



## Neural circuitry of the bilingual mental lexicon: Effect of age of second language acquisition

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### ABSTRACT

Numerous studies have proposed that changes of the human language faculty caused by neural maturation can explain the substantial differences in ultimate attainment of grammatical competences between first language (L1) acquirers and second language (L2) learners. However, little evidence on the effect of neural maturation on the attainment of lexical knowledge in L2 is available. The present functional magnetic resonance study addresses this question via a cross-linguistic neural adaptation paradigm. Age of acquisition (AoA) of L2 was systematically manipulated. Concrete nouns were repeated across language (e.g., French–German, valise<sup>suitcase</sup>–Koffer<sup>suitcase</sup>). Whereas early bilinguals (AoA of L2 < 3 years) showed larger repetition enhancement (RE) effects in the left superior temporal gyrus, the bilateral superior frontal gyrus and the right posterior insula, late bilinguals (AoA of L2 > 10 years) showed larger RE effects in the middle portion of the left insula and in the right middle frontal gyrus (MFG). We suggest that, as for grammatical knowledge, the attainment of lexical knowledge in L2 is affected by neural maturation. The present findings lend support to neurocognitive models of bilingual word recognition postulating that, for both early and late bilinguals, the two languages are interconnected at the conceptual level.

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### 1. Introduction

Second-language (L2) acquisition necessitates the acquisition of various types of grammatical (e.g., phonological, morphological, syntactic) and lexical knowledge. Whereas the development of mental representations of such knowledge and the acquisition of language processing skills seem to be mastered easily in child first language (L1) acquisition, adult learners of L2 achieve native-like knowledge and proficiency only rarely, if at all. The Critical Period Hypothesis (CPH) first proposed by Penfield and Roberts (1959) assumes the existence of a *critical period* for acquisition of segmental phonology, inflectional morphology and syntax. Changes of the human language faculty caused by neural maturation can be argued to explain substantial differences in the course of acquisition and in ultimate attainment of grammatical competences between L1 and L2 learners (see also Chomsky, 1975; Lenneberg, 1967). Concerning the acquisition of lexical knowledge, the CPH did not make any assumptions. On the contrary, a more recent theory of neuro-linguistic development (Locke, 1997) assumes an *optimum biologi-*

*cal moment* for the appropriate organisation and use of the mental lexicon. According to the Locke's theory, pregrammatical children for which the phase of lexical material storage (5–20 months) is affected by external factors including the availability of appropriate stimulation have difficulties to perform analytical operations such as analyse and detection of recurrent structural patterns (20–37 months).

In the present study, we addressed the question of whether the neuroanatomical organisation of the bilingual mental lexicon may also be affected by neural maturation. In psycholinguistic models of the bilingual mental lexicon, a central question is to know at what level of representation, i.e., orthographic/phonological, lexical, and/or conceptual level, a bilingual's two languages are interconnected? One class of models describes the architecture of the bilingual's memory at two different levels of representation, which are hierarchically related (Potter, 1979; Snodgrass, 1984). For example, the Revised Hierarchical (RH) model (Kroll & Stewart, 1994) postulates that words are stored in separate lexical memory systems, whereas concepts are stored in an abstract memory system common to both languages. At the early stage of L2 development, individuals rely more on L2–L1 lexical level translation; with further L2 development (i.e., highly proficient late bilinguals), stronger links are established between the L2 lexical codes and their appropriate conceptual representations. Another class of

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models, which are interactive in nature, posits three levels of representations (e.g., the Bilingual Interactive Activation (*BIA+*) model, Dijkstra and van Heuven (2002); the interactive model proposed by Silverberg and Samuel (2004)). Words are stored at the lexical level, with their meanings represented “above” them at the conceptual level (i.e., lemma), and their constituents (letters for printed words and phonemes for spoken ones) represented “below” them at an orthographic/phonological level (i.e., lexeme). The hierarchical and the interactive models differ with respect to the hypothesis they make concerning the nature of the semantic-conceptual representations for L1 and L2 words, depending on AoA of the L2. Whereas the *BIA+* and the RH models postulate that L1 and L2 share common conceptual representations, irrespective of AoA of L2, the interactive model of Silverberg and Samuel (2004) proposes that only early bilingual exhibit a common system of representations at the conceptual level.

In the present study, we focused on the interconnection of the bilingual’s two languages at the conceptual level. In particular, we investigated whether the semantic-conceptual representation of concrete nouns in a second language (L2) differs depending on age of acquisition (AoA) of L2. AoA of L2 was manipulated by contrasting two groups of bilinguals, i.e., a group of early bilinguals (acquisition of both languages before the age of 3 years) and a group of highly proficient late bilinguals (acquisition of the L2 after the age of 10 years). In order to examine the neural basis of the semantic-conceptual representation, we combined the psychological cross-language priming paradigm with the functional magnetic resonance imaging (fMRI) technique. It is argued that repetition suppression (RS) might be the neural correlate of priming (Schacter & Buckner, 1998; Wiggs & Martin, 1998). RS is a decrease of neural responses following repeated exposure of the same stimulus (Desimone, 1996). RS is a potential neural analogue of the hemodynamic decrease observed in fMRI studies for repeated versus unrepeated stimuli. Different models of blood oxygenation level-dependent (BOLD) RS have been proposed (for a review Grill-Spector, Henson, & Martin, 2006).

However, repeated exposure of the same stimulus is not systematically related to neural suppression. Several neuroimaging data reported repetition enhancement (RE; see James and Gauthier (2005) for a review). These findings were corroborated by single-neuron recordings in neurophysiological studies conducted in non-human primates. The fact that repeated exposure is also related to neural enhancement constitutes a challenge for Suppression models. Recently, James and Gauthier (2005) proposed an Accumulation model that is able to account for both repetition suppression and repetition enhancement effects. Accumulation models are derived from models of reaction times (Luce, 1986). To model object recognition times with an Accumulation model, recognition is considered as a process that accumulates evidence over time until a critical level of evidence is achieved, the process is terminated, and a response is made. Similarly, to model neural activity, an Accumulation model postulates that the population of neurons which underlie the recognition process accumulate activity until a critical level is reached, at which time the process is complete. In such a model, priming effects can be modelled as a shift in time of peak activity, which leads to shorter reaction times and smaller BOLD responses. An Accumulation model would account for repetition enhancement (RE) with later peak times in the primed condition than in the unprimed condition. Later peak times mean that the processing system needs more time to accumulate neural activity for completing a specific process.

In L1 semantic priming studies using fMRI, *semantic enhancement* (SE) has been reported in several bilateral fronto-temporal-parietal regions, including the middle and superior temporal gyrus, supramarginal gyrus, inferior parietal lobule, inferior and medial frontal gyrus (Kotz, Cappa, von Cramon, & Friederici, 2002; Raposo,

Moss, Stamatakis, & Tyler, 2006; Rossell, Price, & Nobre, 2003). To date, only a few studies have investigated the cortical organisation of the bilingual mental lexicon using fMRI – adaptation paradigm (for a review, see Chee (2009)). Chee, Soon, and Lee (2003) reported cross-linguistic priming evidence suggesting that the networks for Chinese and English word processing share components at a conceptual level. Cross-language repetition priming effects were measured while early English–Chinese bilinguals (exposure to both English and Chinese by 4 years of age) read pairs of concrete nouns (i.e., visual reading task). Chee et al. showed repetition-induced reductions in BOLD signal change in the left prefrontal and in lateral and inferior temporal regions for repetition in the same language (i.e., English-only condition) or in mixed-languages. However, signal change was greater in mixed-language condition than in English-only condition. Chee et al. interpreted this increase in signal change as reflecting the greater attentional resources needed when reading different scripts in the two languages. In contrast, Klein et al. (2006) examining across language adaptation with a passive listening task in English–French bilinguals (AoA of L2 after the age of 5 years; mean AoA 7.9, range 5.2–14) showed that a forward translation condition (L1–L2 translate: *Bed Bed Bed Bed Bed Lit*) compared with a no-word change condition (L1 same word: *Bed Bed Bed Bed Bed Bed*) caused an increase in fMRI signal along the superior temporal gyrus bilaterally as well as in the left inferior frontal gyrus (BA 44/6). However, Klein et al. failed to show a significant correlation between AoA of L2 and the forward translation condition. Finally, Crinion et al. (2006) reported cross-linguistic repetition priming effects (i.e., *duche-SHOWER*) in the calcarine sulcus for highly proficient late learners of L2 (AoA was not indicated) using a verification task (i.e., to decide whether an animal has long legs or short legs). To sum, there is a lack of consensus concerning the neural correlates of cross-linguistic priming. The discrepancies between studies may be related to differences in the task requirements and in onset of L2 acquisition. Other factors such as the nature of the baseline task and the language proficiency have been also invoked to account for the discrepancies (Klein et al., 2006).

