping surface’) of this interlingual homograph (Dijkstra et al., 1998; Van Heuven et al., 2008). This inevitably leads to a need for control operations to take place for a bilingual reader to quickly and efficiently settle on the context-dependent correct interpretation of a perceived word form. Our results suggest that bilinguals recruit left prefrontal areas, in particular left IFG and left superior medial frontal gyrus extending into pre-SMA, when encountering an interlingual homograph (see Figs. 1–2 and Tables 4 and 5). These

findings are in line with previous neuroimaging studies that used interlingual homographs as stimulus materials (Hsieh et al., 2017; Van Heuven et al., 2008). It has been suggested that the involvement of inferior frontal cortex in processing interlingual homographs is particularly critical in learners of a second language with beginning to intermediate L2 proficiency (Grant et al., 2015; see also Raboyeau, Marcotte, Adrover-Roig, & Ansaldo, 2010). The present study, however, shows robust activation of IFG also in unbalanced bilinguals with a relatively high L2 proficiency.

The involvement of left prefrontal cortex in the processing of interlingual homographs was independent of our stimulus list composition manipulation. This makes sense, because in both task settings the English and the Dutch reading of interlingual homographs were linked to different response alternatives (‘yes’ and ‘no’ respectively), thereby inducing a similar conflict in both cases. Nevertheless, when Dutch (L1) words were added to the stimulus list in the mixed language

Table 5 – Brain regions showing significantly more activity for the experimental conditions than for the English control word condition in the mixed language setting ($p < .001$, $k > 46$ voxels).

Contrast	k (extent)	Zmax	MNI coordinates			Region/Peak
Interlingual homographs > English control words						
	2990	5.20	–50	20	18	left inferior frontal gyrus
		4.67	–54	34	–2	left inferior frontal gyrus
		4.60	–36	28	–2	left inferior frontal gyrus
	1172	5.69	46	32	–2	right inferior frontal gyrus
		4.54	34	26	–2	right insula lobe
		3.90	54	30	28	right inferior frontal gyrus
	608	4.09	–8	26	40	left superior medial frontal gyrus
		3.88	8	22	44	right superior medial frontal gyrus
		3.80	–6	16	52	left supplementary motor area
Identical cognates > English control words						
	1207	4.98	6	24	42	right superior medial frontal gyrus
		4.21	12	16	52	right supplementary motor area
		3.65	–4	4	62	left supplementary motor area
	849	5.38	32	30	–6	right inferior frontal gyrus
		4.58	40	38	–6	right inferior frontal gyrus
		4.56	26	22	–2	right putamen
	766	4.13	–50	20	10	left inferior frontal gyrus
		3.85	–42	12	30	left precentral gyrus
		3.64	–34	10	30	left inferior frontal gyrus
	517	4.60	52	30	22	right inferior frontal gyrus
		3.81	38	12	30	right inferior frontal gyrus
		3.66	58	18	12	right inferior frontal gyrus
	485	4.26	–14	0	18	left caudate nucleus
		4.08	–10	–12	2	left thalamus
		3.68	–14	6	10	left caudate nucleus
	346	4.10	14	–10	–6	right cerebral white matter
		3.92	18	–12	6	right thalamus
		3.56	10	10	6	right caudate nucleus
	161	4.07	–54	–52	–8	left inferior temporal gyrus
		3.17	–46	–56	–18	left fusiform gyrus
	137	3.82	24	–94	0	right calcarine gyrus
		3.36	28	–84	2	sub-gyral white matter
	117	3.70	–30	–70	52	left superior parietal lobule
		3.39	–32	–60	40	left inferior parietal lobule
	117	4.09	–48	–40	38	left inferior parietal lobule
		3.29	–42	–42	32	supramarginal gyrus
	92	4.58	48	–38	–10	right cerebral white matter
		3.26	58	–38	–6	right middle temporal gyrus
		3.26	44	–42	–2	right cerebral white matter
Non-identical cognates LD1 > English control words						
	61	3.84	44	16	24	right inferior frontal gyrus
	55	3.46	–8	–12	6	left thalamus
		3.29	–10	–16	–2	left thalamus
Non-identical cognates LD2 > English control words						
	172	5.05	44	–44	–4	right cerebral white matter
		4.51	40	–36	–8	right cerebral white matter
		3.37	38	–44	6	right cerebral white matter

setting, additional activation elicited by interlingual homographs was found in right IFG (see Fig. 2 and Table 5). This finding is in line with right IFG's putative role in response inhibition (e.g., Abutalebi & Green, 2016; Aron et al., 2007). Adding L1 words to the stimulus list in an L2 lexical decision task leads to the establishment of a link between L1 word forms and a no-response (Dijkstra, 2007). Arguably the link between the L1 Dutch reading of interlingual homographs and a no-response thereby became more prevalent in the mixed language setting. The subsequent need to inhibit this no-response explains the additional activation in right IFG in the mixed language setting. In other words, interlingual

homographs did not require a no-response in the tasks because they are correct English words. As they also have a Dutch reading, and fully Dutch words required a no-response in the mixed language setting, nevertheless in that setting there was the stronger need to inhibit the propensity to give a no-response upon seeing an interlingual homograph.

