FACULTY OF PSYCHOLOGY
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The representation of language in bilinguals: Neural overlap as a function of modality, representational level, language proficiency and context

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CHAPTER 1
INTRODUCTION

NEURAL REPRESENTATION OF L1 AND L2 IN DIFFERENT LANGUAGE MODALITIES AND REPRESENTATIONAL LEVELS

Investigating how language is represented in the brain is an interesting way to get a better understanding of how meaning is created in the human mind. In the literature about language organization, three different language representational levels can be distinguished. The first level is the semantic representational level, which refers to the meaning of words. The second level is the orthographic lexical representational level, which refers to the mental lexicon that can be compared with a dictionary that includes the different word forms. Different word forms across languages (e.g.: the French word form 'fleur' and the Dutch translation word form 'bloem', flower in English) can refer both to the same meaning. The third level is the phonological lexical representational level, which refers to the sound associated with the word forms. In addition to the language representational levels another distinction can be made between four language modalities, reading (visual comprehension), listening (auditory comprehension), speaking (auditory production) and writing (visual production).

Given the high prevalence of people who speak more than one language in the world, it is not only important to investigate the language organization of a first language (L1), but also how multiple languages are organized. In the present dissertation, 'bilinguals are defined as people who need and use two or more languages in their everyday lives without necessarily being equally proficient in both languages' (Grosjean, 1992).

This definition captures a broad range of bilingual profiles, from simultaneous bilinguals who acquired both languages at the same time, to sequential bilinguals who first acquired one language and later on the second language. Secondly, not only the age of acquisition (AOA) can be different, also the proficiency level can be diverse, from balanced bilinguals with an equal proficiency in both languages, to unbalanced bilinguals with different proficiency levels in the different languages. Thirdly, also switching experience can be variable, from bilinguals who seldom switch between both languages, to bilinguals who switch frequently between both languages. An important question in the bilingual literature has been whether the languages in bilinguals are integrated in one system or rather rely on separate cognitive/neural representations for each language (Indefrey, 2006; Stowe & Sabourin, 2005; Perani & Abutalebi, 2005). Previous research however often tackled this question without a clear distinction between the different bilingual profiles (e.g.: different age of acquisition (AOA), proficiency levels and switching experience), language modalities (production and comprehension) and language-representational levels (semantic representations or lexical representations), resulting in a lot of contradictions. In the next paragraphs, we will discuss the findings about overlap across languages at the semantic representational level and the lexical representational level within the behavioural research, the three most influential models of bilingual language organization and the neuroimaging research.

Behavioural findings

Lexical representations of L1 and L2 in bilinguals

Behavioural findings demonstrating that the processing of words in one language is influenced by orthographic or phonological similar words in another language support the idea that lexical access is not language specific and raises doubts about the intuitive idea that L1 and L2 are stored in separate lexical stores. To dissociate language selective lexical access or non-selective lexical access previous research often used homographs / homophones (words that share orthography / phonology, but not meaning across languages) or cognates (words that share orthography and meaning across languages). For example, the homograph ‘mug’ has the same orthography in English and Dutch, but a different meaning in English (cup) and Dutch (mosquito), whereas the cognate ‘tent’ has the same orthography, phonology and meaning in both English and Dutch (a collapsible shelter used for camping). Hence, if lexical access is not language specific, we can expect facilitation for cognates in comparison to non-cognates, because cognates are more strongly activated through activation from both cognate names. Comparably, if lexical access is not language specific, interference can be expected for inter-lingual homographs or homophones because the automatically activated representations in the two languages might compete for recognition.

To investigate access to orthographic lexical representations, lexical decision tasks are often used in which participants had to decide whether the written word was an existing word or not. Dijkstra, Timmermans and

Schriefers (2000) for example showed that reaction times were slower and error rates were higher for inter-lingual homographs than for control words that only existed in one language. Access to phonological lexical representations is investigated with a similar approach. Within an auditory lexical decision task, Lagrou, Hartsuiker, and Duyck (2011) for example showed that reaction times were again slower for inter-lingual homophones (e.g. ‘cow’ in English has the same pronunciation as the Dutch word ‘kou’, but a different meaning: cow = animal, kou = cold) than for control words that only existed in one language. Additionally, Bultena, Dijkstra, and van Hell (2013) found that participants responded faster to cognates that had the same meaning and pronunciation (e.g., ‘tent’ in both English and Dutch) compared to control words in a lexical decision task. These findings indicate that lexical representations of the irrelevant language are accessed or co-activated during word recognition in the relevant languages.

Comparable results on the parallel activation of both languages were additionally observed for word production. In a picture naming task, Catalan-Spanish bilinguals displayed longer naming latencies for non-cognate targets than cognate targets in L1 and L2 (Costa, Caramazza, & Sebastián-Gallés, 2000). Similarly, In the study of Colomé and Miozzo (2010) Spanish-Catalan bilinguals saw two colored pictures and had to name the green picture in Spanish (ex: hoja, meaning leaf) and ignore the red picture, which was either a cognate across Spanish (taza) and Catalan (tassa), meaning cup or a non-cognate across Spanish (red) and Catalan (xarxa), meaning net. They observed that distractor pictures with cognate names across Spanish and Catalan interfered more with the Spanish naming of the target picture in comparison to distractor pictures with non-cognate names.

To conclude, the outcome of these behavioral studies are firmly in favor of the language non-selective lexical access hypothesis, which states that bilinguals always activate both of their languages when accessing lexical representations.

Semantic Representations of L1 and L2 in bilinguals

Most behavioural research has provided evidence for the integration of L1 and L2 conceptual representations in a common semantic system. In semantic categorization tasks where participants had to decide whether the second word was a member or a non-member of the category indicated by the first word, response times were equivalent whether word pairs were from different languages or not (Caramazza & Brones, 1980; Dufour & Kroll, 1995; Francis, 1999). In addition, the majority of the primed lexical decision tasks has shown facilitation of target words preceded by semantically related primes in a different language (Francis, 1999; Grainger, 1998). For example, responses to the word ‘girl’ were not only faster after the prime ‘boy’ but also after the Dutch translation equivalent: ‘jongen’ (Schoonbaert, Duyck, Brysbaert, & Hartsuiker, 2009). These cross-language priming effects were often stronger from L1 to L2 than from L2 to L1 (Keatley, Spinks, & de Gelder, 1994; Schoonbaert et al., 2009) and for concrete than abstract wordpairs (Jin, 1990), which suggests that the difference between L1 and L2 representations is of a quantitative nature, rather than a qualitative nature, in accordance with the distributed feature model. Additionally, Van Hell & De Groot (1998) used a word association task in which Dutch-English bilinguals saw a Dutch or an English word on the screen and were asked to give as quickly as possible a semantic related word, either in the same language (in the within language condition) or in the other language (in the other language condition). They found that retrieving an associate word (both in the same language as in the other language) was easier for concrete than abstract words, for cognates than non-cognates and for nouns than verbs. Therefore they argued that the amount of shared features is smaller for abstract translations, non-cognates and verb translations in contrast to concrete translations, cognates and noun translations. Note however that Francis and Goldmann (2011) reported somewhat different findings, with similar and symmetric cross-language priming effects for abstract and concrete words, indicating a complete overlap in semantic representations across languages, independent of the level of concreteness.

Still some behavioural studies provided evidence for distinct semantic representations across languages. De Groot and Nas (1991) for example failed to find significant semantic cross-language priming effects and other bilingual studies showed that semantic representations are more strongly connected to one language than to the other language. Jared, Pei Yun Poh and Paivio (2013), for instance, showed that culturally-biased images were named significantly faster in the culturally-congruent language than in the culturally-incongruent language. Furthermore, language-dependent memory effects were found, when Mandarin-English bilinguals were asked questions as: “name a statue of someone standing with a raised arm while looking into the distance”. They were more likely to answer the Statue of Liberty if the question was asked in English and the Statue of Mao if the question was asked in Mandarin (Marian & Kaushanskaya, 2007).

Models

The observation that most behavioural studies are in favor of at least partially overlapping semantic representations across languages led to the development of psycholinguistic models of bilingual language representation and processing, that assume partially or complete overlapping semantic representations across languages. However, in the three most influential behavioral models of bilingual language organization, different predictions are made about the way lexical representations are represented across languages. The revised hierarchical model (Kroll & Stewart, 1994) and the distributed feature model (Van Hell & de Groot, 1998) were used as general models of language organization without making explicit distinctions between the different modalities, whereas the BIA+ model (Dijkstra & Van Heuven, 2002) was specifically designed to model visual word recognition, hence reading (Brysbaert, Verreyt, & Duyck, 2010). Despite the huge contribution of these models to the understanding of bilingual organization, predictions about how the different modalities might influence bilingual language organization could be more elaborated. Hence, to investigate this in more detail, **CHAPTER 3** compared the neural overlap of L1 and L2 semantic representations in both production and comprehension within the same individuals.

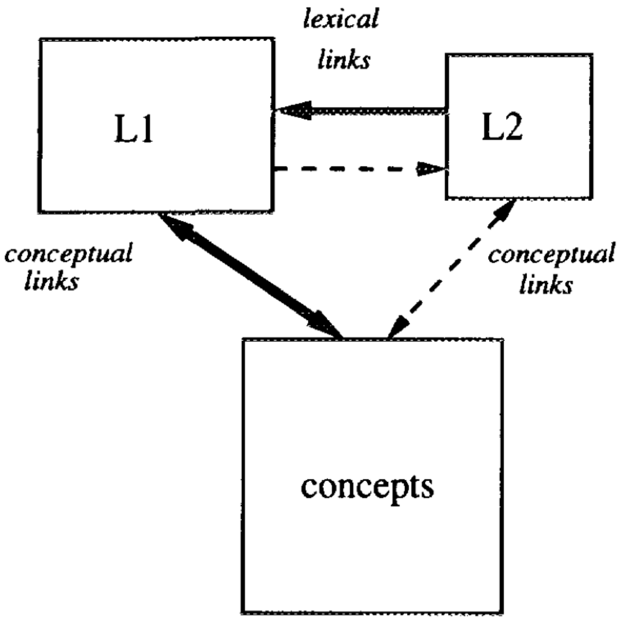

Figure 1. *The revised hierarchical model (Kroll & Stewart, 1994)*

The revised hierarchical model (Kroll & Stewart, 1994, figure 1), with its focus on asymmetric lexico-semantic links, assumes different lexical representations for each language and common semantic representations. This model was mainly used to explain how lexical and semantic representations interact during forward translation (when words are translated from L1 to L2) and backward translation (when words are translated from L2 to L1). This model assumes stronger connections between L1 lexical word forms and the semantic representations than between L2 lexical words forms and the semantic representations. During language acquisition L2 word forms are often learned by associating them with the L1 word forms. As a consequence this model also assumes that the connections are stronger from the L2 word forms to the L1 word forms than the other way around. Therefore it is more likely that forward translation engages semantic representations than backward translation. However, in highly proficient L2 bilinguals are the connections between the L2 word forms and the semantic representations expected to strengthen with increasing L2 proficiency. Therefore it can be expected that with increasing L2 proficiency, backward translation will also start to rely more directly on the semantic system.

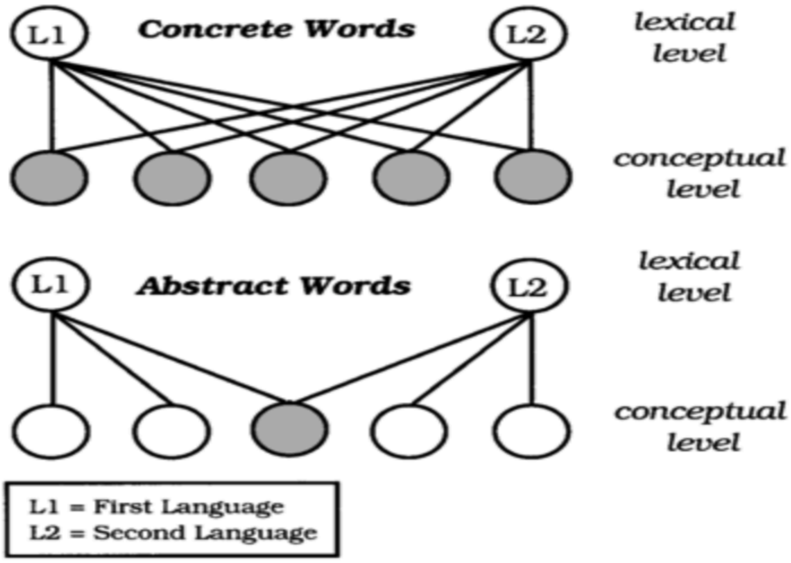

Figure 2. *The distributed feature model (Van Hell & de Groot, 1998)*

The distributed feature model (Van Hell & de Groot, 1998; figure 2) proposes different lexical stores for each language, but assumes partially overlapping semantic representations across L1 and L2, depending on specific characteristics of the concepts and the individual and cultural context in which the concept is learned and processed in both languages. Only the distributed feature model has focused in somewhat more detail on the organization of semantic representations (we investigated this in **CHAPTER 2** and **CHAPTER 3**) and the factors that may influence it, such as concept/word concreteness. More specifically, Van Hell and De Groot (1998) argued that conceptual representations in bilingual memory depend on word-type and grammatical class. They found that the overlap in meaning, indexed by the number of shared semantic features, is larger for concrete translations, cognates and noun translations, relative to abstract translations, non-cognates and verb translations. Abstract concepts (e.g. love) might for example be used in more different contexts across languages than concrete words (e.g. chair). Therefore they claim that abstract words are more likely to have less overlap across languages in semantic features than concrete words.

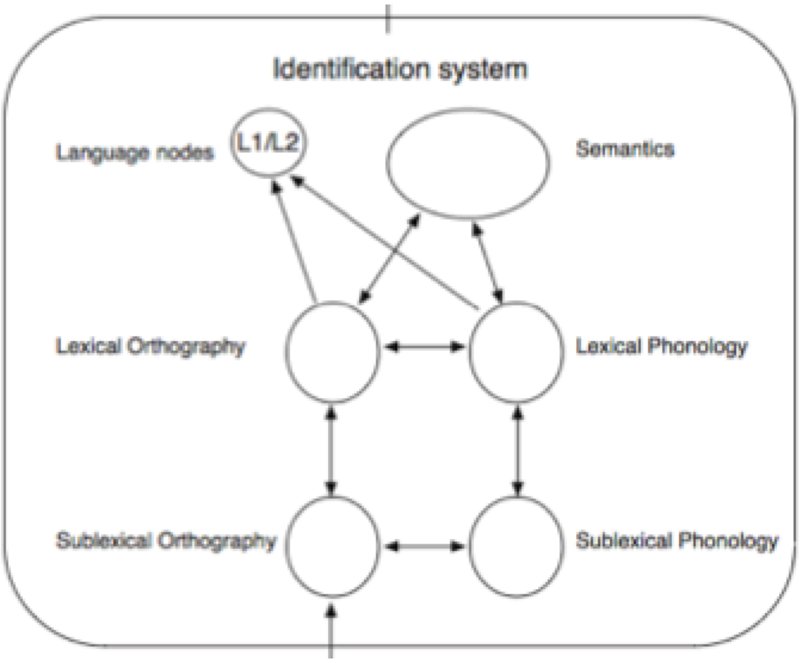

Figure 3. *The BIA+ model for bilingual word recognition (Dijkstra & Van Heuven, 2002)*

Additionally, the Bilingual Interactive Activation model (BIA+ model; Dijkstra & Van Heuven, 2002; figure 3) has focused in more detail on orthographic lexical representations for bilingual word recognition (we investigated the lexical representations in **CHAPTER 4**). This model assumes common semantic representations, but questions the idea that L1 and L2 word forms are stored in different lexicons for each language. They postulated the integrated nonselective access view, in which word candidates of both languages are activated in parallel and are stored in an integrated lexicon. In this model a written word activates its sublexical and lexical orthographic and phonologic representations. These, in turn, activate the semantic representation and language nodes that indicate membership to a particular language and can inhibit activation of word candidates from other languages.

Although behavioural studies can provide interesting insights in the semantic and lexical representation of L1 and L2, another question is whether functional representations, either overlapping across languages or not, are also reflected by neural overlap between representations of both languages of bilinguals. To answer this question, the neural overlap of semantic representations across languages is investigated in **CHAPTER 2** and **CHAPTER 3**. In addition **CHAPTER 4** tackles both the neural overlap of semantic and lexical representations across languages.

Neural univariate findings

Functional magnetic resonance imaging (fMRI) is a non-invasive method with a high spatial, but a low temporal resolution. fMRI maps neural activity associated with a variety of brain functions based on blood-oxygen-level-dependent (BOLD) contrasts. In the Classical univariate approach all voxels (three-dimensional rectangular cuboid measured in millimeters) within a certain region are treated as similar and the average activation over this set of voxels is used as an indication of whether or not the region is involved in a certain task or experimental condition (Mahmoudi, Takerkart, Regragui, Boussaoud, & Brovelli, 2012).

In the neuroimaging literature, the question about overlapping representations across languages has been operationalized as the hypothesis that both languages are represented by common rather than distinct cortical language areas. However, to date, these neuroimaging studies also provided divergent results as a consequence of methodological heterogeneity and the use of different language modalities (comprehension vs. production), language representation levels (lexical vs. semantic representations) and bilingual profiles (age of acquisition, proficiency, exposure), despite the obvious consequences of such factors for neural activation.

Semantic Representations of L1 and L2 in bilinguals

Both the reviews of Indefrey (2006) and Stowe & Sabourin (2005), who investigated the neural overlap across L1 and L2 in a range of tasks, concluded that the majority of studies reported no differences in semantic activation between L1 and L2 in word production (Hernandez, Dapretto, Mazziotta, & Bookheimer, 2001; Hernandez, Martinez, & Kohnert, 2000; Klein, Milner, Zatorre, Meyer, & Evans, 1995; Pu et al., 2001; Rodriguez-Fornells et al., 2005) and L1 and L2 semantic activation in word comprehension (Ding et al., 2003; Illes et al., 1999; Pillai et al., 2004). Although they also found that some studies showed stronger activation for L2 processing in regions that are also involved in L1 processing, this was only for some subgroups of L2 speakers and this influence of bilingual profile on the neural representation of a bilingual semantic system seems to depend on the specific language modality at hand (production, comprehension). More specifically, they concluded that L2 Age of acquisition (AOA), proficiency and exposure influence the neural overlap of L1 and L2 semantic representations during word level production, whereas the neural overlap of L1 and L2 semantic representations during word level comprehension is mostly influenced by proficiency. For word production, De Bleser et al. (2003), Perani et al. (2003) and Vingerhoets et al. (2003) reported stronger activation during L2 picture naming compared to L1 picture naming in the posterior inferior frontal gyrus, for late bilinguals. For word level comprehension by low-proficient bilinguals, stronger activation was reported during semantic decisions in L2 compared to L1 in the left posterior inferior parietal lobe and the left anterior cingulate gyrus (Xue, Dong, Jin, & Chen, 2004). The same conclusion was drawn in the study of Chee, Hon, Lee, & Soon (2001), although with additional involvement of the left posterior middle frontal gyrus and the left posterior inferior frontal gyrus for the low proficient bilinguals. This complexity makes it hard to generalize findings about the effects of language use parameters (AOA, proficiency, exposure) on the neural representations of L1 and L2 based on a single study.

Additionally, previous studies often focused on the representation of language in general and did not make an explicit distinction between the semantic representational level (meaning) and the lexical representational level (representation of orthography/phonology). It is obvious however that the results found at one representational level cannot necessarily be generalized to the other representational levels. It could be for example that L1 and L2 recruit different brain regions at the lexical representational level, but overlapping brain regions at the semantic representational level, or vice versa. Within the classical neuro-imaging studies that used contrast designs many studies used however tasks in the experimental (semantic) condition that differed on phonological or orthographic processing demands and task difficulty, in addition to the targeted semantic processing demands (Binder, Desai, Graves, & Conant, 2009). For example, a semantic task like animacy judgment (e.g. horse: ‘is it living or nonliving’?) also relies on additional phonological and orthographic processes when comparing it with a control task that for instance involves nonword stimuli (e.g. nbgsj, nbqsj: ‘are they identical’?). Then, the comparison between L1 and L2 across such tasks may reveal the targeted cross-lingual semantic overlap, but also the overlap in the peripheral untargeted processing that may result from phonology, orthography, or even mere task difficulty, because the semantic tasks are often also more difficult than the control tasks that they are compared with (Binder et al., 2009). To really disentangle these levels it is important that the experimental condition only represents one level and doesn’t reflect both semantics and orthography or phonology in comparison to the control condition. As such, the question about neural overlap of semantic representations across languages also needs to be assessed using other approaches.

In addition to this classical univariate approach, the univariate adaptation paradigm has been proposed as a useful tool to study the neural convergence between L1 and L2 representations in bilinguals (Chee, 2009). Adaptation refers to the phenomenon where the successive presentation of two identical stimuli elicits a smaller neural response than the successive presentation of two dissimilar stimuli. Neural overlap between the L1 and L2 semantic systems has been demonstrated with this approach. In the study of Crinion (2006) a semantic priming design was combined with the neural adaptation approach. In this word reading task, participants saw sequentially presented word pairs and had to ignore the first prime word and had to make a semantic decision based on the meaning of the second target word (ex: Is the target word multi-coloured or plain?). To avoid confounds from orthographic and phonological priming, the prime and the target were always orthographically and phonologically dissimilar. They found that neural adaptation was equivalent when prime and target were represented in different languages (e.g. forelle (fish) - salmon (fish) < löffel (cutelery) - salmon (fish)) as when prime and target are represented in the same language (e.g. trout (fish) - salmon (fish) < spoon (cutlery) - salmon (fish)). More specifically, reduced neural activation in the left anterior temporal lobe was observed when two successive presented words had a related meaning (fish-fish) compared to different meanings (cutlery-fish) and this was both the case when prime and stimulus were in the same language as in different languages. In contrast, in the left caudate reduced neural activation for semantic related word pairs in comparison to semantic unrelated word pairs was only observed when prime and target were in the same language and not in different languages. These results were obtained for both German-English bilinguals as Japanese-English bilinguals and provide evidence for the existence of both overlapping semantic representation across languages as language dependent semantic representations. Within a comparable word reading adaptation approach, Chee, Soon, & Lee (2003) reached a similar conclusion for Chinese - English bilinguals and argued that Chinese and English semantic systems have shared components, but also components that may be language-specific. Note however that adaptation results are difficult to interpret given their largely unknown neurophysiological underpinnings and its susceptibility to experimental demands, attentional confounds and novelty or mismatch effects especially for exact stimulus repetitions (e.g.

Jimura & Poldrack, 2012; Epstein & Morgan, 2012). Compared to the univariate activation or adaptation approaches, decoding has been suggested to provide more direct measures of representations (Davis & Poldrack, 2013). Therefore, in **CHAPTER 2**, **3** and **4** we applied decoding to get a more fine-grained look at the neural overlap across languages of semantic and lexical representations.

Semantic representations across modalities

Most univariate fMRI studies on the representation of semantics have investigated word listening, word reading and production separately. Given that the different tasks and modalities, and the underlying cognitive processes, might recruit distinct neural structures, this paradigmatic diversity may therefore confound conclusions about the core issue of the assumed neural representation of semantics. Binder et al. (2009) therefore reviewed 120 classical functional neuroimaging studies, rigorously selected on well-defined task contrasts focusing on the neural representation of the semantic system in word reading and word listening in the first language (L1), without additional phonological or orthographic confounds. They concluded that semantic processing occurred in a distributed network including prefrontal, parietal and temporal areas. They highlighted the role of these regions in the representation of amodal conceptual knowledge where information from different modalities is integrated. Binder et al. (2009) did however only focus on word listening and word reading and excluded all the studies that tapped into production. Complementary, a second meta-analysis from Price (2012) included all three modalities (word reading, word listening and production) and provided an anatomical model that indicates the location of the language areas and the most consistent functions that have been assigned to them. More specifically, she found that the left inferior temporal gyrus, the left middle temporal gyrus, the left superior temporal sulcus, the left ventral occipital lobe, the left superior frontal gyrus, the left inferior frontal lobe and the left and right angular gyrus are activated when neurologically normal participants had to rely on semantics during production, word reading and word listening.

However, brain areas that are commonly activated in semantic tasks in different language modalities do not necessarily represent amodal conceptual information. In the univariate fMRI approach, activation in a common brain area in different modalities does not necessarily imply that the semantic representations overlap across the different modalities. More specifically, activation in common brain areas can both reflect different semantic representations for the different modalities or overlapping semantic representations across modalities within the same brain areas reflecting amodal representations. However, within this classical fMRI approach a distinction between these two possibilities can’t be made. Hence, in **CHAPTER 3**, we used decoding to investigate the neural overlap between Dutch and French semantic representations, within and across auditory and visual language modalities, within the same participants. This approach does not only allow finding support for integration or separation of L1 and L2 representations. It also allows a cross-validation across different language modalities, contrasting language production with comprehension.

Lexical Representations of L1 and L2 in bilinguals

Only a few neuroimaging studies investigated the specific issue of integrated lexical representations across languages with language-nonselective lexical access versus distinct lexical representations across languages with language-selective lexical access. For example, the neuroimaging study of Van Heuven, Schriefers, Dijkstra, & Hagoort (2008) investigated inter-lingual homograph word recognition in English-Dutch bilinguals with a lexical decision task. In this task they had to decide whether a string was a correct English word or not. The inter-lingual homographs that existed in both languages with a common orthography but a different meaning were than compared with English control words that only existed in English. They observed significant slower reaction times and greater activation in the LIPC and the medial part of the superior frontal gyrus for inter-lingual homographs relative to the English control words. These results showed that conflicts appeared in the LIPC and the superior frontal gyrus as a consequence of the automatic activation of both languages. These findings could therefore be interpreted as evidence for language non-selective lexical access for word recognition.

Additionally, for picture naming, similar cross language interference results have been obtained. Rodriguez-Fornells et al. (2005) used a phonological go/ no-go task and observed phonological interference from the irrelevant language during picture naming in the target language in German-Spanish bilinguals. In this task, the participants had to name the pictures when the stimulus name began with a vowel (go) in the target language and had to inhibit the response when the stimulus name began with a consonant (no-go) in the target language. They observed more errors, slower reaction times and more activation in the left middle frontal cortex when the first letter of the target language required a different response (go/no-go) than the irrelevant non-target language. These findings could therefore again be interpreted as evidence for language independent non-selective lexical access for speech production.