## 2. The present study

We aimed to test the assumption that the mental representation of lexical knowledge in L2 is affected by neural maturation. For this purpose, we investigated whether bilingual’s two languages share a common conceptual system and share the same underlying neural representation, and if so, to what extent AoA of L2 affects these representations. Our manipulation consisted of monitoring cross-language L1–L2 repetition priming effects of visually presented French–German pairs of concrete nouns (e.g., *valise<sup>suitcase</sup>–Koffer<sup>suitcase</sup>*). The difference in BOLD signal elicited by cross-linguistic related pairs consisting of a French concrete noun (e.g., *valise<sup>suitcase</sup>*) and its German translation equivalent (e.g., *Koffer<sup>suitcase</sup>*) and cross-linguistic unrelated French–German word pairs in which none of the words shared identical meanings (e.g., *témoin<sup>witness</sup>–Koffer<sup>suitcase</sup>*) was calculated. Ten early and 10 highly proficient late French–German bilinguals performed a semantic categorisation task (natural/manmade) on the second word of each pair, i.e., the target word. Price, Green, and Von Steudnitz (1999) have suggested that, in forward translation (i.e., L1–L2), the semantic route dominates, whereas, in backward translation (i.e., L2–L1), the lexical route dominates, reflecting the acquisition of the L2 word in the context of a pre-existing lexical concept-word form link in L1. In behavioural studies, Kroll and Stewart (1994) have shown that directionality effects occur when using translation tasks; translating word from L1 to L2 (forward) takes longer than translating from L2 to L1 (backward). To account for this dif-

ference, Kroll and Stewart (1994) have argued that forward translation proceeds via conceptual memory, whereas backward translation typically exploits the direct links between nodes in lexical memory. As in the current study we aimed to tap cognitive processes at the semantic-conceptual level of processing, we therefore choose to use an immediate uni-modal (visual–visual) forward translation (L1–L2) priming paradigm.

At the behavioural level, we predicted that if bilingual's two languages are interconnected at a semantic-conceptual level, irrespective of AoA of L2, then a behavioural forward translation repetition priming effect should be observed for both early and highly proficient late bilinguals.

At the neural level, we predicted that if bilingual's two languages share a common conceptual system and share the same underlying neural representation, then repetition-related effects should occur in several bilateral fronto-temporal regions. Based on the Memory, Unification, Control (MUC) model (Hagoort, 2005), we expected to observe repetition-related effects in the temporal (superior temporal gyrus assumed to support L1 and L2 lexical information) as well as in the prefrontal (dorsolateral prefrontal cortex (DLPFC) assumed to support language switching mechanism) brain areas of the left hemisphere. Moreover, based on previous semantic priming studies in L1 and L2, repetition-related effects should also be expected in the inferior frontal gyrus (IFG), the medial frontal gyrus, and the anterior insula. Concerning the polarity of the neural priming, we predict that the processing of a word preceded by a conceptually related prime should be associated with an enhancement of the neuronal activity in the above-mentioned language specific brain areas.

Finally, with respect to AoA of the L2, which constitutes the question of central interest of the present study, if bilingual's two languages are interconnected at a semantic-conceptual level, irrespective of AoA of L2 (*BIA+* and *RH* models), then repetition enhancement effects should be observed for both early and highly proficient late bilinguals in a prefrontal–temporal network. Involvement of the prefrontal brain region (language switching) should vary as a function of AoA of L2. In contrast, if bilingual's two languages are interconnected at a semantic-conceptual level for early but not for late bilinguals (Silverberg & Samuel, 2004), then RE effects should be observed in a prefronto-temporal network for early L2 learners only.

### 3. Materials and methods

#### 3.1. Participants

Twenty healthy French–German bilingual adults were assigned to two groups according to onset of L2 acquisition and L2 proficiency. Late bilinguals were matched with respect to degree of exposure to their L2 (mean years 6, range 3–9). We created one group of 10 early bilinguals (five females, mean age 32.5, range 24–39), and one group of 10 highly proficient late bilinguals (five females, mean age 30.3, range 20–42). All subjects were right-handed according to the Edinburgh Inventory (Oldfield, 1971). They had normal or corrected-to-normal vision and none had a history of neurological or psychiatric diseases. Each gave informed consent and was paid for participation. The study was approved by the research ethical committee of the University Medical Center Hamburg-Eppendorf.

#### 3.2. Language proficiency assessment

Early bilinguals have been exposed to both French and German before the age of 3 years and attended school in Germany since early childhood. They started learning French at home with their

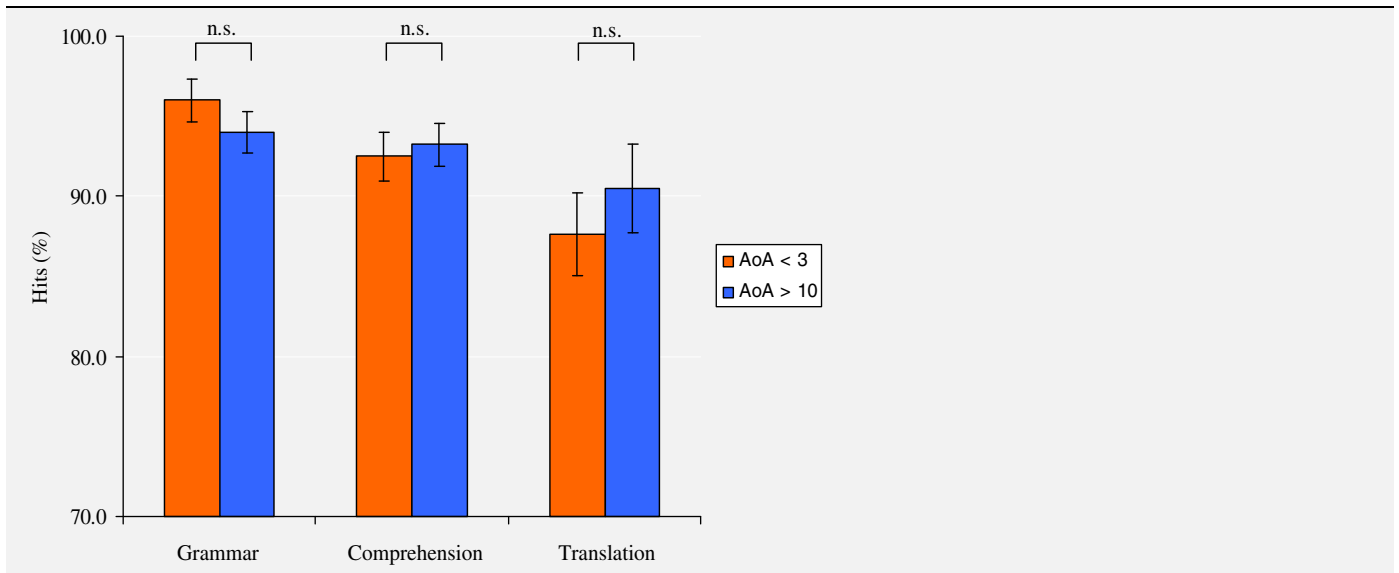
mother, whose L1 was French. The 10 highly proficient late bilinguals were all native speakers of French who formally began to learn German as an L2 at the secondary school in France, on average at the age of 11 (range 10–13). The language of the mother of the 10 early and the 10 late bilinguals was French. All participants learned British English at the secondary school as a third language (L3). Prior to the experiment, participants had all completed a questionnaire assessing the amount of actual exposure to both languages in various domains such as media, family, university, friends, girlfriends/boyfriends, reading, and other activities (see for details Wartenburger et al., 2003). This assessment allows having an approximation of the overall actual exposure to a given language at the time when the tests were administered. On average, late bilinguals were exposed to the L1 for  $4.5 \pm 1.5$  h and to the L2 for  $6 \pm 4$  h per day for the daily activities investigated. Similarly, early bilinguals were less exposed to French ( $4.0 \pm 1$  h) than to German ( $6.5 \pm 4.5$  h) in their daily activities in Germany. The two groups were matched on degree of proficiency in German using various objective measures provided by standardized high school language tests administered prior to admission to university in Germany (*Das Zertifikat, Deutsch als Fremdsprache, Einstufungs- und Diagnostiktest*). In addition, the level of proficiency in L2 for early and late French–German bilinguals was also assessed by means of a test of translation that evaluates the quality of translation from L2 to L1 (performance mean for early bilinguals  $87.7 \pm 2.6\%$  and for late bilinguals  $90.5 \pm 2.7\%$ ;  $P > 0.10$ ), as an index of proficiency. The translation test consisted of translating into French the German target words employed in the priming experiment. This translation test was performed post-scanning. Table 1 displays a summary of the results.