Note that we do not claim that the involvement of right IFG, while part of the language control network, is limited to situations of language control. Rather, its observed recruitment in the current study suggests response inhibition as a consequence of activation of language membership information when bilinguals encounter words with cross-linguistic overlap

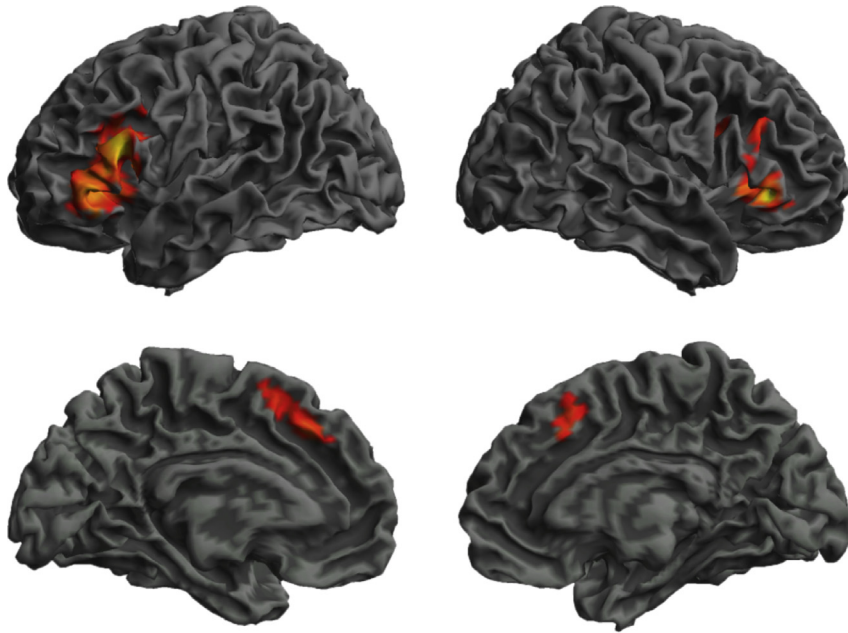


Fig. 2 – Brain regions showing significantly more activation for interlingual homographs than for English control words in the mixed language setting ($p < .001$, $k > 46$ voxels).

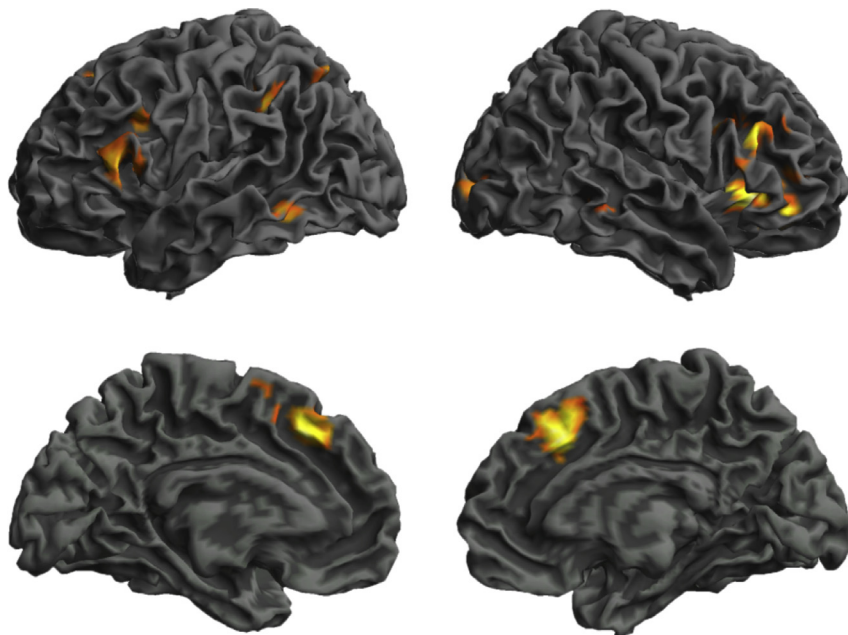


Fig. 3 – Brain regions showing significantly more activation for identical cognates than for English control words in the mixed language setting ($p < .001$, $k > 46$ voxels).

in form. Indeed, domain-general inhibition areas such as right IFG have commonly been implicated in multilingual language processing (De Bruin, Roelofs, Dijkstra, & FitzPatrick, 2014).