To conclude, the outcome of these neuro-imaging studies are in line with the behavioral results that also provided evidence in favor of language non-selective integrated lexical representations across languages in both production and comprehension. In contrast to the neuroimaging literature about semantic processing that investigated both semantic neural representations across languages as semantic neural representations across modalities, to our knowledge there are currently no neuroimaging studies that specifically investigated the neural overlap of lexical representations across modalities.

Neural multivariate findings

Within the univariate approaches, common activation between languages within an area can be caused by different neural representations within the same area representing the different languages or by the same neural population representing both languages. Only the latter observation is supportive of a real integrative view of L1 and L2 in bilinguals. Because the univariate fMRI approach is unable to separate these two possibilities, a shift towards a decoding approach is of added value (see figure 4 for an example). In a multivariate decoding approach it's only possible to predict or classify stimuli across different languages if overlapping neural populations are involved across languages. The implementation of multi-voxel pattern analysis (MVPA) is therefore useful to get a more fine-grained look at the overlap of lexical and semantic representations across languages and modalities. Compared to univariate activation or adaptation results, Multi-voxel pattern analysis (MVPA) has been suggested to provide more direct measures of representations, is sensitive to distributed neural representations and distinguishes patterns of neural activity associated with different stimuli (Davis and Poldrack, 2013; Epstein and Morgan, 2012; Haynes et al., 2007; Jimura and Poldrack, 2012; Norman, Polyn, Detre, & Haxby, 2006). Instead of looking at the overall activation of a region as is typically the case in the univariate approach, MVPA uses a regions multivariate pattern information as reflection of the representational content.

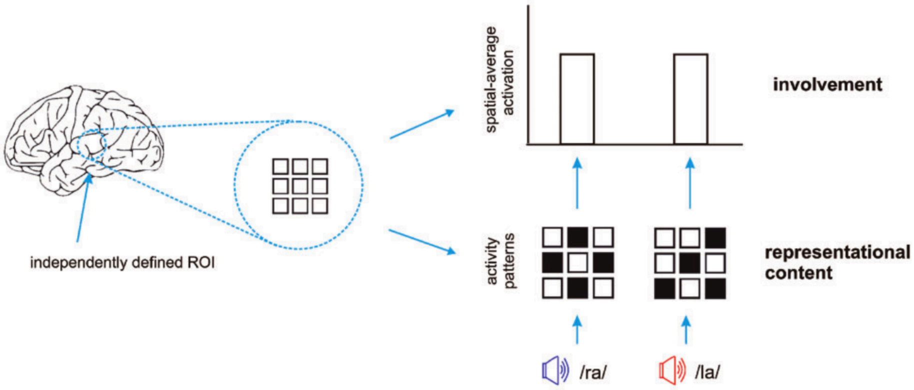

Figure 4. *This figure shows a hypothetical ROI consisting of nine voxels. With MVPA, the difference between the two experimental condition (/ra/ vs. /la/ speech sounds) can be distinguished, because the multivoxel pattern of activity is different for /ra/ than /la/ speech sounds. In the classical univariate approach this difference might however go undetected, because the different patterns can result in the same average activation (Mur, Bandettini, & Kriegeskorte, 2009).*

Semantic representations across languages

The logic of using an MVPA approach to investigate whether L1 and L2 semantic representations are overlapping in the brain is that tasks are used in which the L1 vs. L2 response tap into very different orthographic, phonological, and sensory representations, but common semantic representations (translation equivalents). As a consequence, the classifier will only be able to predict the concept in one language based on the brain responses for the (translation) equivalent concept word in the other language if these two concepts in the different languages elicit similar semantic neural representations. If this is the case, this serves as direct evidence for the neural overlap of semantic representations in L1 and L2, supporting an integrative view of L1 and L2 semantic representations in bilinguals. In the literature, there are currently only 2 studies that used MVPA to investigate neural overlap of semantic representations in bilingual language processing and both are situated in the language comprehension domain. Buchweitz et al. (2012) focused on semantic representations in word reading (visual comprehension) and Correia et al. (2014) focused on semantic representations in word listening (auditory comprehension). Both studies showed that significant encoding of semantic information was possible across languages. These findings provide evidence for overlapping neural populations in L1 and L2 semantic processing. However, the brain regions in which significant encoding of semantic information were observed did differ in the different modalities that were used in the different studies. In visual comprehension, eleven proficient Portuguese-English late bilinguals were asked to silently read concrete nouns from two semantic categories (tools and dwellings). It was possible to identify the word seen in one language based on the brain activity while reading the word in the other language in the left inferior frontal gyrus, the left posterior superior temporal lobe, the postcentral gyrus and the left inferior parietal sulcus (Buchweitz et al., 2012). In auditory comprehension, ten proficient late Dutch-English bilinguals had to listen to concrete animal nouns and non-animal nouns in both languages and pressed a button whenever they heard a non-animal word. It was possible to identify the word heard in one language based on the brain activity while listening to the word in the other language in the left anterior temporal lobe, the left angular gyrus and the posterior bank of the left postcentral gyrus, the right posterior superior temporal gyrus, the right medial anterior temporal lobe, the right anterior insula and bilateral occipital cortex (Correia et al., 2014).

Until now, decoding was only applied in comprehension to investigate neural overlap across language. Therefore, in **CHAPTER 2** we used decoding to investigate the neural overlap across languages of semantic representations used for language production in bilinguals.

Semantic representations across modalities

To our knowledge, only Fairhall and Caramazza (2013) and Simanova, Hagoort, Oostenveld and Van Gerven (2014) investigated semantic overlap across different language modalities through MVPA. This was however limited to L1 language processing. Hence, in **CHAPTER 3**, we investigated the semantic neural overlap in different modalities across both L1 and L2 semantic processing.

In the study of Simanova et al. (2014) the participants had to judge the semantic category of target words in word reading and listening. Afterwards, as a language production task, there was a free recall session of the stimuli used in the categorization task. In this study, Simanova et al. (2014) found evidence for the involvement of the left inferior temporal cortex and frontal regions in the amodal representation of semantics. In the study of Fairhall and Caramazza (2013), participants saw words and pictures from five semantic categories and they needed to judge how typical each item was for the representation of its semantic category. They argued that the precuneus (PC) and the posterior middle/inferior temporal gyrus (pMTG/ITG) are crucial amodal semantic hubs. Both studies supported the idea of amodal representations of conceptual properties of objects, although they didn't completely converge on the specific neural localization, which may of course also be domain- and stimulus-dependent.

Lexical representations across languages

Within this decoding approach no studies investigated lexical overlap across languages (whether word forms of both languages are activated in parallel and are stored in an integrated lexicon). Hence, in **CHAPTER 4**, we applied decoding to investigate both the neural overlap across L1 and L2 semantic representations and the neural overlap across L1 and L2 lexical representations using a production task.

Conclusion

The shortcomings in previous behavioural and neural research highlight the importance to apply a decoding approach to investigate the neural overlap of both L1 and L2 semantic and lexical representations in different modalities within the same participants, to see to what extent semantic representations and lexical representations are shared across languages and whether this neural overlap depends on the language modality at hand.

NEURAL REPRESENTATION OF LANGUAGE CONTROL

A second part of the debate that closely relates to the neural representation of the bilingual language system is the issue of language control. If two languages are represented in overlapping brain areas that constantly interact functionally (Van Assche, Duyck, Hartsuiker, & Diependaele, 2009; Van Hell & Dijkstra, 2002) and neurally (Van Heuven et al., 2008) and we still want to use one language, than we can assume that a language control mechanism is needed to minimize cross language speech errors (van Heuven & Dijkstra, 2010). In the Inhibitory Control (IC) model set forth by Green (1998) such a language control mechanism was proposed. This model assumes that language selection in bilinguals takes place through activating representations from the current relevant language, while inhibiting those of the irrelevant language. This assumption of inhibition is however more relevant for language production than for language comprehension. For language production, at some point a speaker need to select a language for speech, as multiple responses (languages) are available. This requires inhibition of the non-target language word associated with the depicted semantic concept. However, for word recognition, this mechanism of inhibition does not necessarily need to occur. For word recognition, bilinguals may just rely on bottom-up activation from the stimulus, experience any cross-lingual competition, and proceed to lexical access without inhibition of any language. This is indeed why models of word recognition, like the BIA+ model do not have top-down language inhibition (Dijkstra & Van Heuven, 2002).

The proposed control mechanism in the Inhibitory Control (IC) model is thought to be domain-general and not language specific, because the continuous juggling between two or more languages is assumed to be driven by a shared underlying executive control system that could also manage other types of non-verbal cognitive control. Therefore, it is expected that the constant competition for selection that takes place between language does not only lead to enhanced language control, but also to enhanced domain general cognitive control (Bialystok, 2009). Likewise, in the neuroimaging literature language switching is also proposed as one of the possible moderators that can shape the brain regions on which domain general cognitive control relies (De Baene, Duyck, Brass, & Carreiras, 2015). Therefore, a systematic assessment of the neural representation of bilingualism, as the current dissertation aspires, also implies an assessment of the neural representation of language control (**CHAPTER 5**), in addition to the representation of lexical and semantic information (Chapter 2, 3 and 4).

In **CHAPTER 5**, we engage in a line of research that taps into this issue by looking at situations in which extreme language control is needed, i.e. the cases of professional multi-linguals who master a different degree of language control such as simultaneous interpreters (SIs), consecutive interpreters (CIs) and translators (TRs) (Christoffels and de Groot, 2009). Translators have to render a written source text into a written target text, whereas SIs and CIs have to verbally reformulate a spoken message from the source languages into the target language, although the timing of this process is different between CIs and SIs. CIs are trained to first listen to the source text and only afterwards, with the aid of notes, make a full rendition.

Whereas, SIs have to perform this process in real-time, i.e. immediately after or simultaneous with reception of the source text. Through all these simultaneous processes it is obvious that SI's manage greater levels of language control in comparison to the CIs and the translators, which in turn may lead to greater cognitive gains and changes in underlying neural networks (Babcock & Vallesi, 2017).

Behavioural findings

At the behavioural level only some studies have investigated the cognitive benefits of SI experience. Christoffels, de Groot, and Kroll (2006), Köpke and Nespoulous (2006) and Padilla, Bajo, and Macizo (2005) investigated the influence of SI training on working memory and showed superior working memory for interpreters compared to other bilinguals. Similarly, SI advantages are shown for cognitive flexibility. In the study by Yudes et al. (2011), SIs outperformed both monolinguals and other bilinguals on the Wisconsin Card Sorting Test (WCST). Additionally, Both Becker, Schubert, Strobach, Gallinat, and Kühn (2016) and Babcock and Vallesi (2017) employed a color-shape task switching paradigm and compared professional SIs to other multilinguals. Within this design a better performance was observed for the SI's compared to the other multilinguals (even the CIs) on the mix cost, although no differences were reported for the switch cost. The mix cost, defined as a measure of sustained control, is measured by subtraction of the performance on all trials in a blocked condition where there is no possibility of a task switch with the performance on repeat trials in a switch condition, where there is the possibility of a task switch but it did not occur. The switch cost was measured by subtraction of the performance on repeat and switch trials in a switch condition and is defined as an index of transient control. Hence, it seems that SIs have obtained a higher level of sustained control, which comprises keeping multiple task sets activated and engaging attentional monitoring processes to increase sensitivity to cues that signal task changes (Funes, Lupiáñez, & Humphreys, 2010). Whereas no SI advantage was observer for transient control which entails internal reconfiguration or updating of goals and linking task cues to their appropriate stimulus-response mappings. Despite the reported SI advantages on measures of working memory and cognitive flexibility, less consistent findings are reported for the SI advantage on measures of inhibitory control. Woumans, Ceuleers, Van der Linden, Szmalec, & Duyck (2015) found that SIs outperformed unbalanced bilinguals, but not balanced bilinguals on the overall accuracy on two task that are suggested to require inhibition of irrelevant information: the Attention Network Test (ANT) and the Simon task. Additionally, Dong and Zhong (2017) compared students with more or less interpreting experience on the Flanker task. They revealed smaller interference effects on the RTs for the group who received more interpreting experience, indicating that SI experience may enhance interference inhibition. In contrast others have failed to find any SI advantage on inhibitory control (Babcock & Vallesi, 2017; Dong & Xie, 2014; Morales, Padilla, Gómez-Ariza, & Bajo, 2015; Yudes, Macizo, & Bajo, 2011).

One issue however with these SI studies is that most of them necessarily compare cognitive functioning between groups, that differ in SI experience, but that may also differ on other untargeted variables. To answer the question of causality and ensure that SIs are not predisposed to cognitive superiority, only a few studies have employed longitudinal designs, within participants. For instance, Macnamara & Conway (2014) recruited a group of bimodal (signed Language – spoken language) interpreting students and examined the influence of interpreting training on the development of cognitive control with a longitudinal design. They demonstrated increased fluency in both mental flexibility and task switching over the course of their two-year training. There was, however, no control group. In contrast, Babcock, Capizzi, Arbula and Vallesi (2017) showed that when a matched control group of translators was added to the longitudinal design no cognitive control advantages were observed for the SIs compared to the translators over time. They did only find an SI training advantage in a verbal short memory task, whereas no effects of SI training were observed on the Attention Network Task (ANT) that taps into inhibition, and a switch task.

Neural findings

In the neuroimaging literature even less studies investigated the consequences of SI training on the development of domain general cognitive control and its neural substrate. Only Becker, Schubert, Strobach, Gallinat, and Kühn (2016) specifically investigated the SI advantage on cognitive control tasks within a univariate fMRI approach. They examined both functional and structural brain differences related to SI experience within a cross sectional design. Their results revealed that SI showed less mixing costs in a (non-linguistic) color-shape switch task, performed better in a (non-linguistic) dual task paradigm and showed more gray matter volume in the left frontal pole than translators.

Still, up until now, there were no studies investigating the influence of SI experience on cognitive control tasks using a well-controlled behavioural and neural longitudinal design that manipulated SI experience within subjects. Hence, in **CHAPTER 5**, we longitudinally compared SI training with translation training (two similar training programs that only differ on the amount of language control), in order to identify the cognitive and neural changes specifically related to SI.

OUTLINE OF THE PRESENT DISSERTATION

Studies on bilingualism have investigated language comprehension and production interchangeably, using a wide variety of experimental designs and tasks and different bilingual populations without explicitly acknowledging the consequence for neural involvement. Although this diversity may benefit the generalizability across studies, the different linguistic representational levels, cognitive processes and neural structures that the different tasks recruit may confound firm conclusions about neural overlap of language representations in bilinguals. To get a more coherent idea about the neural representation of a bilingual language system and to compensate for the lack of distinction between different language representational levels and language modalities in previous research, we investigated both semantic representations across languages within and across modalities, within the same participants as lexical and semantic representations across languages within the same participants. To provide evidence for a real integrative view of L1 and L2 in bilinguals we applied a multivariate decoding approach, because within this approach it's only possible to predict or classify stimuli across different languages if overlapping neural populations are involved across languages.

In the first two empirical chapters (**CHAPTER 2** and **CHAPTER 3**) we used decoding to investigate the semantic representations of translation equivalents across languages within and across different modalities. Until now, decoding was only applied in comprehension to investigate neural overlap across language. Therefore, in **CHAPTER 2** we used decoding to investigate the neural overlap across languages of semantic representations used for language production in bilinguals. More specific, we tested whether brain activity during the production of individual nouns in one language allowed predicting the production of the same concepts in the other language. Because both languages only share the underlying semantic representation (sensory and lexical overlap was maximally avoided), this would offer very strong evidence for neural overlap in L1 and L2 semantic representations during production.

Additionally, in **CHAPTER 3**, we used decoding to investigate the neural overlap between L1 and L2 semantic representations, within and across three tasks that placed different demands on production and comprehension, within the same participants. This approach does not only allow finding support for integration or separation of L1 and L2 representations. It also allows a cross-validation across different language modalities, contrasting language production with comprehension. More specifically we investigated whether it was possible to identify the picture or word named, read or heard in one language based on the brain activity while, respectively, naming, reading or listening to the picture or word in the other language.

In **CHAPTER 4**, we applied decoding to investigate the neural representation of identical cognates (words that share orthography & meaning across languages), homographs (words that share orthography, but not meaning across languages) and translation equivalents (words that share meaning but not orthography) across languages within the same individuals to dissociate the semantic and lexical neural representations in a production task. The idea here was that homographs have only orthographic overlap and no semantic overlap across languages, hence correct classifier prediction would imply neural overlap between L1 and L2 lexical representations. Similarly, given that the translation equivalents have only semantic overlap across languages and no orthographic overlap across languages, correct classifier prediction would imply neural overlap between L1 and L2 semantic representations. In addition, correct classifier predictions for cognates across languages, can imply both overlapping semantic as lexical representations, given that both the meaning as orthography are identical across languages.

The study of the neural substrate of bilingual language processing does not only require the investigation of semantic and lexical representations, but also the investigation of language control. If two languages are integrated at the representational level and a person only needs to use one language in a certain communicative setting, than it is obvious that some kind of mechanism is required to prevent interference from the non-relevant language that might otherwise cause cross-lingual speech errors. An interesting line of research that is closely related to the neural representation of language control is what happens in multilinguals that need to use extreme language control. Therefore, in **CHAPTER 5** we tackled the question of language control assessing the long-term anatomical and cognitive effects of simultaneous interpreting. Simultaneous Interpreting (SI) requires concurrent comprehension of a spoken message in the source language (SL) and reformulation of the message into the target language (TL), while at the same time producing a previously transformed source message in the target language (Chernov, 1994). Hence, in chapter 5, we compared two similar training programs (SI versus translation), in order to identify the cognitive and neural changes specifically related to SI. As such, this is the first study to examine longitudinal changes as a result of SI training, both in behavioural performance, using non-linguistic cognitive control tasks, as well as on a neural level, measuring both structural connectivity and functional differences.

In the last section of this dissertation, the **GENERAL DISCUSSION**, we provide an overview of the results and relate our findings to the existing literature. Subsequently, we discuss the generalizability and theoretical implications of these results. General strengths and weakness of our studies are mentioned and we suggest some future research ideas.

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CHAPTER 2

NEURAL OVERLAP OF L1 AND L2 SEMANTIC REPRESENTATIONS IN SPEECH: A DECODING APPROACH[1]

Although research has now converged towards a consensus that both languages of a bilingual are represented in at least partly shared systems for language comprehension, it remains unclear whether both languages are represented in the same neural populations for production. We investigated the neural overlap between L1 and L2 semantic representations of translation equivalents using a production task in which the participants had to name pictures in L1 and L2. Using a decoding approach, we tested whether brain activity during the production of individual nouns in one language allowed predicting the production of the same concepts in the other language. Because both languages only share the underlying semantic representation (sensory and lexical overlap was maximally avoided), this would offer very strong evidence for neural overlap in semantic representations of bilinguals. Based on the brain activation for the individual concepts in one language in the bilateral occipito-temporal cortex and the inferior and the middle temporal gyrus, we could accurately predict the equivalent individual concepts in the other language. This indicates that these regions share semantic representations across L1 and L2 word production.

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[1] Van de Putte, E., De Baene, W., Brass, M., & Duyck, W. (2017). Neural overlap of L1 and L2 semantic representations in speech : A decoding approach. *NeuroImage, 162*, 106–116

CHAPTER 2

INTRODUCTION

Given the high prevalence of multilingualism in the world, the understanding of bilingual language processing is of high relevance for society. In the literature, bilinguals are defined as people who need and use two (or more) languages in their everyday lives (Grosjean, 1992), without necessarily being equally proficient in both languages. The last decennia, the study of bilingual language processing has rapidly gained interest in cognitive psychology.

Although there has been some debate to what extent the bilingual lexicon is integrated across languages, the three most influential behavioral models of bilingual language organization all assume that the semantic systems completely or partly overlap across languages. The Revised hierarchical model (Kroll & Stewart, 1994), with its focus on lexico-semantic links, and the BIA+ model (Dijkstra & van Heuven, 2002), with its focus on orthographic lexical representations, assume a shared semantic system. However, this does not imply that the meaning of every word should be completely identical in every language. Indeed, the distributed feature model (Van Hell & De Groot, 1998) assumes partially overlapping semantic features (instead of whole concepts) across languages, depending on specific characteristics of the concepts. Only the distributed feature model has focused in somewhat more detail on the organization of semantic representations and the factors that may influence it, such as concept/word concreteness. More specifically, Van Hell and De Groot (1998) argued that conceptual representations in bilingual memory depend on word-type and grammatical class. They found that the overlap in meaning, indexed by the number of shared features, is larger for concrete translations, cognates and noun translations, relative to abstract translations, noncognates and verb translations.

As in the behavioral literature, three main theories can also be discerned in the neuroimaging literature of bilingual language processing (Green, 2003; Paradis, 2004, 2009; Ullman, 2001, 2005). Although the behavioral models mainly focused on lexico-semantic representations, the neurally-based accounts consider syntax as well. Across the neural models, there is consensus about the lexico-semantic organization across languages, which is the focus of the present paper, but they mainly diverge with respect to syntactical representations. Ullman (2001, 2005) and Paradis (2004, 2009) both argue that with increasing proficiency the neural representation of second language syntax converges with the neural representation of L1 language syntax, whereas Green (2003) argues that already from the beginning of L2 learning, L2 syntactical representations recruit the same neural circuits as the L1 syntactical representations. Overall, despite the substantive difference between these neural models, all three models make very similar assumptions and predictions and point in the direction of common semantic representations across L1 and L2 in high proficient bilinguals with an early age of L2 acquisition.

Despite the relative consensus among the neural models of bilingual language processing concerning lexico-semantic organization, the neuroimaging studies that investigated the hypothesis that the semantic systems of both languages are represented by overlapping, rather than distinct cortical language areas have provided very divergent results, probably due to their huge methodological heterogeneity. In these classical neuroimaging studies, the neural overlap between L1 and L2 semantic representations has been investigated using contrast designs in which an experimental condition is compared with a control condition. For instance, Illes et al. (1999) reported that semantic decisions activated different brain regions than non-semantic decisions, and then compared results between L1 and L2 words. Within these designs however, many studies used tasks in the experimental (semantic) condition that differed on phonological or orthographic processing demands and task difficulty, in addition to the targeted semantic processing demands (Binder, Desai, Graves, & Conant, 2009). For example, a semantic task like animacy judgment (e.g. horse: 'is it living or nonliving'?) also relies on additional phonological and orthographic processes when comparing it with a control task that for instance involves nonword stimuli (e.g. nbgsj, nbqsj: 'are they identical'?). Then, the comparison between L1 and L2 across such tasks may reveal the targeted cross-lingual semantic overlap, but also the overlap in the peripheral untargeted processing that may result from phonology, orthography, or even mere task difficulty, because the semantic tasks are often also more difficult than the control tasks that they are compared with (Binder et al., 2009). As such, the question about neural overlap of semantic representations across languages also needs to be assessed using other approaches.

Additional to this classical univariate approach, the fMRI-adaptation paradigm has been proposed as a useful tool to study the neural convergence between L1 and L2 representations in bilinguals (Chee, 2009). Adaptation refers to the phenomenon where the successive presentation of two identical stimuli elicits a smaller neural response than the successive presentation of two dissimilar stimuli. Neural overlap between the L1 and L2 semantic systems (e.g. Crinion et al., 2006) has been demonstrated with this approach. However, adaptation results are difficult to interpret given its largely unknown neurophysiological underpinnings and its susceptibility to experimental demands, attentional confounds and novelty or mismatch effects especially for exact stimulus repetitions (e.g. Davis & Poldrack, 2013).

Contrary to these univariate approaches, multi-voxel pattern analysis (MVPA) is sensitive to distributed neural representations and indexes a fundamentally different aspect of the neural code (Jimura & Poldrack, 2012; Epstein & Morgan, 2012). Compared to univariate activation or adaptation results, MVPA has been suggested to provide more direct measures of representations (Davis & Poldrack, 2013). MVPA cannot only detect that equivalent concepts have been presented in the two languages, but also that the representations of these specific concepts are similar across the two languages. MVPA distinguishes patterns of neural activity associated with different stimuli or cognitive states. The logic of using this approach for the present purposes is that one uses a task in which the L1 vs. L2 response tap into very different orthographic, phonological, and sensory representations. Then the classifier may only predict the concept in one language based on the brain responses for the (translation) equivalent concept word in the other language if these two concepts in the different languages elicit similar semantic neural representations. If this is the case, this serves as direct evidence for the neural overlap of semantic representations in L1 and L2, supporting an integrative view of L1 and L2 in bilinguals.

In the literature, there are currently only 2 studies that used MVPA to investigate neural overlap of semantic representations in bilingual language processing (Buchweitz, Shinkareva, Mason, Mitchell, & Just, 2012; Correia et al., 2014), and both are situated in the language comprehension domain. Buchweitz et al. (2012) investigated the semantic representations tapped into by word reading (visual comprehension). Eleven proficient Portuguese-English bilinguals were asked to silently read concrete nouns from two semantic categories (tools and dwellings). Using MVPA, they could predict the individual nouns that the participants were seeing based on the neural representation of the equivalent nouns in the other language situated in the left inferior frontal gyrus, the left posterior superior temporal lobe, the postcentral gyrus and the left inferior parietal sulcus. In the second study, Correia et al. (2014) focused on semantic representations in listening (auditory comprehension). Ten proficient Dutch-English bilinguals listened to concrete animal nouns and non-animal nouns in both languages and pressed a button whenever they heard a non-animal word. They could accurately predict which animal noun was heard in one language based on the brain response of the equivalent noun in the other language. The shared representation across languages was situated in the left anterior temporal lobe, the left angular gyrus and the posterior bank of the left postcentral gyrus, the right posterior superior temporal gyrus, the right medial anterior temporal lobe, the right anterior insula and bilateral occipital cortex. Both studies provide evidence for the existence of common overlapping semantic representations across languages in comprehension, both in the visual and auditory domains.

Besides these two language comprehension studies, to our knowledge, no studies have used MVPA (or decoding) to investigate the neural overlap across languages of semantic representations used for language production (speaking) in bilinguals. In the behavioral literature, language comprehension and production are studied in mostly independent lines of literature, and some theoretical accounts assume different lexicons for production and recognition, and even between auditory and visual domains (Caramazza, 1997; Gollan et al., 2011; Roelofs, 2003). These separate systems are sometimes assumed to eventually contact a semantic system that is shared between modalities (Shelton & Caramazza, 2001). Some fMRI decoding studies supported this assumption: In a monolingual study, Simanova, Hagoort, Oostenveld, and Van Gerven (2014) investigated the possibility to decode the semantic category across modalities within L1. Participants had to perform a semantic categorization comprehension task with 4 types of stimuli (spoken words, written words, photographs and natural sounds) and subsequently produced the same stimuli afterwards in a free recall session. Simanova et al. (2014) found evidence for the shared representation of semantic information across input modality situated in the left inferior temporal cortex and frontal regions. Similarly, Van Doren, Dupont, De Grauwe, Peeters and Vandenberghe (2010) also reported overlapping neural semantic representations between the recognition of L1 words and L1 picture naming in the occipito-temporal regions and inferior frontal regions in a forced choice recognition task.