#### 3.3. Stimuli

Since there is an increasing awareness in monolingual word recognition research that the age at which a word was learned (AoA) can have important consequences for its processing (Zevin & Seidenberg, 2002), we controlled the AoA of both French and German critical words. In order to determine the “real” age at which words have been acquired, i.e., an objective measure of AoA (Iyer, Saccuman, Bates, & Wulfeck, 2001), we selected our linguistic materials from a database of the University of Hamburg that contains spontaneous verbal productions by French–German bilingual children (1.0–5.0 years) who were exposed to both languages since birth (Koeppel, 1994; Schlyter, 1990). In total, 120 French concrete nouns of the open-class category and their 120 translation equivalents in German were selected from this bilingual database. Half of the words ( $n = 60$ ) referred to natural entities (e.g., agneau/Lamm (*lamb*)), whereas the other half ( $n = 60$ ) referred to manmade entity (e.g., valise/Koffer (*suitcase*)). The mean AoA was 2.7 years ( $\pm 0.1$ ) for the 60 natural concrete nouns and 3.3 years ( $\pm 0.1$ ) for the 60 manmade concrete nouns. By keeping the AoA of the French and the German words as low as possible and by matching the AoA of the French–German word pairs, we ensured to reduce possible artefacts due to differences in language experiences in German for the two groups of bilinguals.

In the cross-linguistic related condition (e.g., valise<sup>suitcase</sup>–Koffer<sup>suitcase</sup>), French and German words were matched for concreteness according to concreteness ratings in the MRC Psycholinguistics database (Coltheart, 1981; Natural nouns: mean = 574, SEM = 4.6; Manmade nouns: mean = 568, SEM = 5.4). Words with ratings between 100 and 400 are usually considered abstract and between 400 and 700 as concrete. French target words belonged only to one language; this means that none of the words within a pair were cognates (i.e., words from two languages that are identical in orthographic form and largely overlap in meaning such as FILM in French, German, and English), interlin-

**Table 1**  
Results of measures of proficiency in German for the two groups of bilinguals.



gual homographs (i.e., same orthography but different meaning, for example AUGE is *eye* in German and *trough* in French), or homophones. No words were polysemous. None of the words denoted conceptual units that would have been specific to one language, for example, if that language has a word expressing a concept that does not have a particular lexical correlate in the other language. Moreover, there was neither an orthographic (same letter in the same position) nor a phonological overlap between the French nouns and their translation equivalents in German. Furthermore, word pairs in the cross-linguistic related condition were matched for frequency (CELEX database for German, Baayen, Piepenbrock, & Gulikers, 1995 and Lexique three database for French, New, Pallier, Ferrand, 2005: <http://www.lexique.org/docLexique.php>; French natural nouns: mean = 39.9, SEM = 6.4; German natural nouns: mean = 35.2, SEM = 4.3; French manmade nouns: mean = 26.4, SEM = 3.7; German manmade nouns: mean = 38.7, SEM = 8.9), concreteness and imageability (MRC Psycholinguistics database, Coltheart, 1981) as well as for number of letters (on average, the target words consisted of six letters). In the cross-linguistic unrelated condition (e.g., *témoign*<sup>witness</sup>–*Koffer*<sup>suitcase</sup>), prime words were matched with target words for frequency, concreteness, imageability, and number of letters. Primes and targets had no phonological/orthographic, morphological, or semantic links. Table 2 displays examples of word pairs in the cross-linguistic

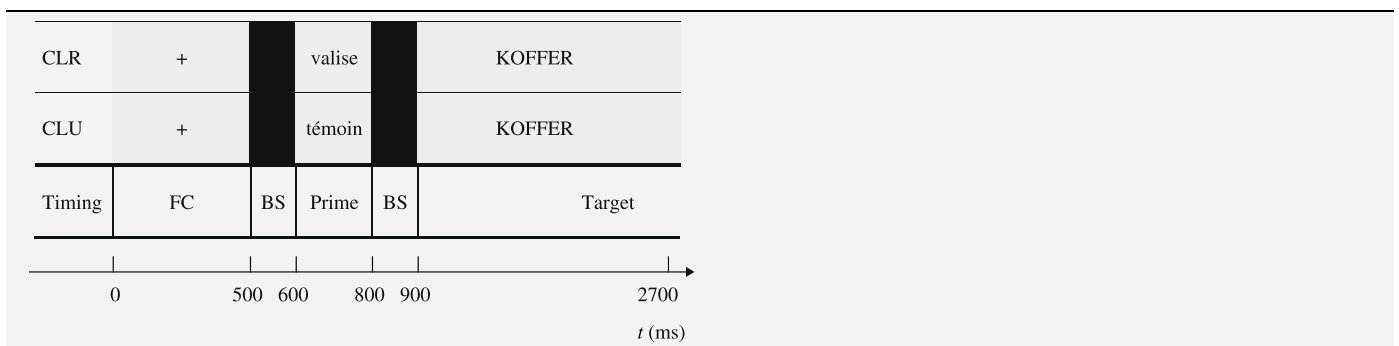
related and unrelated conditions as well as the timing used in each trial.

In addition, we selected 420 filler pairs (300 word–word pairs, 60 “blank screen” – word pairs (12.5%; neutral condition), and 60 symbol pairs (12.5%)). All neutral pairs consisted of a blank screen of 400 ms followed by a target word (50% natural and 50% manmade words). Finally, half of the symbol pairs consisted of a series of six identical symbols (e.g., %%%%), whereas the other half were constituted of six symbols consisting of the repetition of two different symbols (e.g., %\$%\$%).

3.4. Experiment design

In order to minimise the use of processing strategies (for example, a post-lexical semantic matching strategy), a low proportion of related pairs (PRP) was used (i.e., 12.5%). By means of a Latin square design, four experimental lists were created such that cross-linguistic related (e.g., *valise*<sup>suitcase</sup>–*Koffer*<sup>suitcase</sup>) and unrelated (e.g., *témoign*<sup>witness</sup>–*Koffer*<sup>suitcase</sup>) pairs were balanced across the lists. Each target was presented under both priming conditions, but no participant saw the same prime or the same target twice, thus avoiding possible practice effects that could arise from multiple presentations of an item (Slowiaczek & Pisoni, 1986). Furthermore, although there was no orthographic overlap between prime

**Table 2**  
Examples of word pairs in the cross-linguistic related (CLR) and unrelated (CLU) conditions and timing (in milliseconds) used in each experimental trial.



