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[suitcase]–Koffer[suitcase]). 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 neurolinguistic 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 acquisiton (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 repetiton 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 (exposition 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., dusche-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[suitcase]–Koffer[suitcase]). The difference in BOLD signal elicited by cross-linguistic related pairs consisting of a French concrete noun (e.g., valise[suitcase]) and its German translation equivalent (e.g., Koffer[suitcase]) and cross-linguistic unrelated French–German word pairs in which none of the words shared identical meanings (e.g., témoin[witness]–Koffer[suitcase]) 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 Studnitz (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-