However, there's also evidence that semantic processing across comprehension and production might not rely on two completely overlapping semantic representations. Two other monolingual comprehension studies that investigated semantic processing showed different patterns of activation elicited by the passive viewing of pictures than by the silent reading of the names of these pictures (Gates & Yoon, 2005; Reinholz & Pollmann, 2005). A possible explanation for this dissociation could be that names of pictures do not automatically activate the corresponding object-selective areas as pictures do.

In the present study, we will use a similar MVPA approach as Buchweitz et al. (2012) and Correia et al. (2014) used for respectively bilingual reading and listening (all comprehension), and Simanova et al. (2014) for monolingual language processing across modalities (production vs. comprehension). However, instead of looking at bilingual comprehension, we will examine bilingual production using a bilingual picture naming task. As such, this is also the first MVPA study to assess the neural overlap between the semantic representations that L1 and L2 production rely on.

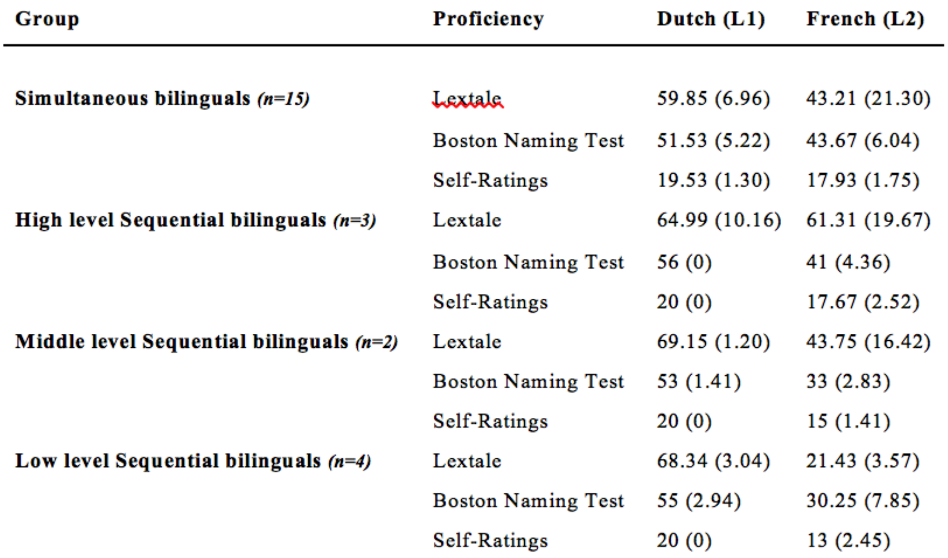
MATERIALS AND METHODS

Participants

Twenty-four right-handed individuals (12 males, 12 females; mean age = 23,38, range = 19-27 years) participated in the study. Fifteen participants were early French-Dutch bilinguals who acquired both languages from birth. Nine participants were late sequential bilinguals who learned French at school at the age of 9, as all children do in the Flemish educational system. The early bilinguals spoke French with their parents, Dutch at school and switched frequently between both languages with their friends. Three late sequential bilinguals followed an additional high level French language education program, two had a job in which they often had to speak both in Dutch and French and four only learned French at primary school, but rarely used it at the time of scanning.

The participants filled out a language background questionnaire to assess their subjective language proficiency, switching frequency and the age of acquisition of both languages. Additionally, proficiency in Dutch and French was measured with the LexTALE and the Boston Naming test (BNT; Kaplan, Goodglass, & Weintraub, 1983). The Dutch LexTALE (Lemhöfer & Broersma, 2012) that consists of 60 items and the French LexTALE (Brysbaert, 2013) that consists of 56 items are tests of vocabulary knowledge that give a good indication of general Dutch and French proficiency. The BNT is a 60-item picture naming test that measures word retrieval (see Table 1 for results on these proficiency measures).

All recruited participants had normal or corrected-to-normal vision. None of them used medication or had a history of drug abuse, head trauma, or neurological or psychiatric illness. All participants gave written informed consent before participating. The study was approved by the Ethical Committee of Ghent University hospital.



Group	Proficiency	Dutch (L1)	French (L2)
Simultaneous bilinguals ***(n=15)***	Lextale	59.85 (6.96)	43.21 (21.30)
	Boston Naming Test	51.53 (5.22)	43.67 (6.04)
	Self-Ratings	19.53 (1.30)	17.93 (1.75)
High level Sequential bilinguals ***(n=3)***	Lextale	64.99 (10.16)	61.31 (19.67)
	Boston Naming Test	56 (0)	41 (4.36)
	Self-Ratings	20 (0)	17.67 (2.52)
Middle level Sequential bilinguals ***(n=2)***	Lextale	69.15 (1.20)	43.75 (16.42)
	Boston Naming Test	53 (1.41)	33 (2.83)
	Self-Ratings	20 (0)	15 (1.41)
Low level Sequential bilinguals ***(n=4)***	Lextale	68.34 (3.04)	21.43 (3.57)
	Boston Naming Test	55 (2.94)	30.25 (7.85)
	Self-Ratings	20 (0)	13 (2.45)

Table 1. *Overview of language proficiency scores (maximum score BNT: 60/ Lextale:100) for the simultaneous and sequential bilinguals. The self-ratings are on a 5-point likert scale and are summed across listening, speaking, reading and writing.*

Stimuli

Pictures of 10 concepts had to be named in French and in Dutch. All stimuli were stored as 720 × 450-pixel images (18.1 x 11.3 visual degrees). Importantly, two completely different images were selected per concept (e.g. horse). Per participant, each image was associated with one language (for an example, see Figure 1). This image-to-language assignment was counterbalanced across participants. Visual similarities (e.g. point of view, colour) between the two images of the same concept and lexical overlap (overlapping phonemes and graphemes) between translation equivalents of the same concept were minimal. In order to avoid visual similarity, for each pair, both a black-white line drawing, and a color picture were used. Also, perspectives of the object were varied, such that no low-level visual features were shared across both pictures. The lexical overlap between translation equivalents of the same concept were quantified with the Levenshtein distance, in which the amount of insertions, deletions or substitutions required to change one word into the other is used as a measure of phonetic and ortographic distance (Levenshtein, 1965). The Levenshtein distance between the translation equivalents in Dutch and French was 1.00 for all stimuli, corresponding with a maximum number of changes, which equalizes a maximum orthographic and phonological distance between the Dutch and French translation equivalents. The translation equivalents were matched on word length (p=0.193) and word frequency (p=0.885). See Appendix 1 for an overview of all experimental stimuli.

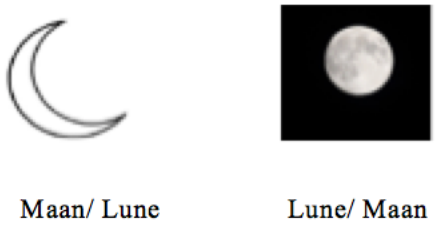


Figure 1. *Pictures had to be named in French and in Dutch. For each concept (e.g. moon) two images with different visual features were selected, so that each language corresponded to a different picture.*

Experimental design

The neural overlap between Dutch and French semantic representations was examined using a production task in which the participants were asked to name the pictures in Dutch and French. This picture-naming task was organized in 2 consecutive parts (a Dutch and a French part). The order of the two language parts was counterbalanced across participants. Each language part included 7 blocks that always started with a familiarization phase to ensure picture-name agreement. To this end, each of the 10 pictures was presented on the centre of the screen with its name below it in the language relevant for the respective part. Participants had to press a button to proceed to the next stimulus. After this familiarization block, they worked through a practice block of 10 trials in which they had to name the 10 pictures, followed by 5 experimental scan blocks of 60 picture naming trials. These 60 trials included 6 randomised picture presentations of the 10 concepts. During each trial, one of the pictures was shown for 1000 ms, followed by a fixation screen of 1000 ms and a jittered stimulus onset asynchrony (mean = 2600 range = 1000-5200 ms, in steps of 300 ms, distribution with pseudologarithmic density). At the start of each stimulus presentation, the naming was recorded during 3000 ms.

fMRI data acquisition

Participants were scanned with a 3T Magnetom Trio MRI scanner system (Siemens Medical Systems, Erlangen, Germany), using a standard 32-channel radio-frequency head coil. They were positioned head-first and supine in the magnetic bore and were instructed not to move their heads to avoid motion artefacts. The scanning procedure started for each participant with a high-resolution 3D structural scan, using a T1-weighted 3D MPRAGE sequence (TR = 2250 ms, TE = 4.18 ms, TI = 900 ms, acquisition matrix = 256 x 256 x 176, FOV = 256 mm, flip angle = 9°, voxels resized to 1 x 1 x 1 mm). After the structural images, whole brain functional images were collected using a T2*-weighted EPI sequence, sensitive to BOLD contrast (TR = 2000 ms, TE = 28 ms, image matrix = 64 x 64, FOV = 224 mm, flip angle = 80°, slice thickness = 3 mm, distance factor = 17%, voxels resized to 3 x 3 x 3 mm, 34 axial slices). A fixed number of images (152) were acquired per run.

fMRI data pre-processing

SPM8 software (Wellcome Department of Cognitive Neurology, London, UK) was used for the preprocessing and data-analyses of the acquired fMRI-data. The first nine scans of all runs were excluded from the analysis to minimize T1 relaxation artefacts. For each run motion parameters were estimated and runs with more than 15% of bad volumes were repaired by interpolation through the ArtRepair Toolbox v4 (http://cibsr.stanford.edu/tools/ArtRepair/ArtRepair.htm). Six runs in four different participants exceeded 15 % of bad volumes. A threshold of 1,5 % from the mean was used as criterion to categorize a volume as bad. From the 6 runs that were categorized as bad, 4 runs occurred in the L1 blocks and 2 runs occurred in the L2 blocks. The repaired motion regressors were used for all further analyses. The images were slice-time corrected and spatially realigned to their mean image by rigid body transformation. Additionally, the high-resolution structural image was co-registered with this mean image and normalized to the Montreal Neurological Institute (MNI) template. These normalization parameters were then applied to the functional images to ensure an anatomically-informed normalization. The time series data at each voxel were processed using a high-pass filter with a cut-off of 128 s to remove low-frequency artifacts.

The normalized but unsmoothed images were used to perform the multivariate decoding analyses to prevent the possible reduced sensitivity to extract the full information in the spatial patterns after smoothing. Therefore, smoothing was applied after the multivariate pattern classification analyses and prior to the second-level analysis using an 8 mm full-width half-maximum (FWHM) Gaussian kernel. Separately for the two language parts, statistical analyses were performed on individual subjects' data using the general linear model (GLM) in SPM8. All events were time-locked to the onset of the visual presentation. The fMRI time series data were modelled by 10 different vectors reflecting the semantic concept of the trial. All these vectors were convolved with a hemodynamic response function (HRF), as well as with the temporal derivative and entered into the regression model (the design matrix), which contained additional regressors to account for variance related to head motion. The statistical parameter estimates were computed separately for all columns in the design matrix.

fMRI Data analysis: MVPA

We performed multivariate decoding analyses with the PyMVPA toolbox (Hanke et al., 2009) to investigate the neural overlap between Dutch and French semantic representations in a production task. We employed a searchlight method (Kriegeskorte, Goebel, & Bandettini, 2006) to reveal local activity patterns that carry information about the semantic concept using a spherical searchlight with a radius of 3 voxels. Normalized but unsmoothed beta images were subjected to the analysis and a K Nearest Neighbours pattern classifier was used for classification. The use of other classifiers (The Gaussian Naïve Bayes classifier, the linear Support Vector Machines Classifier and the Radial Basis Function Support Vector Machines Classifier) yielded similar results. In each analysis, we used a leave-one-run-out cross-validation procedure. That is, for the across-language decoding analyses, the classifier was trained to discriminate between the activation patterns associated with the naming of each of the 10 concepts in one language for four of the five blocks (training data set). Subsequently, this pattern classifier was used to classify the activation patterns associated with the naming of the 10 concepts in the other language in the corresponding fifth block (test data set). Five-fold cross validation was achieved by repeating this procedure independently, with each block acting as a test data set once while the other blocks were used as training data sets. Classification accuracies were averaged across all five iterations, yielding a mean decoding accuracy map for each participant. These analyses were done in two directions: with Dutch trials as training trials and French trials as test trials and vice versa. The classifier was only able to accurately predict which concept was named if semantic representations of Dutch and French overlap in the brain. To assure that classifier performance only reflected the semantic overlap between the two languages, visual similarities between the two images of a concept and lexical similarities between the translation equivalents were maximally reduced. Additionally, we also ran within-language decoding analyses in which the training and test data were from the same language part. This by definition implied sensory overlap between pictures, contrary to the across-language analyses, which were our main focus and implied the use of different images of the same concept in the different languages to particularly exclude the visual confound in that specific comparison.

Classification accuracy significantly above chance (i.e. > 0.10) implied that the classifier was able to accurately predict which concept was named, whereas chance level performance implied that it was not possible to predict the concept that was named. Note, however, that searchlight approaches can lead to interpretation errors such as the misidentification of a cluster as informative. For example, a cluster that is not informative can appear in the searchlight map if other clusters within the sphere provide significant classification accuracies (Etzel, Zacks, & braver, 2013).

Therefore, to show that the significant clusters form the searchlight analyses are informative itself, cluster confirmatory analyses was additionally applied (Etzel, Zacks, & braver, 2013). The main idea here is that the cluster should always be tested for information as a ROI, before describing it in any sense other than that of the centers of searchlights. If the ROI made from the cluster is informative, then there is justification for concluding that the cluster is itself informative (Etzel et al., 2013). Additionally, evidence that the cluster contains the most informative voxels is provided if the global anatomically-defined area (defined on the basis of the AAL atlas) to which the cluster belongs but with the cluster voxels removed contains less information than the global area including the cluster and the cluster itself. If the area is still informative after the cluster has been deleted, the information should be described in terms of the area as a whole.

Group analyses

Whole brain, voxel-by-voxel second-level statistical analyses were performed to see how well decoding could be performed on average across all subjects (Haynes et al., 2007). The across-language decoding accuracies were averaged across the two directions (Dutch as training language and French as test language and vice versa). These resulting decoding accuracy maps were contrasted with chance level of accuracy (10%) using a one-sample t-test to reveal significant coding of semantic concepts across languages. Group maps significance was defined using a threshold of $p<.001$ at voxel level and a cluster level corrected for the whole brain at $p < .05$.

The separate within-language decoding accuracy maps (same language (Dutch or French) as training and test language) were submitted to a flexible factorial design with language (Dutch or French) as within-subject factor. A disjunction analysis was used to identify brain areas showing significant decoding accuracies in Dutch ($p < .001$) but not in French ($p > .05$) and vice versa. This analysis was done to investigate the brain regions that can discriminate between semantic concepts within Dutch, but not in French and vice versa. Note that these within-language disjunction analyses need to be interpreted with care, as within-language comparisons imply lexical overlap besides the semantic overlap. This makes it impossible to distinguish whether differences in the areas involved in the decoding within L1 en the decoding within L2 are due to differences in semantic representations or rather lexical representations.

Additionally, we performed region of interest (ROI) analyses on predefined ROIs. Based on the (monolingual) study of Simanova et al. (2014), we selected a number of candidate regions that we expected to be involved in semantic processing. In that study, a similar decoding approach was used to investigate the semantic processing in L1 during the presentation of pictures, written words, spoken words and sounds. We selected the brain regions that Simanova et al. (2014) reported to be involved in the semantic processing of pictures in L1, to see whether these regions also generalize to L2 (bilateral middle temporal gyrus, left fusiform gyrus, left middle occipital gyrus, right postcentral gyrus and right calcarine). Because of the similar approach that was used to investigate monolingual neural semantic representations, the study of Simanova et al. (2014) was very relevant as the base for the selection of the ROI's in our study to investigate the bilingual neural semantic representations. Spherical ROIs (radius = 10 mm) were centered at the peak coordinates identified for each of these brain regions. To identify significant ROI regions the Bonferroni correction was applied.

Representational similarity analysis

To test whether the classification can really be explained by semantic similarity, rather than visual similarity we additionally applied representational similarity analysis (RSA). To this end, we analysed the response similarities across languages between the evoked fMRI responses across all 10 stimulus pairs in the selected regions of interest (ROIs), based on the regions that we found in our whole brain analysis. To obtain the 10 x 10 similarity matrix for every ROI and for each subject, we correlated the first level L1 beta images for all 10 stimuli with the first level L2 beta images for the 10 stimuli.

The RSA matrices for each ROI (similarity matrices between the brain responses evoked by the 10 stimuli in L1 and the brain responses evoked by the 10 stimuli in L2) were averaged across all subjects and correlated with a semantic similarity matrix of all 10 stimuli combinations and a visual similarity matrix of all the picture combinations using Spearman rank correlations (Kriegeskorte, Mur, & Bandettini, 2008). If the similarities of the brain activations across the 10 stimulus pairs correlated more with the semantic similarity matrix than with the visual similarity matrix, this provides additional evidence that the regions found in our whole brain analyses indeed reflect shared semantic and not higher-order visual processing, even though highly dissimilar pictures were used.

As a conservative approach towards our semantic processing claim, the semantic similarity matrix was drawn from an independent study, Snaut, a program that measures semantic distances between words (Mandera, Keuleers, & Brysbaert, in press). We used 1-semantic distance as a measure of semantic similarity. The visual similarity matrix was created based on subjective ratings of the visual similarity between all the combinations of pictures that were used in the experiment. The subjects that participated in this fMRI study had to respond on a 7-point Likert scale (1 = the pictures do not have any visual similarity, 7 = the pictures are visual identical).

RESULTS

Whole brain statistical analyses

Across-language decoding

To reveal significant coding of semantic concepts across languages, a one-sample t-test was used in which the decoding accuracy maps were contrasted with chance level (10%). For this analysis, the across-language decoding accuracies were averaged across the two directions (Dutch to French and French to Dutch). Significant across-language decoding accuracies were found in the left middle occipital gyrus extending into the left fusiform gyrus, the right lingual gyrus extending into the right inferior temporal gyrus and left inferior temporal gyrus extending into the left hippocampus (Figure 2; Table 2).

Brain region	X	Y	Z	z-score	Cluster size
Left middle occipital gyrus	-39	-85	4	5.25	635
Right lingual gyrus	9	-88	-2	4.94	773
Left inferior temporal gyrus	-42	-43	-26	3.85	113

Table 2. Results of the across-language decoding analyses. All thresholds were FWE corrected.

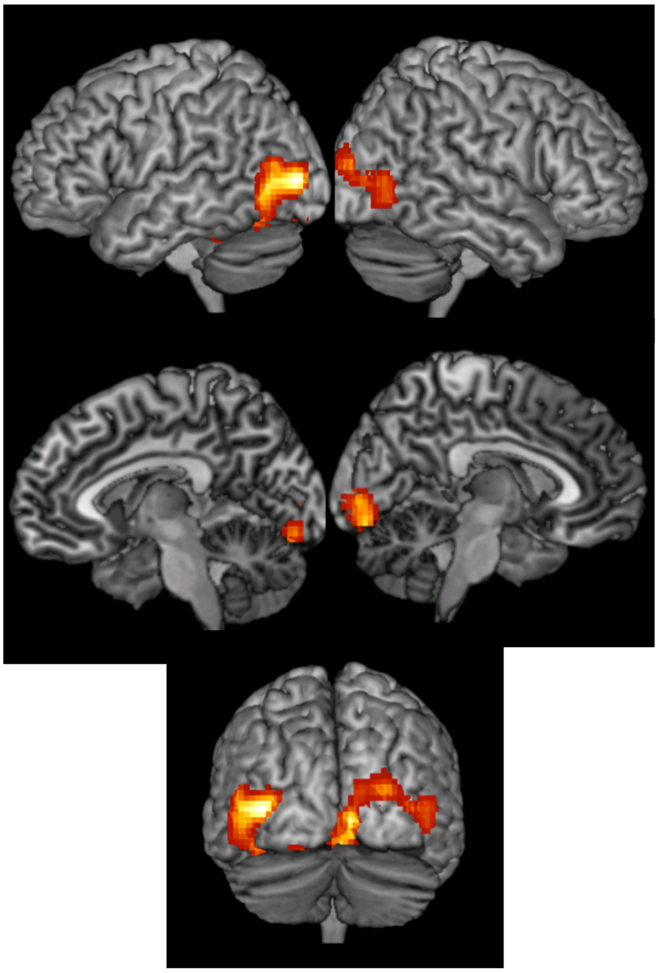


Figure 2. *Results of the whole brain searchlight analysis showing discriminability between semantic concepts in the generalization across languages. The color represents the t-values resulting from the group level analysis using a threshold of* $p<.001$ *at voxel level and a cluster level corrected for the whole brain at* $p < .05$.

To show that the significant clusters form the searchlight analyses are informative itself, cluster confirmatory analyses was applied. For every significant whole brain searchlight cluster three ROI's were made: One ROI was created from the cluster itself, a second ROI was made from the global anatomically-defined area to which the cluster belongs and a third ROI was made from the global anatomically-defined area to which the cluster belongs but with the cluster voxels removed.

After cluster confirmatory analyses, all the clusters from the whole brain analyses were significant ($p < .001$ for the cluster in the left middle occipital gyrus, the cluster in the right lingual gyrus and the cluster in the left inferior temporal gyrus). Both the whole left middle occipital gyrus with the cluster ($p < .001$) and the left middle occipital gyrus without the cluster were significant ($p < .05$). However, the cluster alone contained more information than the brain area with the cluster ($p < .001$) and the brain area without the cluster ($p < .05$). This provides evidence that the information is widespread throughout the left middle occipital gyrus, with the most information found in the cluster centered at -39 -85 4. The whole right lingual gyrus with the cluster was significant ($p < .05$) and the area without the cluster was not significant ($p = .088$). The cluster alone contained more information than the brain area with the cluster ($p < .001$) and the brain area without the cluster ($p < .001$). This provides evidence that the cluster itself (9 -88 -2) contains the most informative voxels in the right lingual gyrus. The whole left inferior temporal gyrus with the cluster ($p = .53$) and without the cluster ($p = .58$) were not significant. The cluster alone contained more information than the brain area with the cluster ($p < .001$) and the brain area without the cluster ($p < .001$). This provides evidence that the cluster (-42 -43 -26) itself contains the most informative voxels in the left inferior temporal gyrus. To conclude, all the clusters contained the most informative voxels, but the involvement in the left middle occipital gyrus was additionally more widespread.

Within-language decoding

We also performed within-language decoding analyses to get a more fine-grained look at the regions that might be involved in the semantic processing of one specific language.

Disjunction analyses showed that the bilateral postcentral gyrus extending into the bilateral precentral gyrus, the left superior temporal gyrus, the right supramarginal gyrus, the right cuneus extending into the right superior parietal gyrus and the right middle temporal gyrus extending into the right inferior temporal gyrus were involved in L2 production, but not in L1 production (Figure 3, Table 3).

Brain region	X	Y	Z	z-score	Cluster size
Left postcentral gyrus	-54	-10	19	5.62	421
Right precentral gyrus	60	8	31	4.86	276
Right supramarginal gyrus	57	-22	37	4.93	142
Right cuneus	15	-67	40	4.79	269

Table 3. *Disjunction: brain areas that showed significant decoding accuracies for L2 ($p < .001$), but not for L1 ($p > .05$). All thresholds were FWE corrected.*

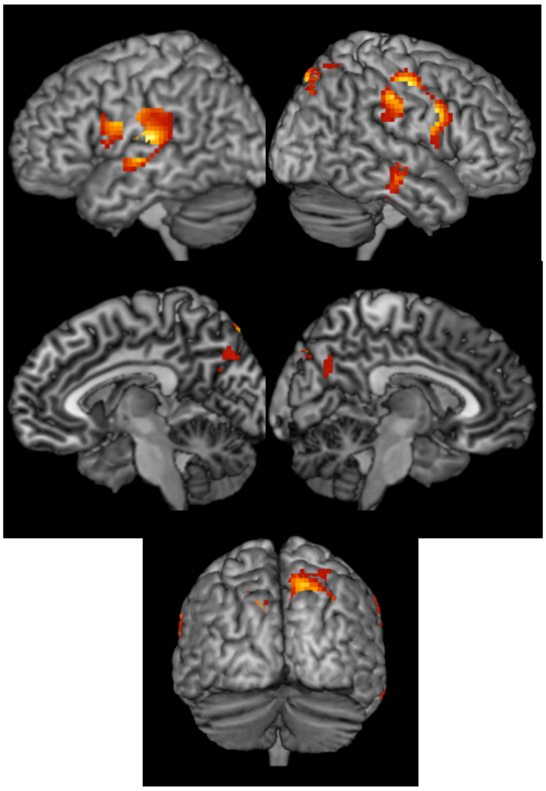


Figure 3. *Results of the disjunction analysis showing the brain areas that yielded significant decoding accuracies in L2 (p < .001), but not in L1 (p > .05).*

In the opposite direction, no significant decoding accuracies were observed for L1 that were not observed for L2. Note that, as mentioned above, this within-language disjunction analysis reveals cross-language differences, but do not allow to fully disentangle semantic from lexical involvement, given that within-language comparisons by definition also contain lexical (and visual) overlap.

Although this wasn't the primary goal of the study, for exploratory purposes, we also included AOA and proficiency as covariates to look at the differences between low and high proficient bilinguals and early and late bilinguals in the brain regions that showed significant decoding accuracies. Only the covariate AOA yielded significant differences between early and late bilinguals. An early age of acquisition of L2 correlates with lower decoding accuracies of L2 in the right calcarine, extending into the right middle occipital gyrus, the right cuneus and the left postcentral gyrus extending into the left inferior temporal gyrus, the left lingual gyrus, the left fusiform gyrus and the left inferior occipital gyrus (Table 4).