Note. FC refers to fixation cross; BS refers to blank screen.



and target words (i.e., a same letter at the same position in the word), primes were presented in lowercase letters, whereas targets were presented in capital letters in order to minimise sensorial match between primes and targets. In each list, the 30 cross-linguistic related, 30 cross-linguistic unrelated, and 420 filler pairs were pseudorandomly organised into five sessions, with session order counterbalanced across subjects. Each session comprised 96 trials (six cross-linguistic related pairs, six cross-linguistic unrelated pairs, and 84 filler pairs). In each session, item pairs were pseudorandomly interspersed according to the following constraints. First, each type of pair (cross-linguistic related, cross-linguistic unrelated, filler, neutral, symbol) was presented in no more than three consecutive trials. Second, no more than three pairs with natural or manmade targets were presented in succession. Third, each session began with three warm-up stimuli that did not belong to the critical conditions.

### 3.5. Procedure

Each word–word trial consisted of a fixation cross presented in the middle of the screen for 500 ms that was followed by: (1) a blank screen presented for 100 ms, (2) a written prime word presented in lowercase letters for 200 ms, (3) a blank screen for 100 ms, and (4) a written target word presented in capital letter and remaining on the screen until participants responded (maximal response time was limited to 1800 ms; see Table 2). The same timing was applied for the neutral and the symbol pairs. For the neutral pairs, the prime word was replaced by a blank screen for 200 ms. For the symbol pairs, the prime word was replaced by a blank screen for 200 ms, whereas the target word was replaced by a series of either identical or different symbols. The SOA between prime and target was 300 ms. The use of a short SOA between prime and target (300 ms) ensures to reduce the risk of semantic expectancies (i.e. creation of a mental list of potential associates). The inter-trial-interval (ITI) separating the single trials varied between 2000 ms and 2000 ms plus one TR to increase the sampling rate of the BOLD response (Josephs, Turner, & Friston, 1997). Participants were asked to decide whether each item presented in capital letters (i.e., the second word of each trial) was natural or manmade (i.e., semantic categorisation). For the symbol pairs, participants indicated whether the series of symbols were identical or different. Participants responded using their left hand. Half of the participants ( $n = 10$ ) used the forefinger for the response “natural” and the middle finger for the response “manmade” and the other half ( $n = 10$ ) used the reversed pattern. Each of the five sessions lasted for approximately 10 min, with 1–2 min rest between each session. The first session was preceded by a short practice session of 12 items before scanning started. Practice was repeated until participants responded without errors. In order to switch the language processing system of the participants to a French mode, early and late bilinguals spoke French with a native speaker for around 1 h before scanning started.

### 3.6. Behavioural data analysis

A counter module was started at the onset of the visual target presentation to register RT using *Presentation* (Neurobehavioural Systems). We recorded both reaction times (in milliseconds) and accuracy (in %). Time-out was set at 200 ms and at 1800 ms; if the participants responded before 200 ms or after 1800 ms, the response was coded as missing. A correction procedure (mean  $\pm$  2SD) was applied on the RTs for correct responses in order to discard extreme values. RTs were then averaged in the four experimental conditions across participants and across items. Priming effects were calculated by subtracting the averaged reaction time in the cross-linguistic related condition from the averaged reaction time

in the cross-linguistic unrelated condition by participants and by items.

### 3.7. fMRI acquisition and analysis

The imaging data were collected with a 3.0-Tesla Magnetom TrioTim syngo MR B13 whole body System (Siemens, Erlangen, Germany). Image acquisition consisted of a fast  $T_1$  – weighted sequence (localizer) and  $T_2^*$  – weighted sequences for functional images. Functional images were acquired in 38 axial slices using a blood oxygenation level-dependent (BOLD)-sensitive gradient-echo echoplanar imaging (EPI) sequence with an echo time (TE) of 30 ms, a flip angle of 90°, a repetition time (TR) of 2.22 s, and an acquisition bandwidth of 100 kHz. The matrix acquired was  $64 \times 64$  with a field of view (FOV) of  $192 \times 192$  mm, resulting in an in-plane resolution of  $3 \text{ mm} \times 3 \text{ mm}$ . Slice-thickness was 3 mm without interslice gap. Each trial had a length of 2.7 s followed by an intertrial interval (ITI) in milliseconds varying from 2000 ms to  $2000 + 1 \text{ TR}$ . The functional measurements were carried out in five sessions of about 10-min length. There were 96 trials per session (480 trials, in total). In each session, 250 volumes were recorded. For each run, the functional scanning was always preceded by six dummy scans to insure tissue steady-state magnetization. After functional scanning, a high-resolution (HR) 3-D  $T_1$  – weighted sequence for anatomical images was performed (12 min). HR  $T_1$  images were acquired for coregistration of the functional images. The data matrix was  $256 \times 256$ , FOV = 192 mm, TR = 2.3 s, TE = 10 ms, and slice-thickness = 1 mm. The whole experiment lasted for about 1 h. Data processing and statistical analyses were carried out with Statistical Parametric Mapping SPM2 software package (Wellcome trust Centre for Neuroimaging, London, UK, <http://www.fil.ion.ucl.ac.uk/spm/>). All functional images were corrected for slice timing, spatially realigned, normalized to the Montreal Neurological Institute (MNI) template, and smoothed using a Gaussian filter of 8 mm. A high-pass filter was used to remove low-frequency drifts.

Random-effects analyses that included only imaging data of correct behavioural responses were conducted. At first-level of analysis (single-subject analysis), the typical SPM2 event-related analysis procedure was applied. The hemodynamic response function (HRF) supplied by SPM2 and its temporal derivatives were used to compile two regressors for each of the three experimental conditions (cross-linguistic related, cross-linguistic unrelated, filler pairs). We modelled each condition by defining the onset of the second word of each pair (i.e., the target word) as the onset of the HRF used in the regressor. To correct the implied imprecision, we included the temporal derivative as additional regressor of no interest. At second-level of analysis (group analysis), activation estimates of the critical conditions (cross-linguistic related, cross-linguistic unrelated) were lifted onto group level analysis using a General Linear Model (GLM) with the factors Condition, Subject and Group. We then modelled the neuronal priming effect as the contrast of cross-linguistic related versus cross-linguistic unrelated effect for: (1) all 20 participants and (2) for each group of participants (AoA < 3; AoA > 10). For the whole brain analysis, the resulting statistical parameter maps were thresholded at  $P < 0.001$  uncorrected ( $Z > 3.0$ ) at the voxel level unless reported otherwise. For regions of interest (ROI) with an a priori hypothesis (i.e., IFG, STG, MFG, medial frontal gyrus, anterior insula), a small volume correction for multiple tests was applied (SVC in SPM2). SVC-volumes were defined by spheres of 10 mm radius around those voxels of our five ROIs, which showed peak activations in the whole brain analysis. The voxelwise threshold was set to  $P < 0.05$  (FWE correction), and clusters were reported if their extent was significant at  $P < 0.05$  corrected for multiple comparisons across the small volume. Only clusters of at least six connected

voxels (i.e., 162 mm<sup>3</sup>) are reported here. All coordinates are reported in MNI coordinates.

## 4. Results

### 4.1. Behavioural data obtained in the MRI scanner

#### 4.1.1. Reaction times

We subjected the correct response times to a three-way analysis of variance (ANOVA) by participants (*F1*) and by items (*F2*) in which Condition (two levels: cross-linguistic related, cross-linguistic unrelated) was considered as a within-subjects factor and in which group (two levels: early bilingual, late bilingual) and list (four levels: list 1, list 2, list 3, list 4) were considered as between-subjects factors. The factor list was introduced merely to extract any variance due to the counterbalancing of critical items. A significance level of  $\alpha = .05$  was used for all statistical tests. The lack of any interaction with or main effect of list ( $F_s < 1$ ) indicates that the counterbalancing of items in the four experimental lists did not introduce variance in the results. Therefore all further tests were performed on data collapsed across list. Table 3 presents the averaged reaction times for each critical condition. Averaged correct response times were significantly faster (55 ms) for the cross-linguistic related than for the cross-linguistic unrelated,  $F_{1,9} = 23.1, P < 0.001$  and  $F_{2,29} = 23.1, P < 0.05$ . Moreover, on average early bilinguals performed the semantic categorisation task faster than late bilinguals (862 ms,  $SEM = 29$  versus 942 ms,  $SEM = 24$ ),  $F_{1,9} = 4.5, P < 0.05$  and  $F_{2,29} = 34.7, P < 0.001$ . Finally, a significant interaction Condition and Group was found ( $F_{1,18} = 5.3, P < 0.05$  and  $F_2 < 1$ ). This interaction reflects a larger cross-linguistic priming effect in the late bilingual group (82 ms,  $P < 0.01$ ) than in the early bilingual group (28 ms,  $P < 0.05$ ). The difference between the priming effects (54 ms) was significant ( $F_{1,9} = 4.6, P = 0.05$ ).