The link between right IFG recruitment and resolving response competition was further confirmed when looking at the results across the two task settings for the processing of identical cognates. No activation differences were observed when contrasting cognate stimuli with English control words in the L2 task setting. One would indeed not expect

recruitment of the language control network for cognates in such a setting, as behavioural measures typically show cognate facilitation in L2 environments for unbalanced bilinguals (e.g., Caramazza & Brones, 1979; Cop et al., 2017; Cristoffanini et al., 1986; Dijkstra et al., 2010; Peeters et al., 2013). In the mixed language setting, in contrast, cognates elicited activation of areas implicated in the language control network, such as bilateral inferior frontal gyri and subcortical areas (e.g., caudate nucleus and thalamus). The strongest

Table 6 – Brain regions showing significant interaction effects when comparing the L2 task setting to the mixed language setting for the contrast between interlingual homographs and English control words and for the contrast between identical cognates and English control words ($p < .001$, $k > 46$ voxels).

Contrast	k (extent)	Zmax	MNI coordinates			Region/Peak
Interlingual homographs > English control words	n.s.	–	–	–	–	–
Identical cognates > English control words	108	3.90	40	34	–2	right inferior frontal gyrus
		3.34	34	32	–8	right inferior frontal gyrus

Abbreviations: n.s., no suprathreshold clusters.

effect of stimulus list composition, as evident from the interaction test, was observed in right IFG. Again, the establishment of a link between the L1 reading of cognates and a no-response, which subsequently required to be inhibited for successful task performance, explains this enhanced right IFG activation. This finding is in line with behavioural data showing slower response times for identical cognates compared to control words in exactly this task setting with another sample from the same bilingual population (Table 3; Vanlangendonck et al., under review). As an interesting avenue for future research, follow-up studies could look into a potential effect of recency of L1 lexical activation on identical cognate processing in L2, as specific manipulations to this end may provide interesting information about the potential decay of L1 activation and its influence on cognate processing in L2.

Activation of the language control network in the mixed language setting was much more limited for non-identical cognates (Table 5). Unlike identical cognates, these words possess two orthographic representations (e.g., OCEAN in English, OCEAAN in Dutch) across a bilingual's two languages, linked to a shared semantic representation. At a behavioural level, they show smaller cognate facilitation effects in L2 task settings and no cognate inhibition effect in mixed language settings compared to identical cognates (Dijkstra et al., 2010; Van Assche, Drieghe, Duyck, Welvaert, & Hartsuiker, 2011; Vanlangendonck et al., under review). The L2 English cognate word form that participants encountered arguably activates an orthographic representation that is separate from the concurrently activated L1 equivalent. Because competing response options are linked to separate representations in this case, no behavioural processing costs are observed, and fewer additional control operations are required to resolve response competition. In this way, non-identical cognates indeed clearly differ from identical cognates and interlingual homographs in terms of cross-linguistic form identity at the orthographic level.

Prima facie, our results are not in line with a recent MEG study that argued for different language control networks in language comprehension and language production on the basis of results from language switching paradigms (Blanco-Elorrieta & Pylkkänen, 2016; see also; Blanco-Elorrieta & Pylkkänen, 2017). Specifically, left ACC was put forward as the locus of bilingual language control in language comprehension, whereas language control processes in production would recruit dorsolateral prefrontal cortex. We observed activation of both the ACC/pre-SMA complex and bilateral prefrontal areas in situations that required control in bilingual

language comprehension. These areas are part of the language control network that we know from the bilingual language production literature (Abutalebi & Green, 2016). We therefore parsimoniously suggest that the network supporting bilingual language control is shared across modalities (production and comprehension), but that different nodes in the network may be taxed differentially as a function of task demands (e.g., language switching vs lexical decision) and modality (e.g., language switching in production vs language switching in comprehension). This proposal is in line with recent behavioural work that indicates that language control mechanisms must be shared between comprehension and production (Gambi & Hartsuiker, 2016). It is also in line with the adaptive control hypothesis that proposes that cognitive control processes are adapted to the needs of the specific interactional context (Green & Abutalebi, 2013). Furthermore, it is in accordance with the principle that the functional contribution of an individual node in a network of brain areas needs to be characterized by taking into account the network that it is part of as a whole (Mesulam, 1998).

To sum up, the present study observed recruitment of the language control network in bilingual language comprehension. Future studies may go beyond this finding by focusing on the interaction between the language control network and other networks important for successful language comprehension, such as the perisylvian language network and the theory of mind network (see Hagoort, 2017), in ecologically valid experimental paradigms (Blanco-Elorrieta & Pylkkänen, 2017; Peeters & Dijkstra, 2017) investigating bilingual language processing.

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Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.cortex.2018.10.012>.

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