Brain region	X	Y	Z	z-score	Cluster size
Right calcarine	21	-79	10	4.47	379
Left postcentral gyrus	-27	-43	67	4.38	121

Table 4. *Mean accuracy L2 X covariate AOA L2. All thresholds were FWE corrected.*

Region of interest analyses (ROI)

In the ROI analyses, we selected the brain regions that Simanova et al. (2014) reported to be involved in the semantic processing of pictures in a first language to see whether these regions also generalize to a second language. After Bonferroni correction, the ROI's in the left middle temporal gyrus, the right middle temporal gyrus, the left fusiform gyrus, the left middle occipital gyrus and the right calcarine showed significant across-language decoding accuracies. Only the ROI in the right postcentral gyrus was not significant (Table 5).

Brain region	X	Y	Z	Accuracy	P
Left middle temporal gyrus	-43	-63	10	0.1077	p < .01
Right middle temporal gyrus	48	-70	-1	0.1133	p < .01
Left fusiform gyrus	-40	-56	-15	0.1093	p < .01
Left middle occipital gyrus	-47	-81	-1	0.1170	p < .001
Right postcentral gyrus	45	-21	45	0.1040	p = .13
Left middle occipital gyrus	-22	-95	17	0.1089	p < .01
Right Calcarine	13	-98	3	0.1113	p < .01

Table 5. *Across languages Region of interest (ROI) analyses.*

Representational similarity analysis

The RSA matrices of the three ROI’s (Right lingual gyrus, Left inferior temporal gyrus, left middle occipital gyrus) correlated more with the semantic similarity matrix (ROI 1: r = .15; ROI 2: r = .05; ROI 3: r = .07) than with the visual similarity matrix (ROI 1: r = .05; ROI 2: r = .02; ROI 3: r = .06). For ROI 1, this correlation was significantly different, and for ROI 2 and 3 this correlation was not significantly different (ROI 1: p < .01; ROI 2: p > .23; ROI 3: p >.72; paired-sample t-test).

DISCUSSION

In the present study, we investigated the neural overlap between the semantic representations needed for L1 and L2 production, using multivariate decoding analyses. The results showed that significant decoding of individual concepts is possible across languages. Because lexical or sensory overlap was excluded across L1 and L2, the classifier could have only accurately predicted which concept was named in one language given the activation pattern for naming in the other language if semantic representations of L1 and L2 do overlap in the brain. These findings provide evidence for the existence of shared semantic representations that are situated in the bilateral occipito-temporal cortex and the inferior and the middle temporal gyrus. These regions align with monolingual studies that also situated (L1) semantic representations in the posterior temporal regions (Rodd, Vitello, Woollams, & Adank, 2015; Van Doren et al., 2010). Furthermore, these results indicate that when learning a L2, new lexical forms are mapped onto the existing areas that represent semantics for the existing (L1) language.

A point of discrepancy with previous (comprehension) studies (Binder et al., 2009; Buchweitz et al., 2012; Correia et al., 2014) is that for our production modality, we didn’t replicate the involvement of frontal regions and anterior temporal regions in semantic processing. The dorsomedial prefrontal cortex, inferior frontal gyrus and the ventromedial prefrontal cortex showed up in a meta-analysis of 120 functional imaging studies that investigated the neural representation of the semantic system of spoken and written words in L1 comprehension (Binder et al., 2009). Across languages, the left inferior frontal gyrus showed shared semantic representations in visual comprehension (read concrete nouns in silence; Buchweitz et al., 2012) whereas the left anterior temporal lobe showed overlapping semantic representations across languages in auditory comprehension (listen to concrete nouns; Correia et al., 2014). This might indicate that the involvement of frontal regions and anterior temporal regions in semantics is more specific for comprehension than for production.

To investigate whether neural overlap across languages is shared across modalities, future studies should investigate across-language semantic overlap in the different modalities within the same individuals. Another possible explanation for the absence of frontal structures in our paper should also be considered. The low selection demands and the overlearning of the pictures (through repetition) may explain the absence of frontal structures in this task. Thompson-Schill, D'Esposito, Aguirre and Farah (1997) for example argue that frontal activation is involved in the selection of information among competing alternatives from semantic memory, but is therefore not the result of semantic retrieval per se. They argued that the involvement of the inferior frontal gyrus was absent or reduced in semantic tasks with low selection demands or high repetition. As such, the current picture naming task allows a more focused assessment of semantic processing, irrespective of irrelevant task demands.

In addition to the overlapping semantic representations across languages in the bilateral occipito-temporal cortex and the inferior and the middle temporal gyrus, we also found brain areas that showed significant decoding accuracies in L2, but not in L1. These results suggest that in addition to the shared neural populations representing semantics across languages, there are also neural populations that are recruited specifically by L2 at the semantic or lexical level (the bilateral postcentral gyrus extending into the bilateral precentral gyrus, the left superior temporal gyrus, the right supramarginal gyrus, the right cuneus extending into the right superior partietal gyrus and the right middle temporal gyrus extending into the right inferior temporal gyrus). The distinction between the semantic or lexical level is not possible to make in the disjunction of the within-languages decoding analysis, because only across-languages lexical overlap could be avoided in our design. The involvement of additional regions was more prominent in L2 than in L1, which suggest that the neural representation of a less proficient language is more widespread (Stowe & Sabourin, 2005).

Interestingly, the involvement of the neural populations in L2 semantic processing seems to be influenced by the AOA of L2. Our results seem to indicate that the later L2 was acquired, the more additional neural populations are involved in the semantic processing of L2. This might implicate a more efficient organization of conceptual knowledge in early bilinguals then in late bilinguals, as proposed in the reviews of Indefrey (2006), Perani and Abutalebi (2005) and Stowe and Sabourin (2005) who also suggested more extensive activations for L2 processing compared to L1 processing in late bilinguals, without dissociation between the specific modalities (e.g. comprehension and production). They concluded that late learners might be more likely to draw on additional resources to aid them in L2 processing. Note however, that we can’t dissociate AOA and L2 exposure in this paper, because AOA is highly correlated with the years of use of L2 in our sample. These effects could therefore be driven by both AOA or by the amount of exposure to L2.

Furthermore, we selected the brain regions that Simanova et al. (2014) reported to be involved in the decoding of the semantic category of pictures in L1 to see whether these regions also generalize to the semantic processing of pictures of individual concepts in L2. In the decoding across languages, the bilateral middle temporal gyrus, the left fusiform gyrus, the left middle occipital gyrus and the right calcarine were involved in our study. This finding again replicates the importance of the middle temporal gyrus not only for monolingual semantic representations (Price, 2012; Indefrey & levelt, 2000), but also for common bilingual semantic representations in L1 and L2.

Despite the absence of low-level visual similarity between very dissimilar pictures of the same concepts, the representational similarity analysis for the left inferior temporal region and for the left middle occipital region seems to indicate that both visual and semantic features might have contributed to the classification. However, note that the RSA matrices of the three ROI's (Right lingual gyrus, Left inferior temporal gyrus, left middle occipital gyrus) correlated more with a semantic similarity matrix than with a visual similarity matrix[2], even though semantic similarities were derived from an independent source (Mandera et al., in press). Secondly, Correia et al. (2014) also reported the involvement of occipital regions in a word listening task across languages, although no visual stimuli were used whatsoever. Therefore mental imagery could be a possible explanation in the sense that visual characteristics might be automatically activated during the (semantic) processing of concrete concepts (Binder & Desai, 2012). Thirdly,

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[2] Note that the difference between correlations was significant only for the right lingual gyrus, likely because of the (necessarily) small number of stimuli for which these correlations may be calculated.

note that the other observed inferior and middle temporal regions are not typical reflections of visual involvement, but appear in previous monolingual meta-analyses as areas related to semantic processing (Price, 2012; Indefrey & levelt, 2000).

Overall, the results of our study provide evidence for overlapping semantic representations of concrete concepts across L1 and L2 as suggested by all three theoretical models of bilingual language processing: the BIA + model, the revised hierarchical model and the distributed feature model (Dijkstra & van Heuven, 2002; Kroll & Stewart, 1994; Van Hell & De Groot, 1998). The distributed feature model, however, assumes less neural overlap for the semantic representations of abstract concepts across languages (Van Hell & De Groot, 1998). To test this assumption, future studies should compare the neural overlap in semantic representations of concrete and abstract concepts within the same individuals using a decoding approach.

In the neuroimaging literature, our findings support Green's convergence hypothesis that also highlights the neural overlap between L1 and L2. More specifically, this theory assumes that during L2 acquisition, the neural representations of L2 will converge with the neural representations of L1 (Green, 2003). However, our findings also partially support Ullman's differential hypothesis (Ullman, 2001, 2005) and Paradis' neurolinguistic theory of bilingualism (Paradis, 2004, 2009). Although their focus is on the dissociation of neural areas that are used for L1 and L2, they also agree that with increasing proficiency, experience or an earlier age of acquisition, L2 representations might shift to rely more on the procedural structures of L1.

In our study we only saw an influence of AOA and not proficiency on the neural overlap. However, future studies that specifically compare different (and therefore necessarily larger) subject groups with different AOA, proficiency levels and exposure levels are required to get a more detailed view on the influence of these individual difference variables on the neural overlap.

In addition to the influence of language use parameters (AOA, proficiency) it would also be interesting to look at the influence of language relatedness on the neural overlap of L1 and L2 semantic representations. Using an adaptation approach, Chee, Soon, & Lee (2003) for example investigated the neural overlap of semantic features across a more dissimilar language pair (Chinese – English) and reached a similar conclusion, namely that the Chinese and English semantic system have shared components, but also components that may be language-specific. Future MVPA research may systematically compare closer and linguistically/socioculturally more distant languages.

Conclusion

Brain activity in the bilateral occipito-temporal cortex and the inferior and the middle temporal gyrus associated with the activation of semantic representations of individual concepts during production in one language (e.g. “lune”) accurately predicts the activation of semantic representations of the equivalent concepts in the other language (e.g. “maan”). This suggests that these regions share semantic representations across L1 and L2 production. In addition, there are also brain areas that are recruited specifically by L2. These findings provide evidence for common, overlapping semantic representations.

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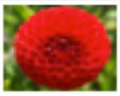
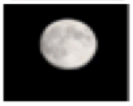
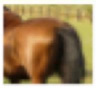
APPENDIX 1

Experimental stimuli. *Overview of the 10 concepts that had to be named in Dutch and French and the two images that were selected per concept.*

Dutch	French	Picture 1	Picture 2
Bed	Lit		
Bloem	Fleur		
Boom	Arbre		
Appel	Pomme		
Maan	Lune		
Brood	Pain		
Hond	Chien		
Glas	Verre		
Voet	Pied		
Paard	Cheval		

CHAPTER 3
NEURAL OVERLAP OF L1 AND L2 SEMANTIC REPRESENTATIONS ACROSS VISUAL AND AUDITORY MODALITIES: A DECODING APPROACH[1]

This study investigated whether brain activity in Dutch-French bilinguals during semantic access to concepts from one language could be used to predict whether the same concepts were being accessed in another language, using various tasks. This was tested using multi-voxel pattern analysis (MVPA), within and across three tasks that placed different demands on production and comprehension encompassing different stimulus modalities (word listening, word reading and picture naming). It was possible to identify the picture or word named, read or heard in one language (e.g. maan, meaning moon) based on the brain activity in a distributed bilateral brain network while, respectively, naming, reading or listening to the picture or word in the other language (e.g. lune). The brain regions identified differed across tasks. During picture naming, brain activation in the occipital and temporal regions allowed concepts to be predicted across languages. During word listening and word reading, across language predictions were observed in the rolandic operculum and several motor-related areas (pre- and postcentral, the cerebellum). In addition, across language predictions during reading were identified in regions typically associated with semantic processing (left inferior frontal, middle temporal cortex, right cerebellum and precuneus) and visual processing (inferior and middle occipital regions and calcarine sulcus). Furthermore, across modalities and languages, the left lingual gyrus showed semantic overlap across production and word reading. These findings support the idea of at least partially language- and modality-independent semantic neural representations.

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[1] Van de Putte, E., De Baene, W., Brass, M., Price, C.J., & Duyck, W. (2017). Neural overlap of L1 and L2 semantic representations across visual and auditory modalities: a decoding approach. *Manuscript submitted for publication*

INTRODUCTION

The representation of semantics in the brain is a fundamental prerequisite to understand human nature and the creation of meaning. A part of this debate relates to how the semantic system is differently organized and recruited across different language modalities such as reading, speaking or listening. Several studies have highlighted the existence of amodal conceptual representations (Bright, Moss, & Tyler, 2004; Buckner, Koutstaal, Schacter, & Rosen, 2000; Kircher, Sass, Sachs, & Krach, 2009; Pobric, Jefferies, & Lambon Ralph, 2010) assuming a semantic system that is shared across modalities. The reviews of Barsalou et al. (2003) and Kiefer and Pulvermüller (2012), however, indicate that concepts may also be flexible, distributed in the brain, and dependent on language modality and the specific sensory and motor characteristics involved. An attempt to reconcile these views was offered by Bonner, Peelle, Cook and Grossman (2013), who assumed a distributed semantic network that includes an amodal, integrative representation and sensory and motor feature representations in modality-specific association areas. However, most fMRI studies of the representation of semantics have investigated language comprehension and production separately, using different experimental designs and tasks that also rely on additional orthographical or phonological demands to a varying degree. As a consequence of this heterogeneity in tasks, a large variety of brain regions have been reported during semantic language processing, often without very explicit delineation of the processes involved in the investigated tasks. Given that the different tasks and modalities, and the underlying cognitive processes, might recruit distinct neural structures, this paradigmatic diversity may confound conclusions about the neural representation of semantics. Binder, Desai, Graves and Conant (2009) therefore reviewed 120 classical functional neuroimaging studies, rigorously selected on well-defined task contrasts focusing on the neural representation of the semantic system in word reading and word listening in the first language (L1), without additional phonological or orthographic confounds. They concluded that semantic processing occurred in a distributed network including prefrontal, parietal and temporal areas. They highlighted the role of these regions in the representation of amodal conceptual knowledge where information from different modalities is integrated.

However, brain areas that are commonly activated in different language tasks (e.g. picture naming, written word reading, listening to spoken words) do not necessarily represent amodal conceptual information. In the classical univariate fMRI approach, activation in a common brain area in different modalities does not necessarily imply that the semantic representations overlap across the different modalities. More specifically, activation in common brain areas may reflect either different semantic representations for the different modalities or amodal semantic representations. However, within this classical fMRI approach a distinction between these two possibilities can not be made.

Here, multi-voxel pattern analysis (MVPA) may be very useful for a more fine-grained analysis of the overlap of semantic representations across modalities (Haynes et al., 2007; Norman, Polyn, Detre, & Haxby, 2006). In MVPA, it is only possible to predict or classify a given concept across different modalities if semantic representations overlap across modalities. To our knowledge, only Fairhall and Caramazza (2013) and Simanova, Hagoort, Oostenveld and Van Gerven (2014) investigated semantic overlap across different modalities in monolingual (L1) language processing through MVPA. In the study of Simanova et al. (2014), the participants had to judge the semantic category of target words in word reading and listening. Afterwards, as a language production task, there was a free recall session of the stimuli used in the categorization task. In this study, Simanova et al. (2014) found support for the involvement of the left inferior temporal cortex and frontal regions in the amodal representation of semantics. In the study of Fairhall and Caramazza (2013), participants saw words and pictures from five semantic categories and they needed to judge how typical each item was for the representation of its semantic category. They argued that the precuneus and the posterior middle/inferior temporal gyrus are crucial amodal semantic hubs. Both studies supported the idea of amodal representations of conceptual properties of objects, although they didn't completely converge on the specific neural localization, which may of course also be domain- and stimulus-dependent.

Interestingly, the studies discussed above have all tackled this debate from a monolingual perspective. However, nowadays more than half of the world population has knowledge of two or more languages, and can therefore be considered bilingual (Grosjean, 1992). Therefore, a second interesting question about the semantic system in the brain has arisen, which is about the extent to which neural representations of meaning overlap not only across modalities, but also across languages. The recruitment of a second, duplicate semantic network during L2 processing to represent almost the same knowledge as L1 would not be very parsimonious. And, indeed, theoretical models of bilingualism often assume shared semantics across languages, such as the revised hierarchical model (Kroll & Stewart, 1994), the BIA+ model (Dijkstra & van Heuven, 2002) and Green's convergence hypothesis (Green, 2003). However, this does not imply that the semantic representation of every concept should completely overlap across languages. Other models, like the distributed feature model (Van Hell & De Groot, 1998) or the model of Duyck and Brysbaert (2004) assume partially overlapping semantic representations between translation equivalents across languages, depending on specific characteristics of the concepts. They argued that the overlap in meaning, indexed by the number of shared semantic features, is larger for concrete translations, cognates and noun translations, relative to abstract translations, non-cognates and verb translations. In this view, the semantic representation of *apple* and *appel* for English-Dutch bilinguals would be shared to a larger degree than the representations of translation equivalents *justice* and *rechtvaardigheid*. Interestingly, there are also some empirical findings that suggest at least partly different semantic systems across languages. For instance, in Sahlin, Harding and Seamon (2005), English-Spanish bilinguals had to remember lists of semantically related words that were later probed for recognition. False recognition of semantic distractors was more frequent if study and test language were the same. This shows that semantic encoding may still be sensitive to the input language.

In addition, the idea of shared semantics that was implied in the early behavioral literature and theory on bilingualism (Kroll & Stewart, 1994) was also confirmed in the majority of classical neuroimaging studies. Hernandez, Dapretto, Mazziotta and Bookheimer (2001), Klein, Milner, Zatorre, Meyer and Evans (1995) and Pu et al. (2001) for example reported overlap in semantic activation between L1 and L2 during word production. Likewise, Ding et al. (2003), Illes et al. (1999) and Pillai et al. (2004) reported overlap in semantic activation between L1 and L2 during word comprehension. However, only a few studies have used MVPA to investigate neural overlap of semantic representations across languages, and those studies were always restricted within a single, specific modality (Buchweitz, Shinkareva, Mason, Mitchell, & Just, 2012; Correia et al., 2014; Van de Putte, De Baene, Brass, & Duyck, 2017). In a prior study, we used a production task that required the naming of the same concepts in both languages and we found significant decoding accuracies across languages in the bilateral middle occipital gyrus, fusiform gyrus and the inferior and middle temporal gyrus (Van de Putte, et al., 2017). This suggests that semantic representations serving speech production in both languages overlap in the indicated brain areas. Correia et al. (2014) used a word listening task that required listening to the same words in both languages while judging the animacy of the words. They found significant decoding accuracies in the left anterior temporal lobe, the left angular gyrus, the left postcentral gyrus, the right posterior superior temporal gyrus, the right medial anterior temporal lobe, the right anterior insula and the bilateral occipital cortex. Buchweitz et al. (2012) used a word reading task, that required the same words to be silently read in both languages. Significant decoding accuracies were found across languages in the left inferior frontal gyrus, the left posterior superior temporal lobe, the postcentral gyrus, the occipital cortex and the left inferior parietal sulcus. In these three studies, reliable prediction of the individual concepts was possible across languages.

However, the identified brain regions differed across studies and, more importantly, across modalities.

Although these studies are very interesting for evaluating the extent to which semantic representations are shared across languages after semantic access from a specific language modality, they are not suited for determining the extent to which these language-independent semantic representations also converge across language modalities, because different tasks, experimental designs and participants were used. There is currently no comprehensive MVPA study that investigates the semantic neural representation across languages in bilinguals, incorporating different language tasks or modalities. Therefore, the goal of this study was to examine how the different languages are represented in the bilingual brain at a semantic level in different modalities, using a decoding approach. We assessed brain activation during L1 and L2 processing using tasks that tap selectively into the different language modalities, and investigated to what extent neural language overlap depends on the language modality at hand, within the same bilingual subjects. This approach not only allows a cross-validation across different language modalities, contrasting language production with comprehension, it also allows finding support for the integration or separation of L1 and L2 semantic representations. In the neuroimaging literature on bilingualism, such integrative research of language production and recognition systems across languages within the same participants does not yet exist.

MATERIALS AND METHODS

Participants

Twenty-two right-handed Dutch-French bilinguals (10 males, 12 females; mean age = 23.64, range = 20-27 years) participated in the study in exchange for a monetary compensation. The same participants who participated in the production part of the study reported in Van de Putte et al. (2017) also completed two other fMRI experiments. Of these 24 participants, 2 participants didn’t want to participate anymore and they were excluded from all analyses. All participants followed French courses at school from the age of 9 as part of the standard educational system in Flanders. Thirteen early simultaneous bilingual participants acquired Dutch and French from birth. They spoke French with their parents, Dutch at school and switched frequently between Dutch and French with their peers. Of the nine late sequential bilingual participants, three followed an additional high level French language education program, two had a job in which they often have to use both Dutch and French and four learned French at primary school but only have been using it occasionally since their graduation from secondary school. All recruited participants reported that they had normal vision and hearing abilities and were neurological and psychological healthy. All participants gave written informed consent prior to the experiments. The study was approved by the Ethical Committee of Ghent University hospital and all methods were carried out in accordance with the relevant guidelines and regulations.

Materials

Information about the participants' self-assessed language proficiency, language switching frequency and the age of acquisition of both languages was measured with a language background questionnaire. To also obtain online measures of bilingual proficiency in Dutch and French, the LexTALE (Brysbaert, 2013; Lemhöfer & Broersma, 2012) and the Boston Naming test (BNT; Kaplan, Goodglass, & Weintraub, 1983) were administered. The LexTALE is a comprehension-focused vocabulary test that gives a good indication of general Dutch and French proficiency. 70 existing words and 20 nonwords were used in the extended version of the Dutch LexTale (Lemhöfer & Broersma, 2012) and 56 existing words and 28 nonwords were used in the French Lextale (Brysbaert, 2013). The BNT is a 60-item picture-naming test that is assumed to measure word retrieval abilities and is more focused on production. The participants were asked to name the pictures in Dutch and French. The order of the languages in the LexTALE and the BNT was counterbalanced across participants (see Table 1 for results on these tests).

Group	Proficiency	Dutch (L1)	French (L2)
Simultaneous bilinguals *(n=15)*	Lextale	59.85 (6.96)	43.21 (21.30)
	Boston Naming Test	51.53 (5.22)	43.67 (6.04)
	Self-Ratings	19.53 (1.30)	17.93 (1.75)
High proficient sequential bilinguals *(n=3)*	Lextale	64.99 (10.16)	61.31 (19.67)
	Boston Naming Test	56 (0)	41 (4.36)
	Self-Ratings	20 (0)	17.67 (2.52)
Middle proficient sequential bilinguals *(n=2)*	Lextale	69.15 (1.20)	43.75 (16.42)
	Boston Naming Test	53 (1.41)	33 (2.83)
	Self-Ratings	20 (0)	15 (1.41)
Low proficient sequential bilinguals *(n=4)*	Lextale	68.34 (3.04)	21.43 (3.57)
	Boston Naming Test	55 (2.94)	30.25 (7.85)
	Self-Ratings	20 (0)	13 (2.45)

Table 1. *Overview of language proficiency scores for the simultaneous and sequential bilinguals. The self-ratings are on a 5-point Likert scale and are averaged across listening, speaking, reading and writing.*

Experimental procedure

To examine whether the semantic neural representations are shared across languages and modalities, the exact same 10 object concepts were used in three separate fMRI experiments, each focusing on a specific task (picture naming, word reading and word listening). To examine whether the neural overlap between L1 and L2 semantic representations is common for the three language modalities, the 3 fMRI experiments were ran within the same participants. For picture naming, the dataset was the same as that used in our previous study (Van de Putte, De Baene, Brass, & Duyck, 2017), so that comparisons of picture naming with word reading and word listening was possible within the same participants. All three fMRI studies were organized in 2 consecutive parts (a Dutch and a French part). The order of conditions was counterbalanced across participants.

The three different tasks were designed to be as dissimilar as possible in terms of sensory processing and task demands, but they all required access to the same underlying semantic representation of the concepts. In the picture naming task, participants were asked to produce the names of 10 concepts in Dutch and French (we maximally reduced the visual similarity of pictures representing translation equivalents, see appendix 1 in Chapter 2 for an overview of all pictures). The other two fMRI experiments focused on semantic representations accessed during language comprehension: in the word-reading task (requiring visual comprehension), participants had to read the same 10 concepts in silence and judge whether each concept was animate or inanimate (accessing semantics) by pushing the left or right button. In the word-listening task (requiring auditory comprehension), participants had to listen to the same 10 concepts while performing another categorization task in which they pushed the right or left button to answer the question: "Is the concept bigger or smaller in size than a football?".

In order to ensure that the MVPA results reflect the underlying (shared) semantic representations and not merely the sensory similarities across languages and/or modalities, we selected two different images, two written translation equivalents without orthographic overlap and two spoken translation equivalents without phonological overlap, for each concept (e.g. horse; Dutch: paard, French: cheval) for each language. We minimized perceptual similarities in both the visual stimuli (view point and color between the two images of the same concept in the naming task and the letter size/font/color between the translation equivalents of the written words in the word-reading task) and the auditory stimuli (speaker gender and age between the translation equivalents of the spoken words in the word-listening task). The stimuli of a concept pair did not have any lexical overlap (overlapping phonemes and graphemes) across languages, as illustrated by the maximal levenshtein distance of 1.00 (SD=0) between Dutch and French translation equivalents (Levenshtein, 1965). Furthermore, the translation equivalents were also matched on word length ($p>0.19$) and familiarity ($p>0.88$).