#### 4.1.2. Accuracy

The error data are presented in Table 4. On average, early bilinguals were more accurate than late bilinguals in deciding to which semantic category (i.e., natural versus manmade) the German target words belonged to (7%,  $SEM = 0.6$  versus 13%,  $SEM = 2.5$ ). Furthermore, Condition had no effect on errors (cross-linguistic related = 10.6%, cross-linguistic unrelated = 9.5%;  $F_s < 1$ ). Finally, the Condition  $\times$  Group interaction failed to reach significance ( $F_s < 1$ ).

### 4.2. Imaging data

In order to investigate in which brain areas cross-language repetition was associated with repetition-related brain activity, we contrasted the cross-linguistic unrelated with the cross-linguistic related conditions. Overall, the imaging data of the 20 bilinguals in the cross-linguistic related condition showed greater activations, i.e., repetition enhancement (RE), in the left mid-insula at the border of the superior temporal gyrus (Brodmann area (BA) 13:  $-42, -12, -6$ ), left inferior frontal gyrus (BA 45:  $-54, 18, 7$ ),

**Table 4**  
Task accuracy: percentages of error.

	Cross-linguistic related	Cross-linguistic unrelated
AoA < 3	7.6 (1.3)	6.3 (1.6)
AoA > 10	11.3 (2.8)	14.9 (3.2)
All	9.5 (2.2)	10.6 (2.9)

Percentages of error for semantic categorisation to target words in subjects analyses in each condition. Standard errors of the mean (*SEM*) are shown in brackets.

right mid-insula at the border of the superior temporal gyrus (39,  $-12, -7$ ), and right middle temporal gyrus (57,  $-45, -12$ ) relative to the cross-linguistic unrelated (Fig. 1 and Table 5).

#### 4.2.1. Early bilinguals

The imaging data of the 10 early bilinguals showed RE in different brain areas. Peak activation was found in the left inferior frontal gyrus (BA 47:  $-39, 21, -9$ ) and medial frontal gyrus (BA 9:  $-6, 54, 39$ ) in the left hemisphere. Moreover, greater activation in the cross-linguistic related relative to the cross-linguistic unrelated condition was also observed in the right superior temporal gyrus (BA 22:  $63, -51, 9$ ; see Fig. 2 and Table 5).

#### 4.2.2. Late bilinguals

In addition to RE effects in several fronto-temporal brain areas, a RS effect was also found. Smaller activations were found in the cross-linguistic related relative to the cross-linguistic unrelated condition in left middle frontal gyrus ( $-36, 33, 45$ ). RE effects were observed in mid-insula at the border of the superior temporal gyrus (BA 21:  $-42, -12, -9$ ) as well as in middle frontal gyrus ( $-36, 15, 42$ ) in the left hemisphere. In the right hemisphere, RE effects were observed in the superior temporal gyrus (BA 22:  $45, -6, -9$ ) and in culmen ( $18, -39, -15$ ; Fig. 3 and Table 5).

#### 4.2.3. Early bilinguals versus late bilinguals

In order to test in which brain areas larger effects can be observed for early bilinguals than for late bilinguals, we contrasted the images relative to the RE in early bilinguals with those relative to RE in late bilinguals (RE early bilinguals > RE late bilinguals). The data showed that RE was significantly larger for early than for late bilinguals in the left superior frontal gyrus ( $-21, 42, 45$ ), and in anterior part of the left superior temporal gyrus ( $-36, 12, -18$ ) at the border of the pars orbitalis (BA 47) as well as in the right superior frontal gyrus ( $15, 54, 36$ ) and in the right posterior insula ( $39, -21, 12$ ) of the right hemisphere (Fig. 4 and Table 5).

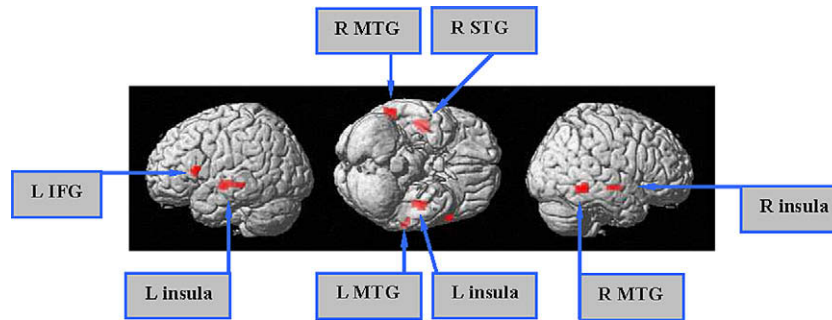
#### 4.2.4. Late bilinguals versus early bilinguals

The contrast between the amplitude of the RE effect obtained in the group of late bilinguals relative to the one obtained in the group of early bilinguals (RE late bilinguals > RE early bilinguals) showed significantly larger RE in the left mid-insula at the border of the superior temporal gyrus (BA 13:  $-42, -9, -9$ ) and in the right middle frontal gyrus ( $27, -3, 42$ ; Fig. 5 and Table 5).

**Table 3**  
Reaction times to correctly answered trials.

	Subjects analysis ( <i>F1</i> )			Items analysis ( <i>F2</i> )		
	Cross-linguistic related	Cross-linguistic unrelated	PE	Cross-linguistic related	Cross-linguistic unrelated	PE
AoA < 3	848 (31)	876 (29)	28	859 (16)	877 (15)	18
AoA > 10	901 (21)	983 (30)	82	917 (19)	979 (21)	62
All	874 (27)	929 (34)	55	888 (14)	928 (16)	40

Mean reaction times (*RTs*; in milliseconds) for semantic categorisation to target words in subjects and items analyses in each condition. Standard errors of the mean (*SEM*) are shown in brackets.



**Fig. 1.** Brain areas that show greater activation for cross-linguistic related than for cross-linguistic unrelated in early and late bilinguals ( $n = 20$ ) performing the semantic categorisation task at  $P < 0.001$  uncorrected.

**Table 5**

Brain area showing repetition enhancement/suppression effects.