The pictures and written words were presented for 1000 ms. Average pronunciation duration of the spoken words was 743 ms (range between 462 ms and 1033 ms). After stimulus presentation, a fixation cross was shown until the start of the next trial. The time between the response and the start of the next trial was jittered (mean = 2600 ms, range = 1000-5200 ms, in steps of 300 ms, distribution with pseudologarithmic density). In all three tasks, each language part included 5 experimental scan blocks of 60 trials. Within a block, each of the 10 concepts was randomly presented 6 times. The experimental blocks of each language part were preceded by a practice block (10 trials each) and in the naming task an additional familiarization block was included prior to the practice blocks to make sure that the participants named the pictures correctly.

fMRI data acquisition

Subjects were scanned with a 3T Magnetom Trio MRI scanner system (Siemens Medical Systems, Erlangen, Germany). We used a standard

32-channel radio-frequency head coil. Participants were positioned head-first supine in the magnetic bore. To avoid motion artefacts, the participants were instructed not to move their heads. For each participant, the scanning procedure began with a high-resolution 3D structural scan, using a T1-weighted 3D MPRAGE sequence (TR = 2250 ms, TE = 4.18 ms, TI = 900 ms, acquisition matrix = 256 x 256 x 176, FOV = 256 mm, flip angle = 9˚, voxels resized to 1 x 1 x 1mm). Next, whole brain functional images were collected using a T2*-weighted EPI sequence, sensitive to BOLD contrast (TR = 2000 ms, TE = 28 ms, image matrix = 64 x 64, FOV = 224 mm, flip angle = 80˚, slice thickness = 3 mm, distance factor = 17%, voxels resized to 3 x 3 x 3 mm, 34 axial slices). Per run, a fixed number of images (152) was acquired.

fMRI data preprocessing

Preprocessing and analysis of the fMRI data was performed using SPM8 software (Wellcome Department of Cognitive Neurology, London, UK). Reduction of T1 relaxation artefacts was pursued by exclusion of the first nine scans of all runs. The functional images were motion corrected with ArtRepair (Artifact Repair Toolbox v4), corrected for slice scan time differences and spatially realigned to their mean image by rigid body transformation. The anatomical image was normalized to the Montreal Neurological Institute (MNI) template brain image. The functional images were aligned with the high-resolution anatomical image to ensure an anatomically-based normalization. The low frequency artefacts in the time series data were removed using a high-pass filter with a cutoff at 128 s.

For each modality and separately for the two language parts, statistical analyses were performed on individual subjects' data using the general linear model (GLM) in SPM8. Trials with incorrect semantic categorization were excluded from the analysis. The fMRI time series data were modelled by 10 different vectors, one for each semantic concept. All these vectors were convolved with a hemodynamic response function (HRF), as well as with the temporal derivative and entered into the regression model (the design matrix). Additionally, six motion parameters were added to the design matrix as regressors of no interest to account for variance related to head motion. The statistical parameter estimates were computed separately for all columns in the design matrix.

Whole brain MVPA analysis

To investigate the neural overlap between Dutch and French semantic representations, within and across the three tasks (naming, word reading and word listening), a multivariate decoding analysis was applied with the PyMVPA toolbox (Hanke et al., 2009). Multivariate decoding analyses were performed on the normalized but unsmoothed images to maximize the sensitivity to extract the full information in the spatial patterns, which might be reduced after smoothing (Misaki, Luh, & Bandettini, 2013). Therefore smoothing was applied after multivariate decoding, prior to the second-level analyses with an 8 mm full-width half-maximum (FWHM) Gaussian kernel. A spherical searchlight with a radius of 3 mm was applied to extract local spatial information from small brain spheres that carry information about the semantic concept (Kriegeskorte, Goebel, & Bandettini, 2006). The searchlight used the K Nearest Neighbours pattern classifier for this semantic classification (Hanke et al., 2009). Note that the use of other classifiers yielded similar results.

Because one aim of the present paper was to investigate cross-lingual overlap, within tasks, we primarily focused on the across-language decoding analysis. For within-language analyses, the exact same stimuli (identical pictures, written words and spoken words) are by definition included, making it difficult to disentangle semantic activation from other overlapping visual, auditory or lexical features when applying MVPA. Across languages, visual and phonetical/acoustical similarities between the stimulus pairs of a concept and lexical similarities between the translation equivalents were maximally reduced in all three tasks to assure that classifier performance only reflected access to the shared semantic representation needed for the task in the two languages. The classifier was trained on the task-specific activation pattern associated with each of the 10 concepts in one language in four of the five blocks (training data set). Subsequently, this pattern classifier was used to classify the task-specific activation pattern for each of the 10 concepts in the corresponding fifth block of the other language (test data set). This procedure was repeated 5 times, so that each block could function as a test block once, while the other blocks were used as training blocks. Mean decoding accuracy maps across all five classifications were achieved for each participant in two directions (Dutch as training blocks and French as test block and vice versa). These across-language decoding accuracies were then averaged across the two directions, resulting in one mean decoding accuracy map across languages for each participant.

Additionally, in order to achieve our second aim, examining whether the semantic representations are shared across the three language modalities, MVPA was applied across modalities. Across modalities, we again only focused on the across-language decoding, because semantic overlap may by definition not be distinguished from lexical overlap in the within language decoding analysis, as this implies decoding activation after exposure to the same stimuli. For instance, a pattern classifier was trained on the activation pattern associated with the performance in L1 during the naming task and then tested on how well it decoded the activation pattern associated with the performance in L2 during reading or listening. The underlying assumption was that the classifier would only be able to accurately predict which stimulus/concept was processed in the reading or listening task based on the activation in the naming task, if semantic representations overlap across these tasks. Across tasks there wasn't any visual or auditory confound, because pictures, spoken words and written words of the same concepts relied on different sensory features.

Within modalities second level analyses

To investigate how well decoding could be performed across all subjects, whole brain, voxel-by-voxel second-level statistical analyses were performed (Haynes et al., 2007). Whole brain searchlight analysis was interpreted as significant if decoding accuracies above chance level (10%) were observed. A one-sample t-test was used to reveal significant decoding of semantic concepts across languages, within the separate tasks. The significance thresholds of the group maps were all corrected for multiple comparisons at the cluster level ($p < 0.05$) and the voxel thresholds were either corrected for multiple comparisons ($p < 0.05$) or $p < .001$ uncorrected. Classification accuracies significantly above chance implied that the classifier was able to accurately predict which concept was named (or heard/read), whereas chance level performance implied that it was not possible to predict the concept that was named (heard/read). In all three tasks, brain regions that showed significant classifier prediction accuracy across languages indicate overlap between the semantic representations of L1 and L2.

Across modalities second level analyses

Next, we investigated the language overlap of brain regions across pairs of tasks that each used different stimulus modalities. More specifically, we wanted to investigate whether it’s possible to predict a concept in one modality/task based on the brain activity of that same concept in another modality/task and language. To reveal significant decoding of semantic concepts across each combination of tasks (naming-word reading, naming-word listening, word reading-word listening) a one-sample t-test was used to examine whether semantic representations overlap across the different language modalities. The one-sample t test and statistical thresholds were the same as for the within modalities second level analyses.

Region of interest analyses (ROI)

In addition to our whole brain approach, we also wanted to investigate whether regions that are reported to be involved in the previous literature on semantic processing in L1 word reading are also involved across L1 - L2 word reading, L1 - L2 production and L1 - L2 word listening. Hence, we additionally applied ROI analyses to distinguish whether neural representations within the same brain regions were different or the same for word reading, word listening and production. Our regions of interest were generated from an independent study of semantic processing of English words, relative to perceptual matching of meaningless symbols in monolingual English speakers. Paradigm details and results from this study have previously been reported by Seghier et al. (2010; 2011; 2012; 2013). The 5 brain regions that were significantly involved in semantic association decisions on written words relative to perceptual association decisions on meaningless visual stimuli of equal complexity were: the left superior motor area, the left inferior frontal gyrus, the left middle temporal gyrus, the cerebellum and the left middle frontal gyrus (see Figure 2). We used these regions of interest (ROI) associated with semantic processing of written words in a first language to test whether they were also activated in L2 word reading, production and word listening. Specifically, we tested whether activation could be predicted across L1 and L2 within word reading and/or word listening and production.

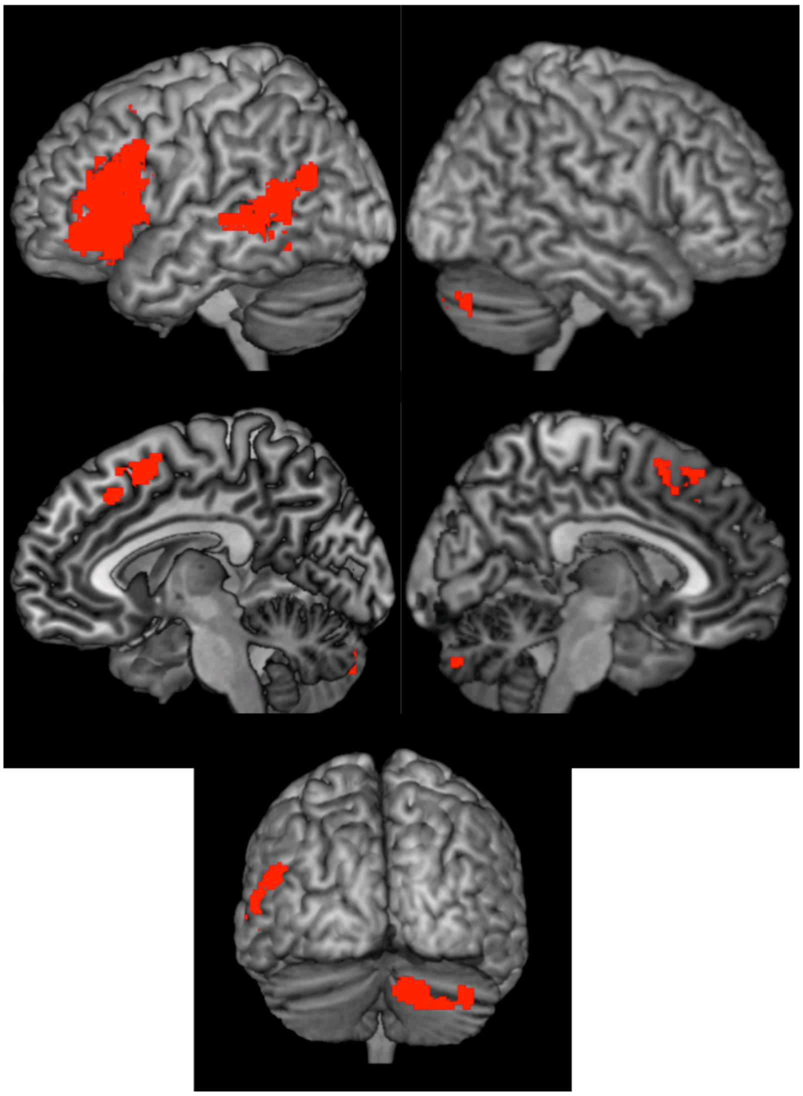

Figure 2. *Regions of interest (ROI's) associated with semantic processing of written words in a first language (Seghier et al., 2010; 2011; 2012; 2013).*

We tested the statistical significance of the group-level mean accuracy using a combination of permutation and bootstrap sampling methods (Stelzer et al., 2013). Specifically, we first permuted the stimulus labels of the 10 stimuli within each run and calculated the accuracies for each ROI for each participant using leave-one-run-out cross-validation. By repeating this procedure 100 times, we obtained 100 chance accuracies at the single participant level. Previous analyses have indicated that this number of repetitions is sufficient to achieve reliable estimation of false positive results (Stelzer et al., 2013). Next, we randomly sampled one of the chance accuracies from each participant and averaged these to obtain a chance group-level accuracy. This sampling (with replacement) was repeated 10000 times to create a group-level null distribution. For each ROI, the observed group-level accuracy was then compared to the group-level null distribution to obtain the associated *p*-value. A multiple comparison correction based on false discovery rate ($P<0.05$ FDR) was then applied at the group level on all P values associated with the 5 ROI's.

RESULTS

Neural overlap across languages within tasks

For picture naming, above chance decoding accuracies across languages were observed in the left middle occipital gyrus extending into the left fusiform gyrus, the right lingual gyrus extending into the right inferior temporal gyrus and left inferior temporal gyrus extending into the left hippocampus (Table 2; Figure 1, red).

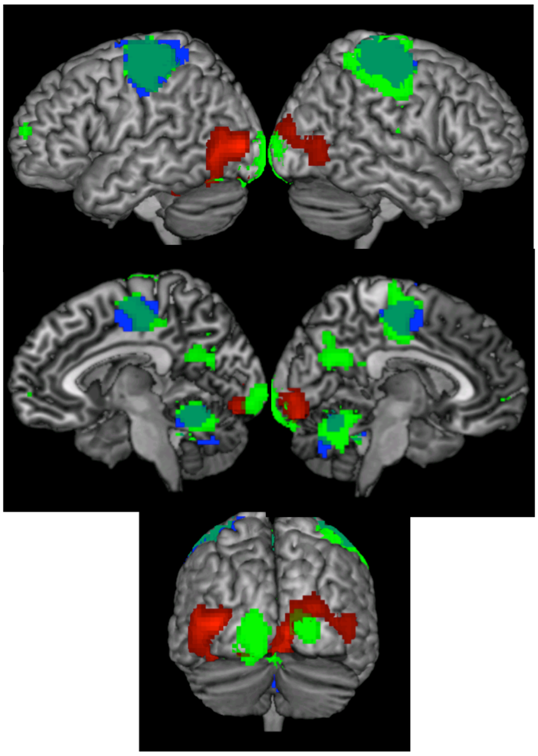

Figure 1. *Results of the whole brain searchlight analysis showing discriminability between semantic concepts in the generalization across languages in naming (red), word reading (green) and word listening (blue). The color represents the t-values resulting from the group level analysis using a threshold of p < .001 at voxel level and a cluster level corrected for the whole brain at p < .05.*

Brain region	X	Y	Z	Z-score	Cluster size
Left middle occipital gyrus	-39	-85	4	**5.25**	635
Right lingual gyrus	9	-88	-2	**4.94**	773
Left inferior temporal gyrus	-42	-43	-26	3.85	113

Table 2. *Results of the across-language decoding analyses in production. All thresholds were FWE corrected in extent (Z scores in bold are also corrected in height).*

For word reading, above chance decoding accuracies across languages were observed in the bilateral precentral gyrus extending into the postcentral gyrus, the left middle occipital gyrus, the left inferior occipital gyrus, the right calcarine sulcus, the bilateral cerebellum, the left inferior frontal gyrus, the left superior frontal gyrus, the right precuneus and the right rolandic operculum (Table 3; Figure 1, green).

Brain region	X	Y	Z	Z-score	Cluster size
Right precentral gyrus	42	-19	58	**6.32**	3998
Left middle occipital gyrus	-12	-97	4	**5.32**	380
Right Calcarine	24	-91	4	**5.22**	180
Vermis	6	-58	-29	4.64	893
Left inferior frontal gyrus	-39	20	19	3.82	118
Left superior frontal gyrus	-18	62	13	3.62	109
Right precuneus	0	-64	22	3.78	180

Table 3. *Results of the across-language decoding analyses in word reading. All thresholds were FWE corrected in extent (Z scores in bold are also corrected in height).*

For word listening, above chance decoding across languages was observed in bilateral precentral gyri extending into the postcentral gyri, bilateral cerebella and the right rolandic operculum (Table 4; Figure 1, blue).

Brain region	X	Y	Z	z-score	Cluster size
Left precentral gyrus	-36	-19	58	**6.15**	1649
Left cerebellum	-15	-49	-20	**5.82**	597
Right postcentral gyrus	33	-28	55	**5.62**	1278
Right rolandic operculum	45	-13	22	4.13	101

Table 4. *Results of the across-language decoding analyses in word listening. All thresholds were FWE corrected in extent (Z scores in bold are also corrected in height).*

Neural overlap across tasks and languages

We also applied MVPA across tasks to investigate whether shared neural representations across languages are involved across modalities. This would provide strong evidence for an integrative semantic neural representation across modalities, because stimuli were not sensory or phonologically confounded across tasks. Across modalities and languages, only significant encoding of semantic information was observed for the decoding analyses across production and word reading, namely in the left lingual gyrus (Table 5). Lowering the voxel-level threshold to $p < .005$ (instead of $p < .001$) did not result in any additional regions across the other tasks.

Modality	Brain region	X	Y	Z	z-score	Cluster size
Production – word reading	Left lingual gyrus	-18	-82	-2	**4.90**	240

Table 5. *Results of the across-language decoding analyses across modalities. The threshold was FWE corrected in extent and height.*

Region of interest analyses (ROI)

Within five regions of interest (Figure 2) that have previously been associated with the representation of semantics in L1 word reading, we investigated whether there was also evidence of the same semantic representations across L1L2 word reading, across L1L2 production and across L1L2 word listening (Table 6). Three of the five ROI's (the left superior motor area the left inferior frontal gyrus and the left middle temporal gyrus) showed significant across-language decoding accuracies in our word reading task after FDR correction. None of these ROI's however showed above-chance prediction accuracies in the decoding across languages in the word listening task or the production task. Hence, these regions seem specific for the language independent semantic representation during word reading and could not be generalized to the language independent semantic representation during word listening or production.

Brain region	Coordinates	Task	P
Left inferior frontal gyrus	-45 23 12	Word reading across languages	0.0002**
		Word listening across languages	0.3787
		Production across languages	0.4116
Left middle temporal gyrus	-56 -44 4	Word reading across languages	0.0048*
		Word listening across languages	0.3008
		Production across languages	0.1564
Cerebellum	20 -78 -35	Word reading across languages	0.3338
		Word listening across languages	0.8215
		Production across languages	0.6179
Left superior motor area	-3 16 53	Word reading across languages	0.0097*
		Word listening across languages	0.1211
		Production across languages	0.2327
Left middle frontal gyrus	-27 13 52	Word reading across languages	0.1411
		Word listening across languages	0.7881
		Production across languages	0.0664

*p<0.05; **p<0.01; ***p<0.001.

Table 6. *Across languages Region of interest (ROI) analyses within the three modalities.*

DISCUSSION

In the present study, we used MVPA to investigate the neural overlap between semantic representations tapped into by both languages of Dutch-French bilinguals, and the overlap of these representations across language modalities. MVPA was used because of the advantage of this technique to deduct cognitive representations from brain signals (Haxby et al., 2001; Haynes et al., 2007). This is the first study to examine whether decoding of individual semantic concepts across languages was possible across tasks (that used different stimulus modalities), within the same individuals.

In this group of mainly high proficient bilinguals, the results showed that encoding of semantic information was possible across languages, for each of the three tasks. It was possible to identify the picture/word named, read or heard in one language based on the brain activity observed while naming, reading or listening the picture or word in the other language. However, the brain regions that predicted commonality in across-language representations differed across tasks. For picture naming, the across-language overlap was identified in regions associated with object recognition: the bilateral middle occipital and fusiform regions extending into the inferior temporal regions. A first interesting type of regions was observed in the across-language overlap for word reading and word listening. More specifically, significant decoding across languages in word reading was possible in visual processing regions (left middle occipital gyrus extending into the left inferior occipital gyrus, the right calcarine), and in regions associated with higher cognitive functions (the left inferior frontal gyrus, the left superior frontal gyrus and the right precuneus). For word listening, the across-language overlap was identified in the rolandic operculum, which was something surprising given that this region's role for language processing was mostly linked to phonological, rather than semantic processing (Tongkonogy & Goodglass, 1981; Vigneau et al., 2006). Together, the results from these across-language analyses show that all modalities tap into neural representations of semantics that at least partly overlap across languages. Therefore, they are consistent with theoretical models of bilingualism that posit such shared semantics across languages, such as the revised hierarchical model (Kroll & Stewart, 1994), the BIA+ model (Dijkstra & van Heuven, 2002), Green's convergence hypothesis (Green, 2003) and the distributed feature model (Van Hell & De Groot, 1998; for a similar model, see Duyck & Brysbaert, 2004).

In addition, for word listening, and also for word reading, the second type of regions that showed across-language overlap was of less theoretical significance because it concerned regions associated with sensorimotor processing: the bilateral precentral gyrus extending into the postcentral gyrus and the bilateral cerebellum. The involvement of these sensorimotor regions should be interpreted with care in word reading and word listening, because the semantic category required the same button response for each language. In word reading the left button was for example always associated with the judgment *animate* and the right button with *non-animate* or vice versa. Similarly, in word listening the left button was always associated with the judgment *bigger than a football* and the right button was always associated with *smaller than a football,* or vice versa. Hence for the sensorimotor regions it was not possible to distinguish whether significant decoding accuracies could be attributed to overlapping semantic representations or sensorimotor representations.

The involvement of inferior frontal and occipital regions in our word reading task are in line with the results of Buchweitz et al. (2012) who also applied decoding to investigate semantic neural overlap across languages in word reading. The contribution of the inferior frontal gyrus and the left superior frontal gryrus in the word reading task was furthermore consistent with the review of Binder, Desai, Graves, & Conant (2009). They showed that the inferior and superior frontal gyri are typically involved during semantic processing in a broad range of comprehension studies. The engagement of occipital regions and the calcarine in our word reading and production task fits within the embodiment idea, because occipital regions are not only shown to be activated during visual stimulation, but also during tasks that didn't use visual stimuli. Therefore, mental imagery as part of the semantic representations could be a possible explanation (Klein et al., 2000; Lambert et al., 2002). The concept cat for example may include visual features (four legs, tail, whiskers), acoustic features (meows) and emotional aspects (love or disgust) that are dependent on the individual experience with the concept. We only used concrete concepts that are all imaginable, which in accordance with the embodiment view may imply conceptual representations that might differ dependent on the individual experiences that are associated with the concepts throughout life experiences (Kiefer & Pulvermüller, 2012). Therefore, the comparison with conceptual representations of abstract words across languages and modalities within the same subjects would be of added value in this research field. As shown by Wang et al. (2010) concrete concepts could for example be associated more profoundly with perceptual regions than abstract concepts, because concrete concepts are more imaginable than abstract concepts.

Additionally, we applied ROI analyses on five brain regions that have previously been associated with the representation of semantics in L1 word reading to investigate whether these regions also generalize to L2 word reading and production and word listening. In our word reading task, we replicated the involvement of the left superior motor area, the left inferior frontal gyrus and the left middle temporal gyrus in the decoding across languages. We could therefore assume that these regions that are reported to be involved during semantic processing in L1 word reading generalize to L2 word reading. However, none of these ROI's was significant in the decoding across languages within word listening, nor in the decoding across languages within production. Hence, the activated brain regions for semantics might fluctuate depending on the language modality involved and the specific task characteristics that are associated with language modality. This might explain the varying brain regions identified in different studies, because depending on the experimental task, different aspects of semantics could result in the involvement of different brain regions. These results provide evidence for distributed semantic models in which concepts are flexible, distributed in the brain, and dependent on the specific modality at hand (Barsalou et al., 2003; Kiefer & Pulvermüller, 2012; Tyler & Moss, 2001; Musz & Thompson-schill, 2016).

In addition to the question whether semantic representations overlap across languages, the other aim of the present paper was to investigate whether semantic representations also overlap across both languages ànd modalities. Importantly, in this analysis the unintentional lexical, sensory and motor overlap is ruled out, as there wasn't any lexical confound across languages (overlapping graphemes and phonemes were minimal between the translation equivalents of the same concepts) and there wasn't any sensory or motor confound across modalities (different tasks were used across modalities that relied on different sensory features and required different motor responses). This analysis showed that across-language decoding was only possible across production and word reading in the left lingual gyrus. Hence, across modalities, it was only possible to identify the picture the participant was naming in one language based on the neural activation patterns in the left lingual gyrus observed during the presentation of the equivalent written word in the other language and vice versa. This suggests that the lingual gyrus might play a crucial role in the integration of language independent semantic information across modalities (at least across production and word reading). The role of the lingual gyrus in semantic integration across modalities converges with the findings of Musz and Thompson-schill (2016), who argued that the lingual gyrus is an important semantic hub across different semantic contexts. More specific they showed that variation of neural patterns in the lingual gyrus reflects variation in the conceptual processing of concepts across variations in their semantic contexts. Despite the common brain regions that are involved in the across-modality decoding analyses across word reading and production, no significant brain regions were observed in the decoding across word reading and word listening and the decoding across production and word listening. These findings support the idea of both a-modal and modality-dependent semantic representations that nevertheless overlap across languages (Bonner et al., 2013).

The evidence for an amodal semantic hub in our findings is in line with the results of Fairhall and Caramazza (2013) and Simanova et al. (2014), who also adopted a similar decoding approach and also provided evidence for the existence of amodal semantic representations. They didn't, however, completely converge on the specific neural localization, which may of course also be domain- and stimulus-dependent. Simanova et al. (2014) argued that these amodal representations are located in the left inferior temporal cortex and frontal regions, while Fairhall and Caramazza (2013) argued for the localization in the precuneus and the posterior middle/ inferior temporal gyrus**.** An important difference was however that the current study tried to predict individual semantic concepts across modalities, whereas the studies of Fairhall and Caramazza (2013) and Simanova, Hagoort, Oostenveld and Van Gerven (2014) assessed the representation of broad semantic categories across modalities.

In the literature about semantic organization, an interesting debate has also arisen about whether or not semantic representations are more local than distributed. According to the local view, a concept is represented as a single node within a unitary semantic network (Bowers, 2009; Collins & Quillian, 1969; Kiefer & Pulvermüller, 2012). In these localist models, meaning is represented by fixed unitary concept nodes that are connected within a semantic network. To compensate for the absence of conceptual flexibility in these localist models, distributed semantic models have suggested that concepts are represented by multiple representational units that can be adjusted through experiences. These models assume that meaning results from the interactions of neurons through synaptic connections, in which the meaning of a concept ("dog") arises due to the activation of a combination of semantic features (barks, animal, tail) or processing units (Barsalou et al., 2003; Kiefer & Pulvermüller, 2012; McClelland & Rogers, 2003; Smith, Shoben, & Rips, 1974; Tyler & Moss, 2001). Although this is an interesting question that also tackles the way semantics are represented, we can't really distinguish the two possibilities in the current study because we didn't investigate whether the individual concepts are represented by separate neurons that reflect local representations for each concept or separate neural networks that represent multiple representation units for each concept.

To conclude, our results provide evidence for at least partially language-independent semantic representations that rely on a distributed semantic network that includes both an a-modal, integrative representation and modality specific representations.

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CHAPTER 4

BILINGUAL NEURAL REPRESENTATION OF HOMOGRAPHS, COGNATES AND NON-COGNATES: A DECODING APPROACH[1]

Although most research agrees that both languages of a bilingual are represented in at least partly shared neural semantic systems for language production, it remains unclear whether lexical neural representations of different languages share neural systems as well. In the current study, we therefore investigated the neural overlap of lexical and semantic representations across languages during speech production. In order to dissociate cross-lingual lexical and semantic overlap, we used a decoding approach to investigate the neural activation during production of homographs, cognates and non-cognate translations.

The decoding results for the non-cognate translations showed shared semantic representations across first- and second-language production in the inferior occipital, fusiform regions and lingual gyrus. Decoding results for the homographs showed shared lexical representations across languages in the superior frontal, superior temporal, inferior parietal, middle and superior occipital and sensorimotor regions. In addition, decoding results for cognates, which share both semantic as lexical representations across languages, showed neural overlap across languages in inferior and middle temporal, middle and superior frontal, inferior parietal, inferior occipital, fusiform and sensorimotor regions. These findings support the BIA+ model that assumes both integrated lexical and semantic representations across languages.

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[1] Van de Putte, E., De Baene, W., Demanet, J., Duyck, W., & Carreiras, M. (2017). Bilingual neural representation of homographs, cognates and non-cognates: a decoding approach. *Manuscript in preparation*

INTRODUCTION

Understanding bilingual language processing is of high relevance for society given that more than 50% of the world's population knows more than one language (Grosjean, 1989). The three most influential models of bilingual language organization make different predictions about the way lexical representations (word form) and semantic representations (meaning) are represented across languages. The revised hierarchical model (Kroll & Stewart, 1994) with its focus on asymmetric lexico-semantic links assumes different lexical representations for each language but common semantic representations. The distributed feature model (Van Hell & de Groot, 1998) proposes different lexical stores for each language and partially overlapping semantic representations across L1 and L2. This overlap depends on specific characteristics of the concepts and the individual and cultural context in which the concept is learned and processed in both languages. They postulated for example that the overlap in meaning is larger for concrete translations, cognates and noun translations in comparison to abstract translations, non-cognates and verb translations. Finally, the Bilingual Interactive Activation model (BIA+ model; Dijkstra & Van Heuven, 2002), with its focus on orthographic lexical representations for bilingual word recognition, also assumes common semantic representations, but questions the idea that L1 and L2 word forms are stored in different lexicons for each language. They postulated the integrated non-selective access view, in which word candidates of both languages are activated in parallel and are stored in an integrated lexicon. In the present study, we will try to distinguish how the lexical and semantic representations are represented across languages at the neural level.

Lexical representations of L1 and L2 in bilinguals

In order to assess whether languages of bilinguals are represented in separate or integrated lexicons previous research investigated whether the processing of words in one language is influenced by the knowledge of orthographic or phonological similar words in another language. Influence of knowledge of words in a language that is irrelevant for the task at hand on target language processing provides strong evidence for integrated lexicons.

A first line of such research involves cognates, which share meaning and lexical form across languages. In a picture naming task, Catalan-Spanish bilinguals displayed longer naming latencies for non-cognate targets than cognate targets in L1 and L2 (Costa, Caramazza, & Sebastián-Gallés, 2000). Similarly, in the study of Colomé and Miozzo (2010) Spanish-Catalan bilinguals saw two coloured pictures and had to name the green picture in Spanish (ex: hoja, meaning leaf) and ignore the red picture, which was either a cognate across Spanish (taza, meaning *cup*) and Catalan (tassa), or a non-cognate across Spanish (red, meaning *net*) and Catalan (xarxa). They observed that cognate distractor pictures interfered more with Spanish naming of the target picture than non-cognate distractor pictures. These findings indicate that lexical representations of all languages are accessed or co-activated during word production in the target language. Comparable results on the parallel activation of both languages were observed for word reading. Bultena, Dijkstra, and van Hell (2013) studied both identical cognates that share meaning and identical orthography (e.g., tent in both

English and Dutch) across languages, as non-identical cognates that share meaning but only partial form (e.g., boat in English – boot and Dutch). They found that participants responded faster to both identical and non-identical cognates compared to control words in a lexical decision task.

A second line of research, limited to word recognition, involves inter-lingual homographs. These are words that share orthography, hence lexical information, but not meaning, or semantics, across languages (ex: *pan*, which means *pot* in English and bread in Spanish). Dijkstra, Timmermans and Schriefers (2000) showed that such inter-lingual homographs are recognized slower than control words because of cross-lingual interference.

A third line of research within the recognition literature involves inter-lingual orthographic neighbours. Orthographic neighbours are words that differ by one letter from a target word. Orthographic neighbours may belong to the same language as the target word (purse - nurse) or to a non-target language (e.g., purse – puree, mashed potatoes in Dutch). Van Heuven, Dijkstra and Grainger (1998) found that speed of L2 reading is not only depending on the amount of orthographic neighbours in L2, but also on the amount of such neighbours in Dutch (L1) even though L1 wasn't relevant for the task. In a related study, Thierry and Wu (2007) asked Chinese-English bilinguals to make semantic relatedness judgments on L2 words. Responses were faster when L1 Chinese translations contained a Chinese character repetition, showing orthographic L1 activation during L2 reading, even with different alphabets.

These three behavioural research lines all provided evidence for the integrated non-selective lexical access view, in which word candidates of both languages are activated in parallel and are stored in an integrated lexicon.

However, only a few neuroimaging studies investigated whether lexical representations from both languages are also represented in a common brain region. One exception is the neuroimaging study of Van Heuven, Schriefers, Dijkstra, & Hagoort (2008), who investigated inter-lingual homograph word recognition in English-Dutch bilinguals using a lexical decision task. Homographs were read slower in L2 than control words, and they yielded greater activation in the left inferior parietal cortex and the medial part of the superior frontal gyrus. They argued that this reflects conflict as a consequence of the automatic activation of lexical information from both languages. Furthermore, activation in brain regions related to cognitive control to handle cross language interference was not only observed for alphabetic writing systems, but was also replicated in logogram writing systems (Hsieh et al., 2017). More specific, Hsieh et al. (2017) investigated inter-lingual homograph and cognate word recognition in Chinese-Japanese bilinguals. For the cognates greater activation was only found in the SMA in comparison to the control words, whereas the anterior cingulate cortex, left thalamus and the left middle temporal gyrus were specifically involved during the processing of inter-lingual homographs compared to cognates and control words. They argued that inter-lingual homographs create more conflict than cognates and control words, due to the activation of two different meanings of one orthographic form. Hence, the cross-lingual interference conflict might be resolved by interplay with conflict monitoring in the anterior cingulate cortex. In contrast, they argued that the processing of cognates doesn't require such a control mechanism because cognates share meaning and orthographic form in both languages, what instead might even lead to cross-lingual facilitation instead of interference.

Semantic representations of L1 and L2 in bilinguals

Most behavioural research has provided evidence for the integration of L1 and L2 conceptual representations in a common semantic system. In semantic categorization tasks where participants had to decide whether the second word was a member or a non-member of the category indicated by the first word, response times were equivalent whether word pairs were from different languages or not (Caramazza & Brones, 1980; Dufour & Kroll, 1995; Francis, 1999). In addition, the majority of the primed lexical decision tasks have shown facilitation of target words preceded by semantically related primes in a different language (Francis, 1999; Grainger, 1998; Perea, Duñabeitia, & Carreiras, 2008). For example, responses to the word 'girl' were not only faster after the prime 'boy' but also after the Dutch translation equivalent: 'jongen' (Duyck & Warlop, 2009; Schoonbaert, Duyck, Brysbaert, & Hartsuiker, 2009). These cross-language priming effects were often stronger from L1 to L2 than from L2 to L1 (Keatley, Spinks, & de Gelder, 1994; Schoonbaert et al., 2009) and for concrete than abstract word pairs (Jin, 1990), which suggests that the difference between L1 and L2 representations is of a quantitative nature, rather than a qualitative nature, in accordance with the distributed feature model.

While behavioural studies can provide interesting insights in the functional semantic organization of L1 and L2, another question is whether semantic representations across languages are subserved by common or distinct cortical areas. Both the reviews of Indefrey (2006) and Stowe & Sabourin (2005), who investigated the neural overlap across L1 and L2 in a range of tasks, concluded that the majority of studies reported no differences in semantic activation between L1 and L2 for both word production and comprehension. Nonetheless, some studies found stronger activation for L2 processing in regions that are also involved in L1 processing. More specific, Indefrey (2006) concluded that L2 Age of acquisition (AOA), proficiency and exposure influence the neural representation during word level production, whereas word level comprehension is mostly influenced by proficiency.

Limitations of previous literature

A shortcoming in the previous literature on the neural lexical and semantic representation of L1 and L2 is that the majority of studies have used a univariate analysis approach. In the univariate approach the average activation over a set of voxels, that are all treated as similar, is used as an indication of whether or not a region is involved in a certain task or experimental condition (Mahmoudi, Takerkart, Regragui, Boussaoud, & Brovelli, 2012). Hence, it could be that a brain region seems to be involved in two experimental conditions despite the fact that the pattern of voxel activity is different for these two conditions. Within the univariate approaches, common activation between languages within an area can therefore be caused by different neural representations within the same area representing the different languages, or by overlapping neural representations for both languages. Only the latter observation is supportive of a real integrative view of L1 and L2 in bilinguals. Because the univariate approach is unable to separate these two possibilities, a shift towards multivariate decoding is of added value to complement the previous literature. In contrast with the univariate approaches, a multivariate decoding approach distinguishes patterns of neural activity associated with different stimuli (Haynes et al., 2007; Norman, Polyn, Detre, & Haxby, 2006). Hence, it's only possible to predict or classify stimuli across different languages if overlapping neural representations are involved across languages.

Currently, no studies assessed lexical neural representation across languages using MVPA and only three studies (Buchweitz, Shinkareva, Mason, Mitchell, & Just, 2012; Correia et al., 2014; Van de Putte, De Baene, Brass, & Duyck, 2017) used MVPA to investigate neural overlap of L1 and L2 semantic representations in bilingual language processing. Each of these studies investigated a different language modality (word reading, word listening, word production) and all three studies showed that significant decoding of semantic information was possible across languages, implying (at least partly) overlapping neural representation of meaning. However, the brain regions in which significant encoding of semantic information were observed differed across studies and hence across studied modalities. For word reading, significant decoding of semantic information was obtained in the postcentral gyrus and frontal, temporal and parietal regions (Buchweitz et al., 2012). For word listening, significant decoding of semantic information was found in temporal and occipital regions, insula, angular gyrus and postcentral gyrus (Correia et al., 2014). For production, significant decoding of semantic information was obtained in occipital, fusiform and temporal regions (Van de Putte et al., 2017). These findings provide evidence for overlapping semantic representations in L1 and L2 that might be modality specific. However, the neural activation of lexical representations across languages, as highlighted in the behavioural literature is still unknown. In the present study we investigated the neural overlap of both L1 and L2 semantic and lexical representations in language production within the same participants using the decoding approach, to see to what extent neural representation of semantic and lexical information are shared across languages.

Current research

In order to dissociate cross-lingual overlap in lexical vs. semantic representations, we studied stimuli that differ on those dimensions across languages. Unlike classical univariate fMRI studies, that compare neural activation during processing of critical items with activation during processing of control words, decoding tries to predict neural activation during processing of a stimulus in one language from activation when processing the stimulus in the other language. More specifically, we applied a decoding approach to investigate the neural representation of identical cognates (words that share lexical form and meaning across languages), homographs (words that share lexical form, but not meaning across languages) and non-cognate translation equivalents (words that share meaning but not orthography) within the same individuals. The rationale is that since homographs only have lexical overlap and no semantic overlap across languages, correct classifier prediction of neural activation during production of the homographs in one language from activation during production of the same homograph in the other language would imply neural overlap between L1 and L2 *lexical representations*. Similarly, since non-cognate translation equivalents only have semantic overlap across languages but no lexical overlap, correct classifier prediction of neural activation during production of non-cognates in one language based on activation during production of the same non-cognate in the other language would imply neural overlap between L1 and L2 *semantic representations*. In addition, correct classifier predictions for production of cognates across languages, may imply overlapping *semantic AND lexical representations*, given that both the meaning as lexical form are identical across languages. We investigated the neural overlap across languages for these three word categories in a production task.

MATERIALS AND METHODS

Participants

14 participants (19-30 years of age, 7 males, 7 females) took part in the production task. All participants were native Spanish speakers with a high proficiency in English, living in the vicinity of San Sebastian. Most participants acquired Spanish and Basque early on in childhood and they acquired knowledge of English later on as a third language during their education. They now frequently use English in daily life and work environment. Since the number of useful concrete cross-lingual homographs between Spanish and Basque is limited, we were restricted to investigate the neural overlap across Spanish and English instead of Spanish and Basque. None of the participants had a history of neurological disorders and all participants had normal or corrected-to-normal vision. Prior to the

experiment, written informed consent was given in accordance with the guidelines of the ethical committee from the Basque Center on Cognition, Brain and Language.

Experimental procedure and design

In order to get a more fine-grained insight in semantic and lexical neural representations, we investigated the neural representation of identical cognates, homographs and non-cognate translation equivalents across languages during production by the same individuals. Translation equivalents had an almost maximal levenshtein distance of 0.95 (SD=0.1), conforming absence of lexical overlap. Both homographs and cognates had minimal levenshtein distance of distance of 0 (SD=0; Levenshtein, 1965).

The procedure consisted out of 6 blocks for each language. The experimental scan blocks included 4 blocks of 84 trials (in which the 12 concepts were randomly presented 7 times), preceded by a practice block of 24 trials and a familiarization block of 12 trials. The language that had to be used was varied following a blocked design. The first 6 blocks were in one language. The last 6 blocks were in the other language and the order of the languages (Spanish - English/ English - Spanish) was counterbalanced across participants. We used a go - no go production task to keep the attention of the participants. The participants performed a picture naming task in which they had to name the pictures in English out loud if they saw the cue (go). If the cue was not shown, they had to name the pictures in silence (no go). This cue was shown after the stimulus presentation in 1/7 of the trials in the experimental blocks. In the practice blocks, the cue was shown in 1/2 of the trials.

Stimuli

12 concepts, 4 concepts of each category (cognates, homographs and non-cognate translation equivalents) were selected for the experiment (see figure 1). These concepts were matched on word frequency and word length across English and Spanish and across the different categories to create comparable conditions. Similar as in Van de Putte et al. (2017), we selected two completely different images (and minimized the visual similarities) per concept for each language in order to ensure that neural overlap across languages is not merely a reflection of visual similarities.

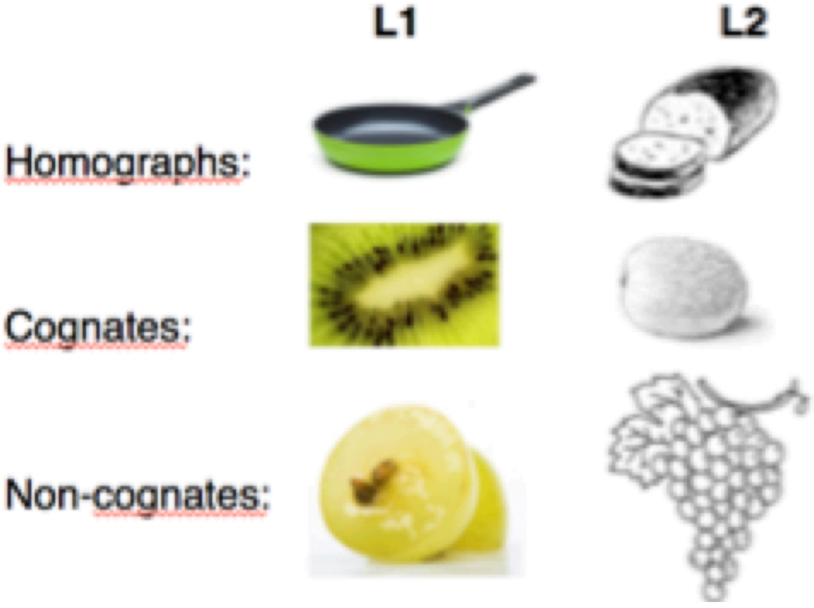

Figure 1. *Example of a homograph (pan meaning pot in L1, pan meaning bread in L2), a cognate (kiwi in both L1 and L2, both meaning the same edible fruit with a brown hairy skin and green flesh) and a non-cognate translation equivalent (grape in L1 and uva in L2, both meaning fruit that is used to make wine) that we used as experimental stimuli within the production task.*

fMRI data acquisition and pre-processing

A 3T Magnetom Trio MRI scanner system (Siemens Medical Systems, Erlangen, Germany) with a standard 32-channel radio-frequency head coil was used for the data collection. Prior to the scan session, the participants were instructed not to move their heads to avoid motion artefacts. The data acquisition started with a high-resolution 3D structural scan, using a T1-weighted 3D MPRAGE sequence (TR = 2530 ms, TE = 2.97 ms, TI = 1100 ms, acquisition matrix = 256 x 256 x 176, FOV = 256 mm, flip angle = 7˚, slice thickness = 1 mm, slice gap = 0.5 mm). Next, whole brain functional images were collected using a T2*-weighted EPI sequence, sensitive to BOLD contrast (TR = 2000 ms, TE = 28 ms, image matrix = 64 x 64, FOV = 192 mm, flip angle = 20˚, slice thickness = 3 mm, distance factor = 20%, voxels resized to 3 x 3 x 3 mm, 33 axial slices). A fixed number of images (222) were acquired per run.

SPM12 software (Wellcome Trust Centre for Neuroimaging, Institute of Neurology, University College London, UK; http://www.fil.ion.ucl.ac.uk/spm/) was employed for the preprocessing and analysis of the fMRI data. Reduction of T1 relaxation artefacts was pursued by exclusion of the first nine scans of each run. The functional images were then co-registered to the structural images, which were normalized to the Montreal Neurological Institute (MNI) template brain image. This was done to assure a high resolution anatomically-based normalization. The low frequency artefacts were removed by applying a high-pass filter with a cutoff at 128 s.

These normalized but unsmoothed images were used to perform whole brain searchlight decoding on the individual subjects' data. The fMRI time series data of all trials were modelled by 12 vectors representing the 12 different concepts. After alignment with a hemodynamic response function (HRF) and temporal derivative, these vectors and movement regressors were than entered into the regression design matrix and statistical parameter estimates were calculated for all columns in the design matrix.

Whole Brain Searchlight Decoding

We implemented a whole brain searchlight approach with a radius of 3 voxels to decode between the 12 stimuli, using a combination of permutation and bootstrap sampling methods (Stelzer et al., 2013). For each participant, the classification kernel was trained to discriminate between the activation patterns associated with the naming of the 12 concepts in one language. Next, this classification kernel was used to classify the activation patterns associated with the naming of the 12 concepts in the other language. The results of this decoding analysis resulted in single subject chance accuracy maps for each location within the whole brain mask. Next, permutation tests were applied to construct a null hypothesis for each participant to evaluate the decoding accuracies relative to the chance level. As suggested by Stelzer et al. (2013) this whole brain permutation procedure was repeated 100 times per participant to get a reliable estimation of the false positive results. Subsequently, one of the 100 chance accuracy maps was then randomly selected for each participant using a bootstrapping method. Next, we created a distribution of 10.000 random group accuracy maps by averaging the individual chance accuracy maps that we randomly selected for each individual. This was done for each category, by averaging the results of the 4 stimuli within each category. A binary accuracy map was then created by selecting all voxels that fell within the .005 range across the two (L1L2 and L2L1) distributions. Furthermore, a cluster threshold of 10 was used to construct a voxel-wise significance threshold map for the prediction of the 12 stimuli across languages.

RESULTS

Whole brain across language decoding analyses

To dissociate the semantic and lexical representational level, we used a decoding approach to investigate the neural overlap of the representation of homographs, cognates and non-cognate translations across languages. The classifier will try to predict the individual stimuli in one language based on the pattern of brain activation of the corresponding stimuli trained in the other language. For this analysis, the across-language decoding accuracies were taken together across the two directions (Spanish to English and English to Spanish). The results of the decoding analyses revealed a significant widespread set of brain regions for the three word categories in the production task across languages (see table 1, figure 2).

For the translation equivalents (figure 2, green), significant higher-than-chance decoding accuracies were observed in the left inferior occipital lobe and the left fusiform gyrus extending into the left lingual gyrus. Hence, the decoding results for the translation equivalents showed shared semantic representations across languages in these regions.

For the homographs (figure 2, blue), significant higher-than-chance decoding accuracies were observed in the left superior temporal lobe extending into the left superior temporal pole and the left middle temporal lobe, in the bilateral superior frontal lobe, in the left calcarine extending into the left superior occipital lobe, the left middle occipital lobe and the left cuneus, in the left middle cingulum and the bilateral superior motor area, in the bilateral precentral gyrus extending into the left postcentral gyrus and the left inferior frontal lobe and in the left inferior parietal lobe extending into the left precuneus, the left insula and the left paracentral lobule. Hence, the decoding results for the inter-lingual homographs showed shared lexical representations across languages in these regions.

For the cognates (figure 2, red), significant higher-than-chance decoding accuracies were observed in the left inferior temporal lobe extending into the left middle temporal lobe, in the left superior frontal lobe extending into the left middle frontal lobe, in the left inferior parietal lobe, in the left fusiform gyrus extending into the inferior occipital lobe, in the right precentral gyrus extending into the postcentral gyrus, in the right cuneus and in the right caudate. Hence, the decoding results for the cognates may imply both overlapping semantic as lexical representations across languages in these regions, given that both the meaning as lexical form are identical across languages.

Word category	Brain regions	X	Y	Z
Cognates	Left inferior temporal lobe	-51	-58	-6
	left superior frontal lobe	-19	2	52
	left inferior parietal lobe	-53	-49	46
	left fusiform gyrus	-35	-49	-13
	right precentral gyrus	43	-15	53
	right cuneus	9	-69	27
	Right caudate	7	8	6
Translations	Left fusiform gyrus	-35	-74	-18
	Left inferior occipital lobe	-43	-81	-5
Homographs	Left superior temporal lobe	-47	2	-14
	Left medial superior frontal lobe	-8	41	30
	Right medial superior frontal lobe	6	41	45
	Left inferior parietal lobe	-25	-50	53
	Left calcarine	-11	-93	0
	Left insula	-42	12	-9
	Left middle cingulum	-14	-14	43
	Left superior motor area	10	-7	56
	Right superior motor area	-6	-3	59
	Left precentral gyrus	-55	2	20
	Right precentral gyrus	37	4	31
	Left paracentral lobule	-16	-30	72

Table 1. *Results of the whole brain searchlight decoding across languages in production with a voxel threshold of 10 and a significance level of* $p < .005$.

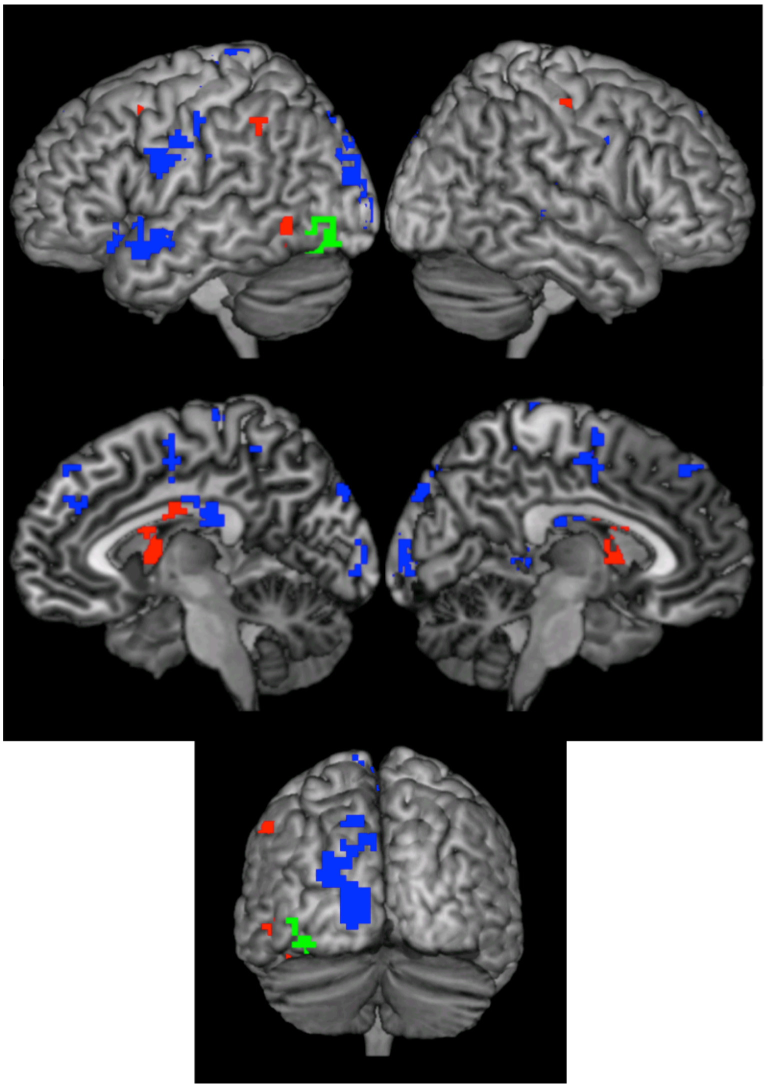

Figure 2. *Results of the whole brain searchlight decoding showing discriminability between cognates (red), homographs (blue) and translation equivalent (green) in the generalization across languages in production. The color represents the t-values resulting from the group level analysis using a voxel threshold of 10 and a significance level of p < .005.*

DISCUSSION

Using a decoding approach, Van de Putte, De Baene, Brass, & Duyck (2017) provided evidence for the idea that the neural representation of semantics overlaps across languages during production. Nevertheless, such a decoding approach was never used to investigate neural overlap across languages during production at the lexical level. Therefore, we did not only examine whether the neural overlap of semantic representations is shared across languages, but also whether lexical representations are shared within the same Spanish-English bilinguals. To dissociate the lexical and semantic representations we assessed word production of three different word categories: a) inter-lingual homographs that only share lexical form across languages, b) translation equivalents that only share meaning across languages and c) cognates that share both lexical form and meaning across languages.

For the homographs, the across language overlap was identified in regions typically associated with the high level integrative processing of language: the middle and superior temporal regions, the inferior and superior frontal regions and the inferior parietal regions. In addition, regions associated with sensorimotor processing (pre- and postcentral regions, the superior motor area and the insula) and visual processing regions (the left calcarine and middle and superior occipital regions) were also involved. Because semantic or sensory overlap was excluded across the inter-lingual homographs, the classifier could have only accurately predicted which concept was named in one language given the activation pattern for naming in the other language if lexical representations of L1 and L2 do overlap in the brain. Note that this condition implied naming of different pictures/concepts (e.g. a picture of a *pan* and of *bread*) in each language (excluding the sensory overlap), each associated with the same lexical form (*pan*). This lexical overlap is present both at the orthographic level and in the partially associated phonological level, so that neural overlap may reflect orthography, phonology, or both.

For the translation equivalents, the across language overlap was identified in regions associated with object recognition and visual processing: the left inferior occipital lobe and the left fusiform gyrus. Because lexical or sensory overlap (different pictures) was excluded across the non-cognate translation equivalents, the classifier could have only accurately predicted which concept was named in one language given the activation pattern for naming in the other language if semantic representations of L1 and L2 do overlap in the brain.