Area	Number of voxels in cluster	Cluster-level ( $p$ -value corrected)	Z value at local maximum	MNI coordinates		
				x	y	z
<i>Global analysis (N = 20)</i>						
<i>RE</i>						
L mid-insula	24	<.01	3.87	-42	-12	-6
L inferior frontal gyrus	8	<.05	3.99	-54	18	7
R mid-insula	23	<.01	3.73	39	-12	-7
R middle temporal gyrus	20	<.05	3.82	57	-45	-12
<i>Early bilinguals (N = 10)</i>						
<i>RE</i>						
L inferior frontal gyrus	33	<.05	3.20	-39	21	-9
L medial frontal gyrus	26	<.05	3.48	-6	54	39
R superior temporal gyrus	28	<.05	3.56	63	-51	9
<i>Late bilinguals (N = 10)</i>						
<i>RS</i>						
L middle frontal gyrus	14	<.05	3.10	-36	33	45
<i>RE</i>						
L mid-insula	109	<.01	4.64	-42	-12	-9
L middle frontal gyrus	21	<.05	3.50	36	15	42
R superior temporal gyrus	65	<.01	3.96	45	-6	-9
R culmen	27	<.05	3.09	18	-39	-15
<i>Early &gt; late (N = 10)</i>						
<i>RE</i>						
L superior frontal gyrus	22	<.05	3.37	-21	42	45
	14	<.05	3.31	-36	12	-18
L superior temporal gyrus	15	<.05	3.49	15	54	36
	27	<.05	3.26	39	-21	12
R superior frontal gyrus						
R posterior insula						
<i>Late &gt; early (N = 10)</i>						
<i>RE</i>						
L mid-insula	22	<.05	3.39	-42	-9	-9
R middle frontal gyrus	16	<.05	3.16	27	-3	42

#### 4.2.5. Correlation between behavioural priming and neural priming

We observed several brain regions in which neural responses change with repetition. In order to investigate whether the brain areas showing RE effects directly contribute to behavioural priming, we calculated the correlation between behavioural and neural priming. A simple regression model in which we correlated the contrast images for RE for each participant with their corresponding behavioural priming effects was applied to the whole brain. The observation of a significant correlation between behavioural and neural priming allowed us to determine which changes associated with repetition are central or epiphenomenal to priming. Fig. 6 shows a significant negative correlation between behavioural and neural priming in left middle frontal gyrus ( $-48, 33, 27$ ;  $r = -0.74, P < 0.001$ ).

## 5. Discussion

In the present neuroimaging study, we examined the architecture of the bilingual word recognition system using fMRI. The question of central interest was whether the semantic-conceptual representation of words in L1 and L2 varies as a function of the onset of L2 acquisition. Our manipulation consisted of monitoring cross-language L1–L2 repetition priming effects of visually presented French–German pairs of concrete nouns (e.g., valise<sup>suitcase</sup>–Koffer<sup>suitcase</sup>) using a semantic categorisation task. Our results provide a clear picture: the influence of the prime words (e.g., valise<sup>suitcase</sup>) on the target words (e.g., Koffer<sup>suitcase</sup>) response was demonstrated by both behavioural and imaging data.

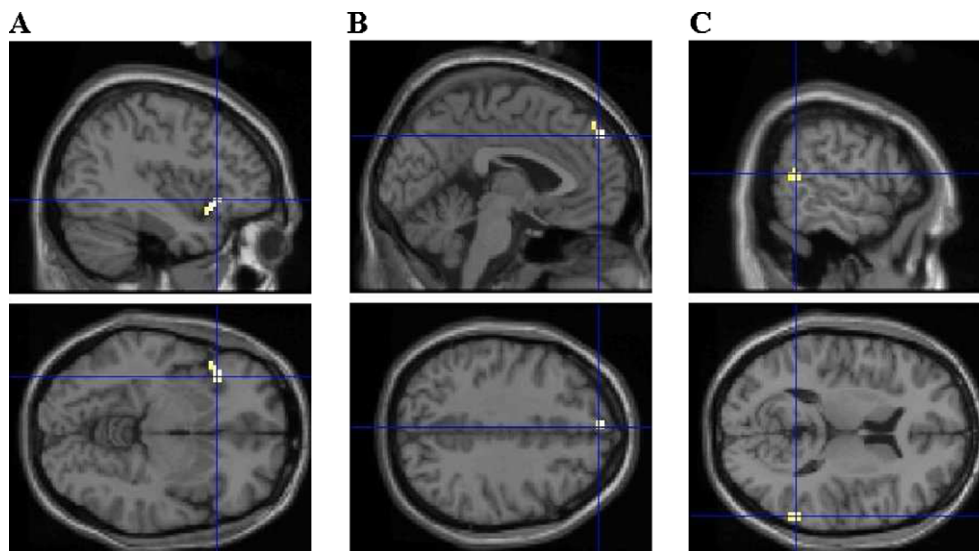


Fig. 2. Peak activations of the RE effects in the 10 early bilinguals in (A) left inferior frontal gyrus, (B) left medial frontal gyrus, and (C) right superior temporal gyrus.

Behaviourally, there was a significant 55-ms repetition priming effect across groups. The cross-language priming effect was significantly larger in the group of late bilinguals (e.g., 82 ms) than in the group of early bilinguals (e.g., 28 ms).

At the neural level, the whole brain analysis showed increasing activation in the cross-linguistic related condition in several bilateral fronto-temporal regions, including the middle and superior temporal gyrus, the inferior, middle/medial and superior frontal gyrus, the mid-insula. In addition, a RS effect was also found in the left middle frontal gyrus (MFG) in the group of late bilinguals. The size of the RE effect differed significantly across groups in multiple brain areas. Whereas early bilinguals showed larger RE effects in the left superior temporal gyrus (STG), the bilateral superior frontal gyrus (SFG), and the right posterior insula, late bilinguals showed larger RE effects in the left mid-insula and the right MFG. Furthermore, a significant negative correlation between behavioural and neural priming was observed in the left MFG.

### 5.1. Age of second language acquisition and the neural representation of words in L2

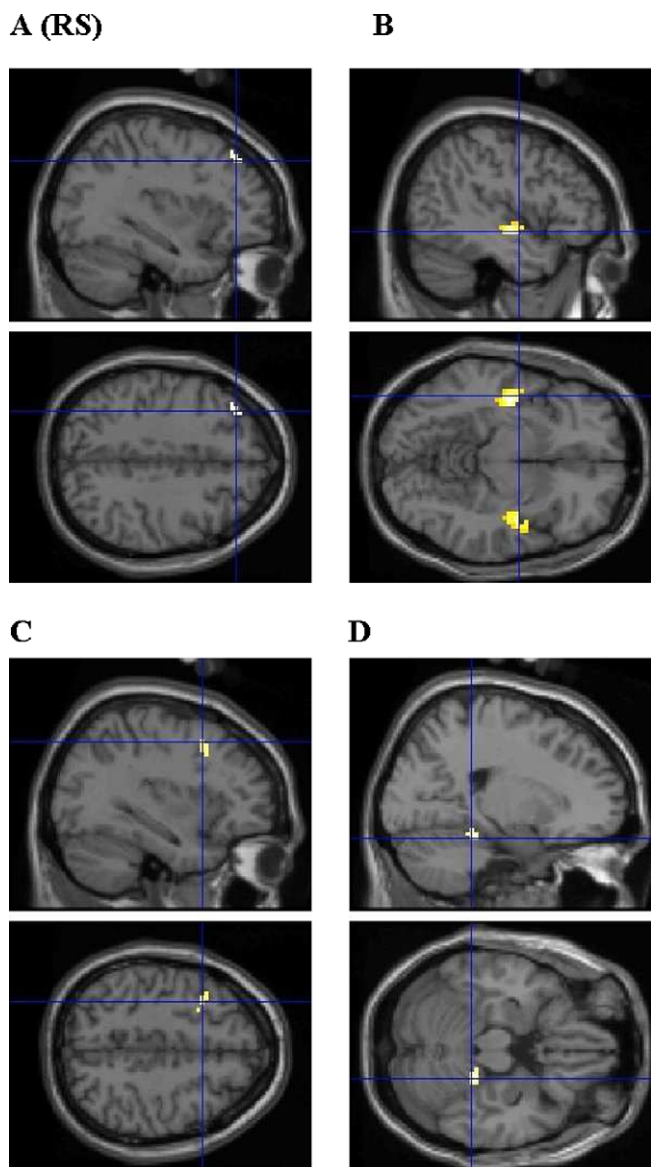
As already mentioned in the Introduction, the Critical Period Hypothesis (CPH) did not make any assumptions concerning the acquisition of lexical knowledge. According to the CPH, only segmental phonology, inflectional morphology and syntax can be influenced by age of onset of acquisition of a language. However, more recent theories of neurolinguistic development (Locke, 1997) assume an *optimum biological moment* for the appropriate organisation and use of the mental lexicon. The present fMRI study aimed to test the assumption that the mental representation of lexical knowledge in L2 is affected by neural maturation. In particular, we examined whether AoA of an L2 affects the neural representation of words. In our study, the observation of differentiated patterns of neural priming for both amplitude and localisation as a function of AoA of L2 suggests that the age at which an individual is first exposed to its L2 might have an effect on the cortical organisation of the mental lexicon of the L2. However, the behavioural data showed that late bilinguals were slower and made more errors. Therefore, one cannot exclude that the variation of neural priming as a function of AoA of L2 observed in the present study might be due to retrieval and decision processes that vary with difficulty rather than to different representation of meaning. To

clarify this point, complementary analyses were run to ensure that the differences observed were attributable to L2 acquisition history and not to individual differences. These analyses consisted to calculate the neural priming by splitting the group of late bilinguals in two subgroups of five participants on the basis of the reaction times. Using the median of the reaction times, we created a subgroup of “fast” reacting bilinguals (in average, 885 ms) and a subgroup of “slow” reacting bilinguals (in average, 998 ms). Accuracy did not significantly differ between the two subgroups of participants (“fast” reacting bilinguals: 13.5%; “slow” reacting bilinguals: 12.7%). Results showed that the neural priming effects were similar in the two subgroups of late bilinguals. This suggests that the variation of neural priming as a function of AoA of L2 observed in the present study might be due to different representation of meaning. We argue that as for segmental phonology, inflectional morphology and syntax, the attainment of lexical knowledge in L2 might also be affected by neural maturation, at least for Indo-European languages. Our data lend support to the theory of Locke (1997) postulating that the organisation and use of the mental lexicon must occur during an *optimum biological moment*. By extending this theoretical framework to the acquisition of L2, we propose that late bilingual adults (i.e., AoA > 10 years) who were not appropriately stimulated with lexical material of the L2 during a pregrammatical period (5–20 months) in their childhood might then have difficulties to perform analytical operations such as analyse and detection of recurrent structural patterns (20–37 months) in the L2. Therefore, along these lines, it is possible to argue that difficulties to process syntax in L2 as usually observed in late bilinguals (Hahne and Friederici (2001), Isel (2005) and Mueller (2005) for reviews) might be explained by the lack of appropriate lexical stimulations in the L2 before the age of 3 years.

### 5.2. Cross-language neural priming: the suppression model calls into question

To date, there is a lack of consensus concerning the neural correlates of cross-linguistic priming. Some studies have reported decreases in the haemodynamic response for cross-linguistic priming, but the regions where suppression occurs are not consistent across studies (Chee et al., 2003: left prefrontal and in lateral and inferior temporal regions; Crinion et al., 2006: calcarine sulcus). In contrast, other studies have reported an enhancement.





**Fig. 3.** Peak activation of the RS effect in the 10 highly proficient late bilinguals in the left middle frontal gyrus is displayed in (A). Peak activations of the RE effects are presented in (B) left and right mid-insula at the border of the superior temporal gyrus, (C) left middle frontal gyrus, and (D) right culmen.

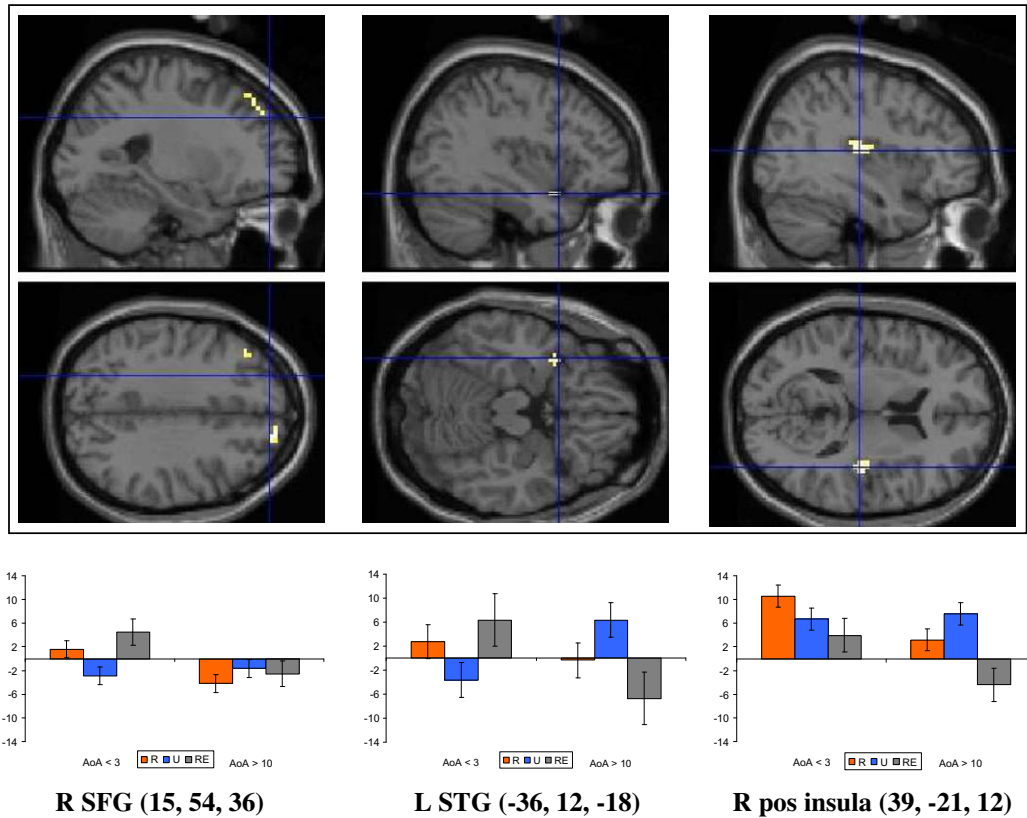
For example, in accordance with the current study, Klein et al. (2006) showed that a forward translation condition compared with a control condition caused an increase in fMRI signal mainly in the left inferior frontal (BA 44/6) and dorsolateral prefrontal cortices as well as in the STG bilaterally. However, Klein et al. (2006) failed to show a significant correlation between AoA of L2 and the size of the neural priming effect in the forward translation condition. However, the absence of correlation in this study could be due to the high heterogeneity of AoA of L2 (AoA range: 5.2–14). Similarly, increased activations were also found in the related conditions in L1 semantic/associative priming studies (Kotz et al., 2002; Raposo et al., 2006; Rossell, Bullmore, Williams, & David, 2001). Raposo et al. (2006) referred to this increased neural activity as *semantic enhancement* (SE). In the present study, due to the semantic-conceptual relationship existing between the primes and the targets, an increased activation in the cross-linguistic related condition (e.g., valise<sup>suitcase</sup>–Koffer<sup>suitcase</sup>) in comparison with the cross-linguistic unrelated condition (e.g., témoin<sup>witness</sup>–Koffer<sup>suitcase</sup>) was

also expected in multiple fronto-temporal regions of the left hemisphere. Our fMRI data confirm this prediction.