For the cognates, the across language overlap was identified in inferior and middle temporal regions, middle and superior frontal regions, inferior parietal regions and pre- and postcentral regions. These regions were also involved for the homographs. Additionally, for the cognates, also the fusiform and the inferior occipital regions showed significant decoding accuracies. These regions were also involved for the non-cognate translations. Since both the meaning as lexical form are identical across languages, correct classifier predictions for the naming of cognates across languages may imply both overlapping semantic as lexical representations. However, the specific localisation within the shared regions seems to differ for the cognates in comparison to the localisation of the homographs and the non-cognate translations.

In this group of late proficient Spanish - English bilinguals, the results showed that significant decoding of individual concrete concepts was possible across languages, for the cognates, translation equivalents as well as homographs. The results do not only confirm previous studies that provided evidence for overlapping semantic representations across L1 and L2, but they also provide additional evidence for integrated lexical representations across languages with language-nonselective lexical access. However, the brain regions that predicted commonality in the across language representations differed across the homographs, cognates and translation equivalents.

The involvement of the left inferior occipital lobe and the left fusiform gyrus in the decoding of the non-cognate translations are in line with the results of Van de Putte et al. (2017), who also applied decoding to investigate semantic neural overlap of non-cognate translations in production. The additional involvement of the left inferior and middle temporal regions was however not replicated in the present study. Note, however that in the study of Van de Putte et al. (2017), Dutch-French bilinguals with a high proficiency and mixed age of L2 acquisition were investigated, whereas in the current study Spanish-English bilinguals with a high proficiency, but late age of L2 acquisition were investigated. Moreover, regions associated with object recognition and visual processing are not only shown to be activated during visual stimulation, but also during tasks that didn't use visual stimuli. Hence, the reasoning that mental imagery is part of the semantic represention could be a possible explanation for the involvement of the inferior occipital lobe and the fusiform gyrus during the prediction of translation equivalents across languages (Klein et al., 2000;

Lambert et al., 2002). For example, during the visual perception of a car, a set of neural feature detectors get activated in the visual system. Hence afterwards when we think about a car in the absence of visual input, these visual features could again be activated as part of the semantic representation of a car (Barsalou, Kyle Simmons, Barbey, & Wilson, 2003). The occipital lobe was involved in all three the word categories. However only for the cognates and the translation equivalents this is a plausible explanation through the shared semantic representations. The homographs only shared lexical representations, so imagery of semantic representations couldn't be the case.

The observation that inter-lingual homographs could be predicted across languages during picture naming is really remarkable given that the participants only saw the completely different pictures with a different meaning in each language and never saw the shared written word form. The involvement of the left inferior parietal and the left superior frontal regions for inter-lingual homographs are in line with the neuroimaging study of Van Heuven, Schriefers, Dijkstra, & Hagoort (2008) who investigated inter-lingual homograph word recognition in English-Dutch bilinguals. They observed significant slower reaction times and greater activation in these regions for inter-lingual homographs relative to the English control words.

One might expect that the same regions would be involved for the cognates as the homographs and non-cognate translations because cognates share both word form (as the homographs) and meaning (as the non-cognate translations). However, our results show that cognates have a unique representation in the bilingual brain that is distinct from the other word categories. These findings are in line with the view that cognates are unique word categories that may be represented differently, rather than just being the sum of homographs and translations (Peeters, Dijkstra, & Grainger, 2013).

The contribution of frontal, temporo-parietal and fusiform regions are typically dedicated to semantic access in both production and comprehension, although the specific contribution of these regions in speech production seems to be task dependent (Binder, Desai, Graves, & Conant, 2009; Price, 2010, 2012). In addition, activation of frontal regions is also connected to word retrieval and activation in the fusiform gyrus is connected to the processing of the lexical word form (Baeck, Kravitz, Baker, Op, & Beeck, 2015; Price, 2012). Furthermore, activation during speech production in the pre- and postcentral regions, superior motor area, the insula and the tempo-parietal regions have also been associated with the initiation and execution of speech movements (Price, 2010, 2012).

The neural overlap across languages at the semantic level investigated with cognate and non-cognate translations is in accordance with the three main theoretical models of bilingual language processing: the BIA + model, the revised hierarchical model and the distributed feature model (Dijkstra and van Heuven, 2002; Kroll and Stewart, 1994; Van Hell and De Groot, 1998), because all three models propose at least partially overlapping semantic representations across languages. In addition, the neural overlap across languages at the lexical level, investigated with homographs, is only in accordance with the BIA+ model that emphasizes integrated lexical representations for L1 and L2 with language-nonselective lexical access. These findings contrast with earlier models of bilingualism such as the revised hierarchical model and the distributed feature model, which still assumed distinct lexical representations across languages. In BIA+, a written word activates its sublexical and lexical orthographic and phonologic representations. These, in turn, activate the shared semantic representations and language nodes that indicate membership to a particular language. Note however, that this model was specifically developed for word recognition, whereas our study focussed on picture naming. Our results therefore suggest a similar bilingual architecture for word production. However, to assess whether different language modalities also tap into the exact same, or rather different neural representations that may still overlap across languages, future research should also assess brain activation for different word categories during L1 and L2 processing in different modalities, within the same bilingual subjects.

Note that several factors such as language history are likely to profoundly influence bilingual neural language representation. The review of Indefrey (2006) specifically concluded that L2 age of acquisition (AOA), proficiency and exposure influence the neural representation during word level production. In this study we did only focus on the neural overlap between a proficient first language (Spanish) and a later acquired proficient language (English). Hence, we can only conclude that neural populations overlap across languages at the semantic and the lexical level in this specific bilingual group of late proficient bilinguals. These findings do therefore not necessarily transfer to low proficient later acquired languages. Hence, future studies that specifically compare different (and therefore necessarily larger) bilingual populations with different AOA, proficiency levels and exposure levels are required to get a more detailed view on the influence of these individual difference variables on the neural overlap of semantic representations across languages in production. Next, not only bilingual profiles, but also similarity between L1 and L2 language systems could influence language representations (Gandour et al., 2000; Chee et al., 2003). Hence, it would also be interesting for future MVPA research to systematically compare linguistically related languages (e.g. German-English) with more distant languages (e.g. German-Spanish or German-Chinese) to look at the influence of language relatedness on the neural overlap of L1 and L2 lexical and semantic representations.

To conclude, overall our findings support the idea of at least partly language-independent integrated semantic and lexical representations in widely distributed brain networks that represent knowledge of different word categories.

ACKNOWLEDGEMENTS

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CHAPTER 5

ANATOMICAL AND FUNCTIONAL CHANGES IN THE BRAIN AFTER SIMULTANEOUS INTERPRETING TRAINING: A LONGITUDINAL STUDY[1]

In the recent literature on bilingualism, a lively debate has arisen about the long-term effects of bilingualism on cognition and the brain. These studies yield inconsistent results, in part because they rely on comparisons between bilingual and monolingual control groups that may also differ on other variables. In the present neuroimaging study, we adopted a longitudinal design, assessing the long-term anatomical and cognitive effects of an extreme form of bilingualism, namely simultaneous interpreting. We compared a group of students starting interpreting training with a closely matched group of translators, before and after nine months of training. We assessed behavioral performance and neural activity during cognitive control tasks, as well as the structural connectivity between brain regions that are involved in cognitive control. Despite the lack of behavioral differences between the two groups over time, functional and structural neural differences did arise. At the functional level, interpreters showed an increase of activation in the right angular gyrus and the left superior temporal gyrus in two non-verbal cognitive control tasks (the Simon task and a colour-shape switch task), relative to the translators. At the structural level, we identified a significant increment of the structural connectivity in two different subnetworks specifically for the interpreters. The first network, the frontal-basal ganglia subnetwork, has been related to domain-general and language-specific cognitive control. The second subnetwork, in which the cerebellum and the SMA play a key role, has recently also been proposed as an important language control network. These results suggest that interpreters undergo plastic changes in specific control-related brain networks to handle the extreme language control that takes place during interpreter training.

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[1] Van de Putte, E., De Baene, W., García Pentón, L., Woumans, E., Dijkgraaf, A., & Duyck, W. (in press). Anatomical and functional changes in the brain after simultaneous interpreting training: A longitudinal study. *Cortex*

INTRODUCTION

Recently, a lively discussion originated both in the scientific and popular literature about the broad effects of multilingualism on general cognition and functioning of the brain. Many recent studies have focused on the relationship between the two, and found that speaking more than one language positively affects cognitive control and problem-solving (e.g. Bialystok & Majumder, 1998; Bialystok, Martin, & Viswanathan, 2005; Costa, Hernández, & Sebastián-Gallés, 2008; Woumans, Surmont, Struys, & Duyck, 2016). This finding is typically termed the 'bilingual advantage' and suggests enhanced cognitive processing in bilinguals compared to monolinguals. It is believed that this enhanced processing is the result of constantly having to juggle two or more languages. Studies on bilingual lexical access have indeed demonstrated that a bilingual's languages are simultaneously activated and interacting at all times (Colomé & Miozzo, 2010; Duyck, 2005; Van Assche, Duyck, Hartsuiker, & Diependaele, 2009; Van Hell & Dijkstra, 2002). A possible mechanism to handle this simultaneous activation was proposed by Green (1998) in his Inhibitory Control (IC) model. This model for language control suggests that bilinguals activate one language for production and inhibit the other. This process is thought to be domain-general and not language specific, implying that training the mechanism by continually activating one language and inhibiting the other may also improve other types of cognitive control.

However, whereas some labs have consistently replicated bilingual advantages (e.g. Bialystok, Craik, Klein, & Viswanathan, 2004; Bialystok, 2006; Bialystok & Feng, 2009), leading to a significant bilingual advantage effect in the meta-analysis of de Bruin, Treccani and Della Sala (2015), the same meta-analysis also showed a publication bias for positive results. Similarly, Paap and Greenberg (2013) and Paap, Johnson, and Sawi (2014) claimed that a large majority of studies, up to 85%, did not show a bilingual advantage. The controversy even led to a special issue of *Cortex* (Paap, Johnson, & Sawi, 2015) devoted to this particular discussion. In this issue, Woumans and Duyck (2015) argued that the literature should move away from the yes/no discussion, and instead focus on the possible moderating factors that seem crucial for the bilingual advantage to occur.

There is empirical evidence that one of those possible moderators may be (extensive) language switching. Prior and Gollan (2011), for example, revealed that frequent language switchers outperformed non-frequent language switchers and monolinguals on a non-verbal switching task. By contrast, the non-frequent switchers did not show any task switching advantage relative to the monolinguals. Verreyt, Woumans, Vandelanotte, Szmalec, and Duyck (2016) confirmed these findings in two conflict resolution tasks: the flanker task (Erisken & Eriksen, 1974) and the Simon task (Simon & Rudell, 1967). The authors compared two groups of highly proficient bilinguals (frequent and non-frequent switchers) and a group of low proficient bilinguals. They only found cognitive advantages for the frequent language switchers and concluded that frequent language switching, rather than mere second language (L2) proficiency is key to developing improved cognitive processes. In addition, Woumans, Ceuleers, Van der Linden, Szmalec, and Duyck (2015), reported a positive correlation between an experimental measure of language switching proficiency in a verbal fluency task on the one hand and conflict resolution in the Simon task on the other hand. Taken together, these results suggest that not merely being a bilingual may lead to better cognitive control, but rather that specific practice in language control (among other possible factors) may be crucial. On the other hand, such moderating effects may be quite complex, given that other studies like those of Paap et al. (2015), Paap et al. (2017) and Yim and Bialystok (2012) failed to find similar effects of language switching experience.

An interesting line of research that is closely related to this notion of switching as the determining factor in the bilingual advantage debate is what happens in bilinguals that need to use extreme language control, namely simultaneous interpreters. Simultaneous Interpreting (SI) requires concurrent comprehension of a spoken message in the source language (SL) and reformulation of the message into the target language (TL), while at the same time producing a previously transformed source message in the target language (Chernov, 1994). Therefore, it is obvious that high-level language control is necessary to manage this extremely challenging task. Through all these simultaneous processes, requiring different languages to a different extent, simultaneous interpreters manage greater levels of language control in comparison to other bilinguals, which in turn may lead to greater cognitive gains.

At the behavioral level, different studies have investigated the cognitive benefits of SI experience. Interpreters typically receive special training to improve working memory, which encouraged some researchers to focus on this aspect and report superior working memory in interpreters compared to other bilinguals (Christoffels, de Groot, & Kroll, 2006; Köpke & Nespoulous, 2006; Padilla, Bajo, & Macizo, 2005).

Others have taken into account more general cognitive processes, looking at the performance of SI on different cognitive control tasks, following the same rationale of transfer from language control to domain-general cognitive control.

The effect of SI on measures of inhibition is an unresolved issue that requires further research to resolve the contradictory findings in previous research. Some researchers have failed to find many differences between SI and other multilinguals on tasks relying on inhibition (Babcock & Vallesi, 2017; Dong & Xie, 1014; Morales, Padilla, Gómez-Ariza, & Bajo, 2015; Yudes, Macizo, & Bajo, 2011), while others did report some interpreter advantage for inhibitory skills (Dong & Zhong, 2017 & Woumans et al., 2015).

In contrast, studies employing cognitive flexibility measures have disclosed more consistent evidence for a SI advantage. In the study by Yudes et al. (2011), SIs outperformed both monolinguals and bilinguals on the Wisconsin Card Sorting Test (WCST). Both Becker, Schubert, Strobach, Gallinat, and Kühn (2016) and Babcock and Vallesi (2017) employed a color-shape task shifting paradigm and compared groups of professional SIs to other multilinguals, one of which was actually a group of consecutive interpreters, who were trained to first listen to the source text and only afterwards, with the aid of notes, make a full rendition. Still, SI seemed to outperform all other groups on a measure called 'mix cost'. This was calculated by comparing performance on all trials in a blocked condition where there is no possibility of a task switch with performance on repeat trials in a switch condition, where there is the possibility of a task switch but it did not occur. Hence, SIs seem to have obtained a higher level of automatic or sustained control, which comprises keeping multiple task sets activated and engaging attentional monitoring processes to increase sensitivity to cues that signal task changes (Funes, Lupiáñez, & Humphreys, 2010). However, no differences were reported for 'switch cost', which indexes transient control, by comparing performance on repeat and switch trials in a switch condition. This transient control entails internal reconfiguration or updating of goals and linking task cues to their appropriate stimulus-response mappings.

One issue however with these SI studies (as well as with studies on the bilingual advantage) is that most of them necessarily compare cognitive functioning between groups, that differ in SI experience, but that may also differ on other untargeted variables. To answer the question of causality and ensure that SIs are not predisposed to cognitive superiority, only a few studies have employed longitudinal designs, within participants. For instance, Macnamara & Conway (2014) followed a group of American Sign Language interpreting students over the course of their two-year training and found that over time, they demonstrated increased fluency in both mental flexibility and task shifting. There was, however, no control group. In another longitudinal design, Dong and Liu (2016) looked into inhibition, shifting, and updating gains in students of consecutive interpreting, written translation, and a general English course. After six months of training, consecutive interpreters displayed progress on both shifting and updating, whereas the translators only marginally improved on updating and the English students showed no progress at all. In contrast, Babcock, Capizzi, Arbula and Vallesi (2017) who also used a longitudinal design with a matched control group of translators, showed no effects of SI training on the performance of two executive control tasks: the Attention Network Task (ANT) that taps into inhibition, and a switch task. They only revealed an SI advantage in a verbal short memory task.

To complement the behavioral research, neuroimaging research has focused on neural plasticity as a consequence of SI. Elmer, Hänggi, and Jäncke (2014a) and Elmer, Hänggi, Meyer, and Jäncke (2011a) investigated structural brain differences associated with SI, using a cross-sectional design. Elmer et al. (2011a) examined the structural networks with DTI in predefined brain regions involved in the mapping of sounds to articulation, the motor control of speech, and interhemispheric transfer. They reported significant lower fractional anisotropy (FA) in the networks that subserve sound to motor mapping for the group of graduated SIs, compared to a multilingual control group. In the same group of participants as in the study of Elmer et al. (2011), Elmer et al. (2014) compared the gray matter volumes between the SI and multilingual control subjects, uncovering a structural difference in a priori defined brain regions that were previously shown to be involved in language control and linguistic functions. More specifically, this study demonstrated reduced gray matter volumes for professional SIs, in the left middle-anterior cingulate gyrus, bilateral pars triangularis, left pars opercularis, bilateral middle part of the insula, and in the left supra-marginal gyrus (SMG). Note, however that the between-group comparison implied an age difference (age was higher in the SI group than in the control group) that may confound anatomical differences.

In addition to structural brain differences, Elmer, Meyer, Marrama, and Jäncke (2011b); Hervais-Adelman, Moser-Mercer, and Golestani (2015); and Hervais-Adelman, Moser-Mercer, Michel, and Golestani (2015) investigated functional brain differences associated with SI. Elmer et al. (2011b) conducted a cross-sectional study on functional differences between 10 professional SIs and 16 equally educated, but younger controls during a non-verbal auditory discrimination task that relies on attention and categorization functions. The results revealed functional differences in fronto-parietal regions between the two groups, despite the absence of behavioral differences. They concluded that intensive language training modulates the brain activity in regions that are involved in the top-down regulation of auditory functions. However, due to an age difference between the two groups, these results should again be interpreted with care. Hervais-Adelman et al. (2015b) compared the functional involvement of brain regions during SI with the involvement of brain regions during simultaneous repetition (i.e. shadowing - SH). Participants were 50 multilinguals without previous SI experience. This comparison revealed that the caudate nucleus, the left anterior superior motor area (SMA), pre-SMA, the left anterior insula, the left premotor cortex, the right cerebellum, the left inferior frontal gyrus, and the dorsal anterior cingulate cortex (ACC) are more activated during SI than during SH. Hervais-Adelman et al. (2015a) opted for a longitudinal design examining brain plasticity as a result of intensive SI training. Nineteen trainee interpreters and 16 multi-lingual control participants were scanned at the beginning and at the end of the fifteen months intensive training course. The multilingual controls were students in non-linguistic fields who reported to have an equal degree of language proficiency in the same number of languages. The authors reported reduced involvement of the caudate nucleus during the SI task after fifteen months of training in the interpreters. The recruitment of the caudate nucleus in both studies, and especially the longitudinally induced brain plasticity in the caudate nucleus after intensive SI training, highlights the role of the caudate nucleus in SI. This region is also known to be implicated in domain-general cognitive control (Aron et al., 2007; Atallah, Frank, & Reilly, 2004).

All these neural SI studies focused on linguistic tasks rather than cognitive control tasks, which are typically used in the behavioral literature to investigate the cognitive benefits of SI, and in the more general literature about the bilingual advantage. One exception is Becker, Schubert, Strobach, Gallinat, and Kühn (2016) who investigated both functional and structural brain differences related to SI experience within a cross sectional design. Their results revealed that SI showed less mixing costs in a (non-linguistic) color-shape switch task, performed better in a (non-linguistic) dual task paradigm and showed more gray matter volume in the left frontal pole than translators.

Still, up until now, there were no studies investigating the influence of SI experience on cognitive control tasks instead of linguistic tasks, using a well-controlled behavioral and neural longitudinal design that manipulated SI experience within subjects. Hence, in the present study, we compared two matched groups of multilinguals, one of which was about to commence SI training and the other starting a translation course. We opted for this very conservative comparison of two very similar training programs (SI versus translation), organized by the same higher education institution, in order to identify the cognitive and neural changes specifically related to SI. We followed the two groups that had been enrolled in the exact same Bachelor program in Applied Linguistics until the start of follow-up, over a period of nine months. As such, this is the first study to examine longitudinal changes as a result of SI training, both in behavioral performance, using non-linguistic cognitive control tasks, as well as on a neural level, measuring both structural connectivity and functional differences. On the basis of previous research our expectation was that, due to the extreme language control, SIs would outperform translators on an inhibitory control task (Dong & Zhong, 2017; Woumans et al., 2015) and on a switch task (Becker et al., 2016; Babcock & Vallesi, 2017), that they would show different levels of neural activation during these tasks, and would show altered connectivity between brain regions that typically subserve domain general cognitive control (Becker et al., 2016).

We chose an inhibition task and a switch task, because these tasks are typically put forward to engage the core functions underlying SI, namely inhibitory control and flexibility (Christoffels & de Groot, 2005; de Groot & Christoffels, 2006; Hiltunen et al., 2016; Pöchhacker, 2004). As specific measures of these functions, we particularly chose the Simon task as the inhibition task and the colour-shape switch task as the switch task, because these tasks are most often used in the literature about the bilingual advantage (e.g. see the bilingual advantage meta-analysis of de Bruin et al., 2015), next to the flanker task. Interestingly, the Simon task and the colour-shape switch task were not only used in the bilingual advantage literature but also in previous research on the effect of SI experience (Babcock & Vallesi, 2017; Becker et al., 2016; Woumans et al., 2015; Yudes et al., 2011). For the colour-shape switch task, Becker et al. (2016) and Babcock and Vallesi (2017) found that SI's outperformed other multi-linguals on the mix cost, but not on the switch cost. In contrast, Babcock et al. (2017) didn't find an SI advantage on the mix cost either. On the Simon task, Woumans et al. (2015)

and Yudes et al. (2011) showed that SI's didn't outperform other bilinguals despite the idea that inhibitory control plays a crucial role during SI (Christoffels & de Groot, 2005; de Groot & Christoffels, 2006)."

We additionally investigated the performance on, and neural activation during, a language switch task as a linguistic verbal control task, because language switching is proposed as one of the possible moderators that can shape the brain regions on which domain general cognitive control relies (De Baene, Duyck, Brass, & Carreiras, 2015). This also allowed relating the present study to the neuroimaging literature discussed above, which also focused on linguistic tasks.

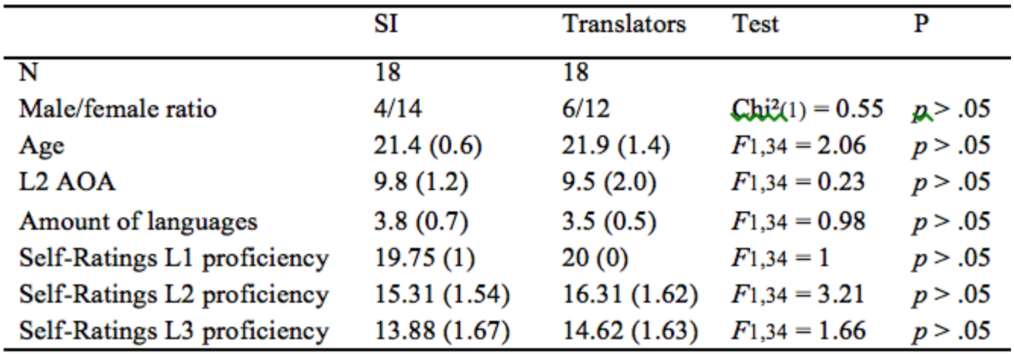
METHOD

Participants

Eighteen right-handed trainee simultaneous interpreters (4 males, 14 females) with an average age of 21.4 years (range 21-23) and eighteen right-handed trainee translators (6 males, 12 females) with an average age of 21.9 years (range 21-26) participated in the study. All participants were scanned before and after a nine-month Master course SI or translating. Four additional participants were excluded, as they were unable to participate in the second round of data-collection. After each scan session, participants received a compensation of €35. Up until the first moment of testing, both translators and SIs had been enrolled in the same three-year Bachelor program in Applied Linguistics. Only in this final Master year, students had to chose between SI and translator training. In the SI training, all courses and an internship were aimed at developing students' interpreting skills for their two chosen foreign languages. The same was the case for the translating training, in which the courses and internship were aimed at developing student's written translation skills for two foreign languages (see Table 1 for an overview of the distribution of the different language pairs). The two groups were comparable on factors such as socioeconomic status (SES), gender, second language (L2) proficiency, and age of L2 acquisition (L2 AoA). Within this design, other differences than the interpreting training itself were excluded. All participants had Dutch as their first language (L1). They reported a high level of proficiency in at least two other languages (see Table 2 for an overview of the demographic data).

Participant	Language pairs
SI 1	German - Turkish
SI 2	German - Russian
SI 3	French - Spanish
SI 4	German - Italian
SI 5	English - Italian
SI 6	French - Italian
SI 7	French - Italian
SI 8	French - German
SI 9	German - Russian
SI 10	English - Russian
SI 11	French - German
SI 12	English - Italian
SI 13	English - Spanish
SI 14	English - Russian
SI 15	English - Spanish
SI 16	English - French
SI 17	French - German
SI 18	French - Spanish
TR 1	English - German
TR 2	English - Russian
TR 3	German - Spanish
TR 4	English - German
TR 5	English - German
TR 6	German - Spanish
TR 7	English - Spanish
TR 8	English - Spanish
TR 9	English - Russian
TR 10	French - Italian
TR 11	English - German
TR 12	French - German
TR 13	French - German
TR 14	English - German
TR 15	English - French
TR 16	English - German
TR 17	English - German
TR 18	English - French

Table 1. *Language pairs that the simultaneous interpreters and translators received during the training program. SI = Simultaneous interpreter; TR = translator*



	SI	Translators	Test	P
N	18	18		
Male/female ratio	4/14	6/12	Chi^2(1) = 0.55	$p > .05$
Age	21.4 (0.6)	21.9 (1.4)	$F_{1,34} = 2.06$	$p > .05$
L2 AOA	9.8 (1.2)	9.5 (2.0)	$F_{1,34} = 0.23$	$p > .05$
Amount of languages	3.8 (0.7)	3.5 (0.5)	$F_{1,34} = 0.98$	$p > .05$
Self-Ratings L1 proficiency	19.75 (1)	20 (0)	$F_{1,34} = 1$	$p > .05$
Self-Ratings L2 proficiency	15.31 (1.54)	16.31 (1.62)	$F_{1,34} = 3.21$	$p > .05$
Self-Ratings L3 proficiency	13.88 (1.67)	14.62 (1.63)	$F_{1,34} = 1.66$	$p > .05$

Table 2*. Means and standard deviations of the participant's demographic data. The self-ratings are on a 5-point likert scale and are summed across listening, speaking, reading and writing.*

Materials and Procedure

A longitudinal design with both fMRI and DTI was employed to investigate, respectively, functional changes and structural connectivity changes in the brain. These were administered before and after 9 months of translator or SI training, so that neural changes could be observed within-subjects, for both groups. During the functional scans, participants completed two non-verbal cognitive control tasks (a color-shape switch task and a Simon task) and one language switching task (verbal fluency task). First, they did the color-shape switch task, followed by the verbal fluency task and the Simon task. Finally, the scan session ended with the DTI-scan, during which participants were asked to lay still and do nothing.