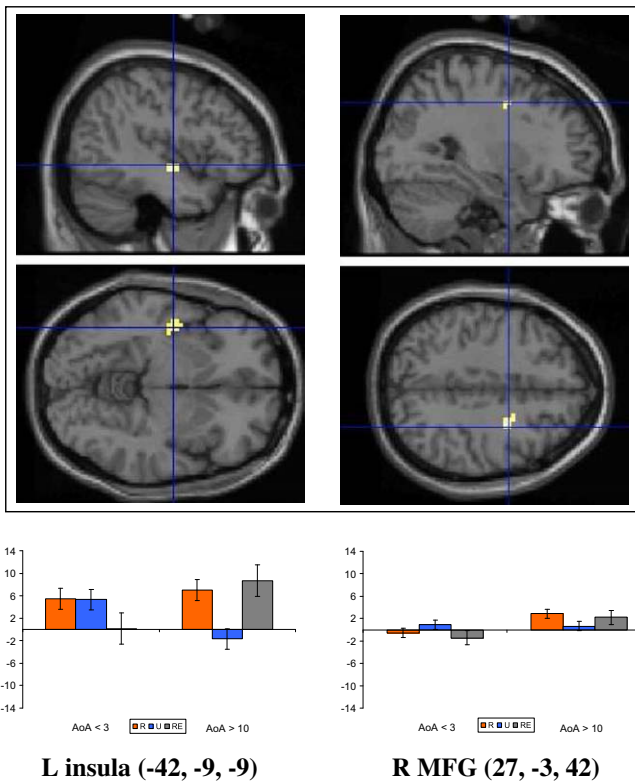
An Accumulation model (James & Gauthier, 2005) postulating that stimulus repetition can lead to enhanced activation is suitable for accounting for the repetition enhancement effects reported in the present cross-language fMRI study. An Accumulation model would account for repetition enhancement (RE) with later peak times in the primed than in the unprimed condition. Later peak times mean that the regions of the brain involved in processing the stimulus needs more time to accumulate activity until a critical level is reached at which time the process is complete. However, once such an explanation has been formulated in terms of peak time shift, the question of why the processing of the target word in the primed condition needs more time to accumulate activity remains open. In order to account for the increased activation in the primed condition of the present fMRI study, we propose an interpretation in terms of qualitative change of processing. This interpretation is inspired by the works of Henson (2001) and Henson, Shallice, and Dolan (2000). These authors proposed, for the processing of famous versus nonfamous faces, that while suppression of neural activation occurs when the *same process* is performed on the repeated stimulus, enhancement of neural activation is observed when an *additional process* operates on the target. Nevertheless, the notion of process repetition versus process change was proposed by Henson and colleagues for specifying the conditions under which RS and RE will be observed in repetition priming. It is therefore unclear if this framework can be applied to semantic-conceptual cross-linguistic priming. In the current fMRI study, participants performed the same task on the target words in both the primed and the unprimed conditions. However, it is possible that when a word follows a semantic-conceptual related prime, the semantic-conceptual relationship between the two words modulates the processing of the target word, perhaps by prompting more fine grained analysis of its meaning/conceptual characteristics (larger deployment of attention on specific features of the target word). Consequently, according to an accumulation model, more time is needed to complete the recognition process. In the case of cross-linguistic related words, the concept associated with the two words is not exactly the same, although the two words belong to the same “conceptual basin”. One can speculate that a fine grained analysis would be engaged in order to process the features that differentiate the conceptual representation of the two words. This fine grained analysis would lead to an increase of processing of the target words.

### 5.3. L2 processing and insular cortex

Previous fMRI studies have linked the anterior part of the left insular cortex (AIC; BA 13) to subvocal rehearsal (Smith, Jonides, Marshuetz, & Koeppe, 1998; but see also Chee, Soon, Lee, & Pallier, 2004). Here we also found involvement of the left insula (BA 13) but in a more posterior part, i.e. the middle insular cortex (mid-insula). More precisely, a larger RE effect was observed for late than for early bilinguals in the mid-insula ( $x = -42, y = -9, z = -9$ ). Increased activity of the mid-insula has been associated with a range of different phenomena like awareness of body control during hand movement, mind-wandering (“stimulus-independent thought” or SIT; Mason et al., 2007), aphasia, amusia, etc. (see Craig (2009) for a review). Here to account for the increased activation observed in the mid-insula for late bilinguals, we can only speculate that the primed condition in late bilinguals might have led the brain to produce spontaneously more images, voices, thoughts, and feelings which constitute the “stimulus-independent thought” associated with a specific concept. This could be due to the fact that the conceptual representation associated with words of L2 in individuals having learnt L1 and L2 successively might activate



**Fig. 4.** Contrasts between RE obtained in the group of early bilinguals relative to the RE obtained in the group of late bilinguals (RE early bilinguals > RE late bilinguals). *R* refers to cross-linguistic related and *U* refers to cross-linguistic unrelated.

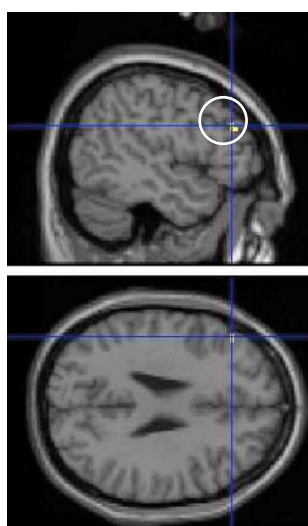
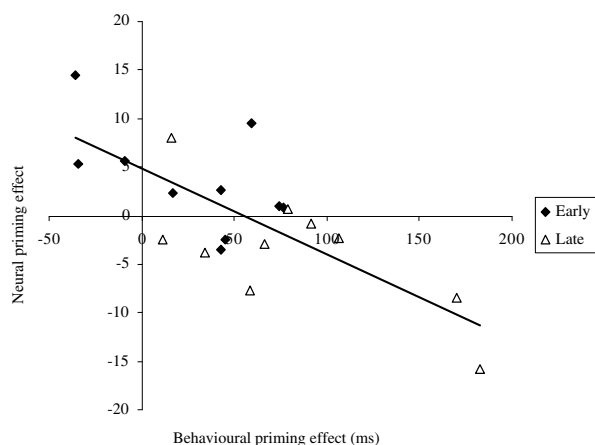


**Fig. 5.** Contrasts between RE obtained in the group of late bilinguals relative to the RE obtained in the group of early bilinguals (RE late bilinguals > RE early bilinguals). *R* refers to cross-linguistic related and *U* refers to cross-linguistic unrelated.

an additional set of semantic features as the one activated by the conceptual representation associated with the translation equivalents in L1.

#### 5.4. Selection of the relevant language in bilingualism context

In the present study, a larger RE in the left DLPC was observed in late bilinguals in comparison with early bilinguals. Previous fMRI studies of L2 processing have proposed that the dorsolateral prefrontal cortex (DLPC) in the left hemisphere might support the mechanism of language switching in bilinguals (Hernandez, Dapretto, Mazziotta, and Bookheimer (2001) and Hernandez, Martinez, and Kohnert (2000); see also Chee (2006) for a discussion on language switch). Along this line, it is possible to argue that the observation of a stronger involvement of prefrontal cortex for late bilinguals in our study might reflect higher between language switching costs. Furthermore, the significant correlation between the behavioural and the neural priming found in the DLPC (left middle frontal gyrus) indicates that this brain area does directly contribute to behavioural priming in bilinguals. The negative correlation suggests that the mechanism of language switching might be less engaged (reduced RE) when the conceptual representation for L1 and L2 words share a large set of features (larger behavioural priming effect). Of interest was the finding that the neural priming effects in the DLPC were observed in two opposed direction for the late bilinguals (RE (-36, 15, 42); RS (-36, 33, 45)): In order to account for this, we speculate that each direction of priming might reflect the involvement of two different subprocesses of language switching: one subprocess in charge of inhibiting the inappropriate language, the other one in charge of activating the appropriate language. Together, the present results are consistent with the view that switching between languages involves aspects of central



**Left middle frontal gyrus**  
(-48, 33, 27)

**Fig. 6.** Plot of the behavioural ( $x$ -axis) and the neural ( $y$ -axis) priming effects for each of the 10 early bilinguals (solid diamond) and each of the 10 late bilinguals (open triangle) as well as the brain region showing a significant negative correlation between the behavioural and the neural priming.

executive functions. Additional work is needed to examine whether prefrontal cortex interacts with the left caudate assumed to be also involved during language control (Crinion et al., 2006).

## 6. Conclusion

The findings of the present study lend support to psycholinguistic models of bilingual word recognition, postulating that L1 and L2 share a common space of conceptual representations for early and for late bilinguals. Of interest is the observation at the neural level that age of acquisition of L2 has a determining effect on the semantic-conceptual representation of words in L1 and L2. This suggests that the attainment of lexical knowledge in L2 is possibly affected by neural maturation. Further fMRI studies may disentangle the effects of AoA, levels of L2 exposure, L2 proficiency, and language family on cortical representation of L2. Nevertheless, the present data shed a new light on the theoretical debate about the relation between human language faculty and neural maturation. Taken together, our findings lend support to theories of neurolinguistic development postulating that the organisation and use of the mental lexicon must also occur during an *optimum biological moment*.

## Acknowledgments

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