Simon task

We used a color version of the Simon task as a non-verbal cognitive control measure, which requires inhibition of irrelevant information and the response associated with it. The Simon task is commonly used in the literature on the bilingual advantage (e.g. Woumans et al., 2015). It primarily taps into inhibitory S-R processes, unlike for instance Stroop tasks that are more focused on S-S competition (Blumenfeld & Marian, 2014).

In the Simon task, a green or red dot appeared on the left or right side of the visual field. Participants responded to the color of the dot with the left or right index finger, while ignoring its location on screen. Response mapping was counterbalanced over participants. Each trial began with a fixation screen, with a fixation cross presented in the center for 500 ms. Then, a blank screen appeared for 500 ms followed by a green or red dot on the left or right side of the visual field with a maximum response time of 1500 ms. Only if an incorrect response was given, a red feedback screen appeared for 200 ms. We used a jittered blank intertrial interval screen (mean = 3345.27; range = 2200-5320 ms; distributed with pseudologarithmic density).

In the test block, each possible combination of position and color was presented 16 times, resulting in one run of 64 trials. Half of the trials were congruent and the other half were incongruent. On congruent trials, location of the stimulus on screen corresponded to the side of the button participants had to press as response to the color. On incongruent trials, location of the stimulus on screen and color of the dot elicited different responses. Before the test block, a practice block of eight trials was applied to make sure that the participants understood the task. An event-related approach was used for the Simon task. More specific, we analyzed the congruency effect as the difference in performance between incongruent and congruent trials (Yudes et al., 2011). This was used as measure of conflict resolution skills (i.e. the congruency or Simon effect). The total duration of this task was approximately 15 minutes.

Color-shape switch task

A color-shape switch task was employed as a second non-verbal cognitive control measure (Prior & Gollan, 2011). In this task, participants judged the color and shape of blue or yellow triangles and squares. They responded with the right or left index and middle finger to the shape or color of the target. Response mapping for both tasks (color and shape) to the right or left side of the hand was counterbalanced across participants. The task consisted of four runs. The experiment started with two single task blocks, in which participants judged either the color or shape of the target, followed by two mixed-task blocks in which they had to alternate between both tasks depending on the cue they were given (when a rainbow is shown, they need to perform the color task, when a geometrical figure is shown they have the perform the shape task. The order of the single task blocks (color-shape or shape-color) was also counterbalanced across participants.

Each trial started with a 600 ms fixation cross. In the single task blocks, the target then directly appeared in the center of the screen and remained on screen until the participant responded or for a maximum duration of 2500 ms. Next, a blank interval screen was presented for 300 ms before the onset of the following trial. In the mixed-task blocks, a task cue additionally preceded the target for 400 ms. The cue for the color task was a rainbow circle and for the shape task, it was a geometrical octagram. The single task blocks included eight practice trials, followed by 36 experimental trials. The two mixed-task blocks were preceded by ten practice trials and included 47 experimental trials each. Twenty trials were switch trials and 27 trials were repeat trials with a maximum of four consecutive repetitions. Before each block, an instruction screen was shown until the participant pushed a button to continue. In previous studies an equal amount of switch/repeat trials was often used (Prior & Gollan, 2017), however previous studies also showed that the sensitivity of the switch cost increases with lower switch probabilities (Duthoo, De Baene, Wühr, & Notebaert, 2012; Mayr, 2006; Monsell & Mizon, 2006; Schneider & Logan, 2006). Because one of our main aims was to assess a possible interaction between (SI vs. control) groups and switching, we opted for a colour-shape switch design with less switch trials, compared to repeat trials, in order to maximize the switch sensitivity.

As in previous studies, both the mix and switch cost were used as dependent variables (Babcock & Vallesi, 2017). The mix cost is the difference between performance on repeat trials in the mixed-task blocks compared to performance on all trials in the single task blocks, whereas the switch cost is the difference between performance on repeat trials and performance on switch trials within the mixed-task blocks. The total duration of this experiment was approximately 17 minutes. This event-related approach was however only used to analyze the behavioral data. As a consequence of the temporal resolution of fMRI, we couldn't dissociate brain activation for switch and repeat trials that occur quickly and interchangeably. To compensate for this we used a blocked approach instead of an event related approach to look both at the transient switch cost and the mixing cost. More specific, we chose for a contrast between mixed and single task blocks, because this measures both the neural correlates of the transient switch cost and the mixing cost, while at the same time keeping the power as high as possible, despite the limited amount of trials (Babcock & Vallesi, 2017).

Verbal fluency task

As a verbal switching performance measure, semantic fluency was assessed. The task consisted of one run, including three experimental blocks of one minute each. During each block, participants had to produce as many names of animals as possible in one minute while a fixation screen was shown. The first two blocks were single language blocks, in which they had to respond in either L1 or L2. The third block was a mixed-language block, in which they had to alternate between both languages. Each block was preceded by an instruction screen with a duration of 8000 ms. A switch cost was calculated by subtracting the number of words produced in the mixed-language condition form those produced in the single language conditions. The total duration of this experiment was approximately 5 minutes.

Data acquisition

Functional scans were acquired using a 3T whole-body Magnetom Trio MRI scanner with a standard 32-channel radio-frequency head coil (Siemens Medical Systems, Erlangen, Germany). To avoid motion artefacts, head fixation pillows were used and the participants were instructed not to move their head during the whole scan session. As required for anatomical localization, each session started with a high-resolution 3D structural scan, using a T1-weighted 3D MPRAGE sequence (TR = 2250 ms, TE = 4.18 ms, TI = 900 ms, acquisition matrix = 256 x 256 x 176, FOV = 256 mm, flip angle = 9˚, voxels resized to 1 x 1 x 1 mm). Next, whole brain functional images were acquired using a T2*-weighted EPI sequence, sensitive to blood oxygen level-dependent (BOLD) contrast (TR = 2000 ms, TE = 28 ms, image matrix = 64 x 64, FOV = 224 mm, flip angle = 80˚, slice thickness = 3 mm, distance factor = 17%, voxels resized to 3 x 3 x 3 mm, 34 axial slices). A varying number of images were acquired per run in the Simon task and the Color-shape switch task as a consequence of the self-paced initiation of the trial. In the verbal fluency, task a fixed number of images (119) were acquired per run.

The experimental tasks in which the participants had to respond to visual stimuli were projected on a screen with a video projector. This screen was visible for the participants through mirror glasses. Two button devices that each consisted out of two buttons were given to the participants. The required buttons depended on the specific task.

DW-MRI was acquired using a single-shot spin echo-planar imaging (EPI) sequence, with 64 gradient directions at b-value = 1200 s/mm2 and 1 unweighted (b = 0) image. Echo time (ET) = 83 ms, repetition time (RT) = 10800 ms, FOV = 240 ×240mm2, matrix size 96 × 96, 60 contiguous slices and an isotropic voxel resolution = 2.5 × 2.5 × 2.5 mm were applied as parameters. The total scan time for the DW-MRI protocol was approximately 14 min.

fMRI analysis

Pre-processing

The acquired fMRI-data were processed and analysed using SPM8 software (Wellcome Department of Cognitive Neurology, London, UK). The first four volumes of each run were excluded from the analysis to reach signal equilibrium. The functional images were corrected for slice timing and were spatially realigned to their mean image by rigid body transformation. To ensure an anatomically-based normalization, this functional mean image was co-registered with the high-resolution structural image and normalized to the Montreal Neurological Institute (MNI) template. Next, the functional images were smoothed with an 8 mm full-width half-maximum (FWHM) Gaussian kernel. Additionally, a high-pass filter with a cut-off of 128 s was used to remove low-frequency noise in the time series data at each voxel.

1st level analysis

Statistical analyses were performed on the data of the individual subjects by adopting the general linear model (GLM) in SPM8. In the Simon task, the fMRI time series data were modelled by two vectors reflecting the congruency of the trial (incongruent vs. congruent). These two vectors were convolved with the canonical hemodynamic response function (HRF) and entered into the regression model (the design matrix). For the verbal fluency task and the color-shape switch task, analyses were done within a blocked design. The predictor variables in the design matrix were composed of epochs representing the different conditions. Each epoch was convolved with a canonical HRF.

For every task, contrast images of interest were defined and created for every subject (contrast Simon task: incongruent > congruent, contrast color-shape switch task: task mix > task A & task B, contrast verbal fluency task: language mix > L1 & L2).

2nd level analysis

Whole brain, voxel-by-voxel second-level statistical analyses were performed to see whether significant differences were found between the two groups in the increase or decrease over time of brain activation recruited by the three fMRI tasks. For each task, the resulting first-level contrast images from the single subject analyses were submitted to a second level flexible factorial design with time (Time1 vs Time2) and group (SI vs translators) as factors. Group map significance was defined using a threshold of $p < .005$ at voxel level and an uncorrected cluster level for the whole brain at $p < .05$. We performed an interaction analysis between the group and time to test whether SI differ from translators over time. We opted for whole brain t-tests to better understand the directionality of the results.

Structural Connectivity Analysis

For this analysis, we followed the same procedure used by García-Pentón et al. (2014).

Pre-processing

The acquired DW-MRI data was pre-processed using FMRIB's Diffusion Toolbox (FDT; Smith et al., 2004) as part of FSL 5.0.2 software package (available at http://www.fmrib.ox.ac.uk/fsl/). To correct for the distortions induced by the diffusion encoding gradients and distortions induced by head motion, Eddy currents correction was applied using affine registration to the b = 0 image (first volume in the dataset). Next, individual diffusion parameters were estimated in each voxel by fitting a tensor model to the raw diffusion data, resulting in fractional anisotropy (FA) images.

For each participant, the T1-weighted images were co-registered to the b0 images and segmented in 3 tissue probability maps: grey matter (GM), white matter (WM) and cerebrospinal fluid (CSF) using the SPM8 software package (http://www.fil.ion.ucl.ac.uk/spm/). Using these three tissue classes and the matrix transformation to MNI space obtained from the segmentation, the cerebral cortex of each participant was automatically parcellated into 115 GM regions taken from the AAL atlas (Tzourio-Mazoyer et al., 2002). This was done with the IBASPM toolbox (http://www.fil.ion.ucl.ac.uk/spm/ext/#IBASPM; Alemán-Gómez, Melie-García, & Valdés-Hernández, 2006). Next, to create the seed points mask needed for the tractography, the individual atlases in T1 native space were resliced to DTI space using the nearest-neighbour interpolation in SPM8.

1st level analysis: White matter tractography

For each participant, the voxel-region connectivity was determined with the probabilistic fiber tractography algorithm implemented in the FSL software (Behrens et al., 2003). This algorithm calculates the axonal connectivity values between each brain voxel and the surface of each of the 115 GM regions. The connectivity values are estimated by calculating the number of generated paths that passed through the brain voxels from the seed region. As tracking parameters we used 5000 paths from each seed point (defaults in the FSL software package as optimum to reach the convergence of the algorithm), 0.5 mm as step length, 500 mm maximum trace length, and a curvature threshold of ±80º.

Next, the whole-brain undirected weighted network was created for each participant. Each of the 115 AAL-based grey matter regions was represented by nodes. When the connectivity value between the boundary voxels of two regions i and j was different from zero, an undirected arc a_{ij} between the nodes i and j was established. Additionally, the arc weights $w(a_{ij})$ were calculated based on the connectivity values between regions i and j (Iturria-Medina et al., 2011). This was done by counting the 'effective' number of voxels over the surface of both regions and weighting each voxel by its voxel-region connectivity value with the opposite zone, relative to the total number of considered superficial voxels.

2nd level analysis: Network-based statistic (NBS) analysis

The NBS approach is generally used to perform a non-parametric statistical analysis to identify components (connected structures) that are formed by a set of links (connections) between regions that exceed an appropriately chosen supra-threshold link (Zalesky et al., 2010a). In the subsequent GLM analysis, a 2 x 2 way ANOVA with one between-subject factor (Group: SIs vs. Translators) and one within-subject factor (Time: Time1 vs. Time2) was applied to isolate the components of the 115 × 115 undirected connectivity matrices that differ significantly between the two groups over time. A component (sub-network) is defined as a set of interconnected edges (i.e. links between GM regions) in the connectivity matrix.

Within the NBS analysis, we first tested the null hypothesis (H0) that the values of connectivity between the two populations come from distributions with equal means. This was done with a two sample T-test that was performed independently at each edge of the connectivity matrix.

To identify the set of supra-threshold edges a T-value of 3 was used as threshold for the statistical values of each edge of the connectivity matrix. All components (formed by interconnected supra-threshold edges at which the H0 was rejected) were identified and there size was estimated. A non-parametric permutation test, consisting out of 10000 independent randomly generated permutations was used to estimate the significance of each component. The group (SIs vs translators) to which each subject belongs was randomly exchanged and the statistical test was then recalculated for each permutation. Next, the same threshold (T-value = 3) was applied to create the set of supra-threshold links for each permutation. Then, the size (number of edges that the components comprise) of the largest component in the set of supra-threshold links of each permutation was used as an empirical estimation of the null distribution of the maximal component size.

Finally, an FWE corrected p-value was assigned to each connected component, based on its size. Therefore, the p-value of each observed connected component was corrected by calculating the proportion of permutations for which the maximal component size was greater than the observed connected component size, normalized by the number of permutations (i.e. 10000) (For more details see Zalesky et al., 2010a. For applications and examples of the NBS approach see Bai et al., 2012; García-Pentón et al., 2014; Verstraete et al., 2011; Zalesky et al., 2010b).

RESULTS

Behavioral data

The behavioral data was analyzed with SPSS 24 (Table 3). A GLM 2x2 mixed design ANOVA (2x2) was used to compare the performance between the two groups over time, with a within-subjects factor time (two levels: Time 1 vs. Time 2) and a between-subjects factor group (two levels: SIs vs. Translators). For the Simon task, the Simon effect (incongruent - congruent) of the reaction times (RT's) and the response accuracies were used as dependent variables. For the color shape switch task, the switch cost (switch trials in the mixed-task blocks - repeat trials in the mixed blocks) and the mix cost (repeat trials in the mixed blocks - all trials in the single blocks) of the reaction times and the accuracies were used as dependent variables. For the verbal fluency task, the dependent variable was the number of produced words. Participants with a total accuracy of less than 60% were excluded in the color-shape switch task, so that 32 out of 36 participants were retained. From the 4 excluded participants, 1 followed the SI program and 3 followed the translator program. In the Simon task, all 36 participants remained in the analysis. The individual RTs that exceeded 2.5 SD of the mean RT across all trials were excluded. This procedure eliminated 3.8% of all Simon data and 7.9% of all switch data.

For the verbal fluency task, we performed our analyses on the data of 25 participants, as the sound recordings of the other participants were disturbed through the scanner noise. From the 11 excluded participants, 6 followed the SI program and 5 followed the translator program.

	T1		*T2*	
	SI	Translators	SI	Translators
Simon task				
RT Simon effect	34 (32)	18 (44)	29 (29)	43 (29)
RT Congruent	510 (86)	529 (111)	492 (95)	439 (31)
RT Incongruent	544 (85)	547 (79)	522 (84)	482 (42)
Accuracy Simon effect	0.2 (0.8)	0 (1.2)	0.1 (0.4)	0.5 (0.8)
Color-shape switch task				
Mix cost	125 (93)	104 (85)	109 (89)	128 (64)
Switch cost	121 (68)	126 (74)	124 (79)	100 (48)
Accuracy all trials	96.3 (3.3)	97.4 (2.6)	95.1 (5.7)	97.5 (2.5)
Verbal fluency task				
L1 block	27.3 (9.4)	25.2 (7.9)	30.5 (6.7)	26.5 (7.6)
L2 block	21.5 (5.8)	17.2 (4.9)	21.7 (5.5)	21.3 (5.9)
Switch block	20.5 (3.6)	18.2 (4.2)	19.9 (3.4)	19.5 (3.9)

Table 3. *Mean RTs and accuracy rates for the Simon task and the color-shape switch task and mean amount of produced words for the verbal fluency task. Standard deviations of all measures are in parentheses.*

Simon task[2]. In the RT analysis of the Simon cost (RT incongruent - RT congruent), the main effects of Time ($F(1,34) = 1.29$, $p > .26$) and Group ($F<1$) were not significant, nor was the interaction effect of Time and Group ($F(1,34) = 2.91$, $p = .097$). In the accuracy analysis of the Simon cost (ACC congruent - ACC congruent), the main effect of Time ($F<1$) and Group ($F<1$) were not significant and also no significant Time*Group interaction was found ($F(1,34) = 3.02$, $p = .091$).

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[2] If we added congruency as a factor to our ANOVA, using plain RTs as the dependent variable, we observed a typical Simon effect, with significantly faster RT's for the congruent trials than incongruent trials (F(1,34) = 68.63, p < .001). The interaction of time x group x congruency was however not significant (F(1,34) = 2.91, p = .097), which also confirms that changes in the Simon effect over time were not significantly different for both groups.

Color-shape switch task[3]. In the mix cost RT analyses (RT repeat trials in the mixed blocks - RT all trials in the single blocks), we found no main effect of Time ($F<1$) or Group ($F<1$). The interaction between Time and Group was also not significant ($F(1,30) = 1.65$, $p > .20$). In the switch cost RT analyses (RT switch trials in the mixed-task blocks - RT repeat trials in the mixed blocks), neither a main effect of Time (F(1,30) = 1.14, p > .29) nor of Group (F<1) was found. An interaction between the two was also absent (F(1,30) = 1.97, p > .17). The accuracy analysis over all trials revealed no significant main effect of Time (F<1) or group (F(1,30)= 2.04, p > .16) and neither was the interaction effect of time with group (F(1,30) = 1.12, p > .30). In the accuracy analysis of the switch cost, the main effect of Time (F<1) and Group (F(1,30) = 1.29, p = .723) were not significant and also no significant Time*Group interaction was found (F(1,30) = 1.91, p = .178). In the accuracy analysis of the mix cost, the main effects of Time (F(1,30) = 1.99, p = .169) and Group (F(1,30) = 3.97, p = .056) were not significant and again no significant Time*Group interaction was found (F<1).

Verbal fluency task. In the L1 condition, the main effect of Time ($F(1,23) = 3.00$, $p = .097$), the main effect of group ($F(1,23) = 1.08$, $p > .30$) and the interaction between the two ($F<1$) were not significant. In the L2 condition, results revealed a significant main effect of Time ($F(1,23) = 4.50$, $p < .05$): the number of words produced was significantly higher in the post-test than in the pre-test. There was, however, no significant main effect of Group ($F(1,23) = 1.38$, $p > .25$) or Time*Group interaction ($F(1,23) = 3.82$,

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[3] When behavioural RTs are analyzed with a blocked approach, as in the neuroimaging data, no effect of time or group was observed either.

p = .063). In the mixed-language condition, analyses did not yield a main effect of Group (*F*(1,23) = 1.30, p > .26) or Time (*F*<1). Neither was there a significant interaction effect of Time and Group (*F*(1,23) = 1.07, *p* > .31).

In the analyses of the language switch cost (amount of produced words in the single language conditions - the amount of produced words in the mixed-language condition), no main effect of Group was found (*F*<1), but there was a main effect of Time (*F*(1,23) = 6.79, *p* < .05): switch cost was significantly higher at the post-test in comparison with the pre-test. However, this difference can be attributed to more fluent L2 production and stable mixed language production in the post-test and is therefore not really a reflection of less fluent switching at Time 2. There was no Time*Group interaction (*F*(1,23) = 1.18, *p* > .67).

Neural data

fMRI results

The whole brain fMRI analysis (Table 4) revealed a higher involvement of the left superior temporal gyrus in the Simon task (Figure 1) and a higher involvement of the right angular gyrus in the colour-shape switch task (Figure 2) after 9 months of SI training, compared to translators, despite the absence of differences between the two groups before their training. In the opposite direction, the translators only showed a higher involvement of the right cerebellum compared to SIs in the Colour-shape switch task after nine months of training (Figure 2). Note, however, that these brain regions were only significant at the uncorrected cluster level. In the verbal fluency task, no significant interactions were found.

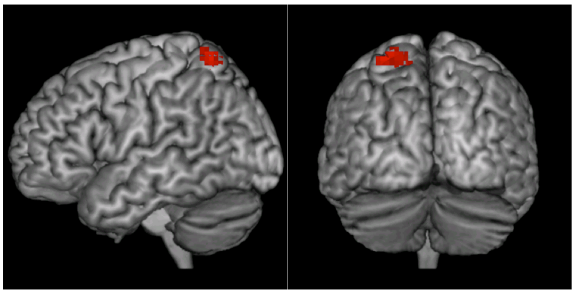
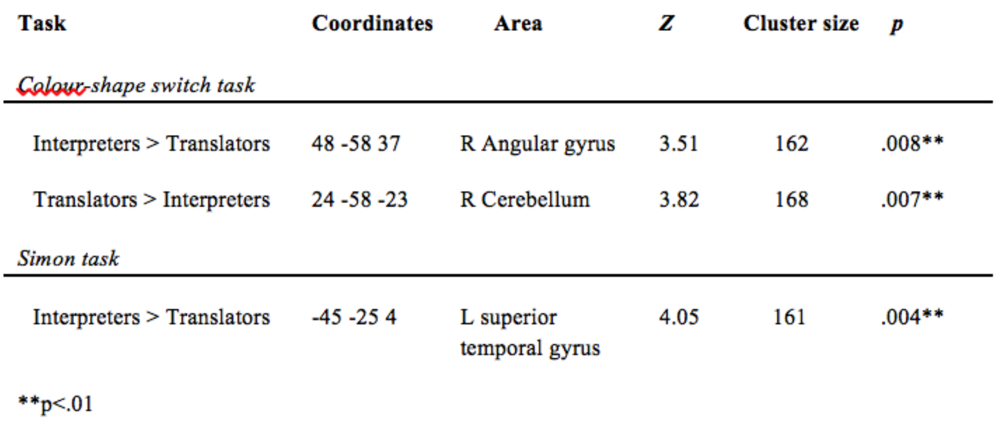


Figure 1. *Results of the whole brain searchlight analysis showing brain areas in which the interpreters showed more activation than the translators for the contrast incongruent relative to congruent trials in the Simon task. The color represents the t-values resulting from the group level analysis using a threshold of p < .005 at voxel level and an uncorrected cluster level for the whole brain at p < .05.*



Task	**Coordinates**	**Area**	***Z***	**Cluster size**	***p***
Colour-shape switch task					
Interpreters > Translators	48 -58 37	R Angular gyrus	3.51	162	.008**
Translators > Interpreters	24 -58 -23	R Cerebellum	3.82	168	.007**
Simon task					
Interpreters > Translators	-45 -25 4	L superior temporal gyrus	4.05	161	.004**

**p<.01

Table 4. *Results of the fMRI whole brain analysis. Significant group x time interactions for the BOLD responses in the colour-shape switch task and the Simon task.*

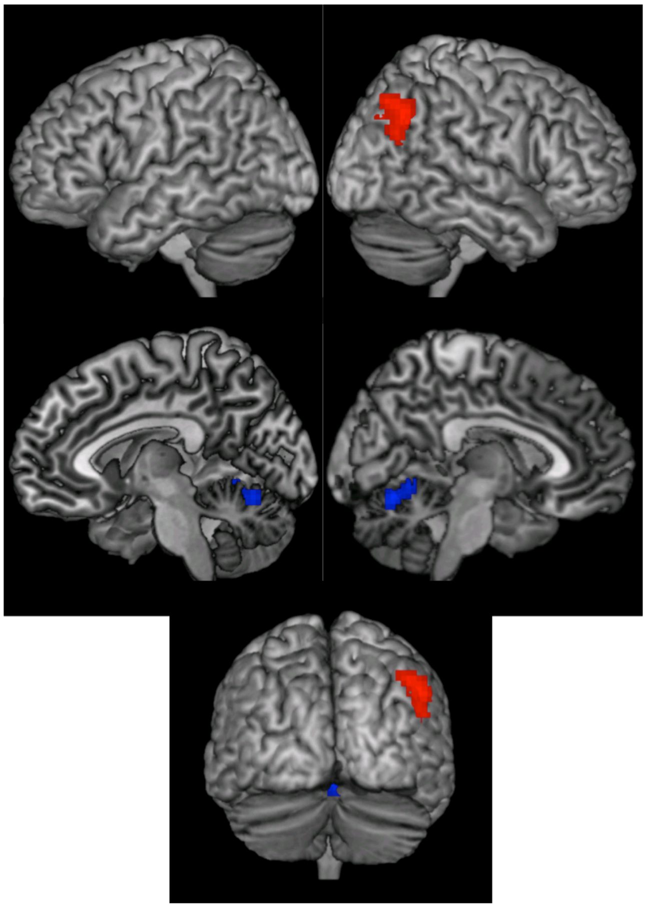


Figure 2. *Results of the whole brain searchlight analysis showing brain areas in which the interpreters showed more activation than the translators (red) and brain areas in which the translators showed more activation than the interpreters (blue) for the contrast task mix block, relative to task A and task B blocks in the color-shape switch task. The color represents the t-values resulting from the group level analysis using a threshold of p < .005 at voxel level and an uncorrected cluster level for the whole brain at p < .05.*

Structural Connectivity results (NBS analysis)

Two set of regions (component/subnetworks) showed a significant increment of the structural connectivity for SIs as compared to translators at $p < 0.01$ FWE corrected (Figure 3). The first component (subnetwork I) interconnected frontal regions with basal ganglia, comprising a total of 5 regions (Figure 3a): left superior frontal gyrus (SFG); left/right medial superior frontal gyrus (SFGmed); left orbital superior frontal gyrus (SFGorb) and the right pallidum. The second component (subnetwork II) involved 8 nodes (Figure 3b): left supplementary motor area (SMA); right postcentral gyrus (PoCG); right SFG; right middle temporal pole (TPOmid); right amygdala (AMYG), vermis 3 of the cerebellum; left inferior parietal gyrus (IPG) and superior parietal gyrus (SPG).

Translators did not show any set of regions with an increment of the interconnectivity, relative to SIs. Schematic representations of the subnetworks are depicted in Fig. 3 using BrainNet version 1.5 (Xia et al., 2013, http://www.nitrc.org/projects/bnv/). The anatomical name by which each node is labeled was taken directly from the Anatomical Automatic Labeling (AAL) atlas (Tzourio-Mazoyer et al., 2002).

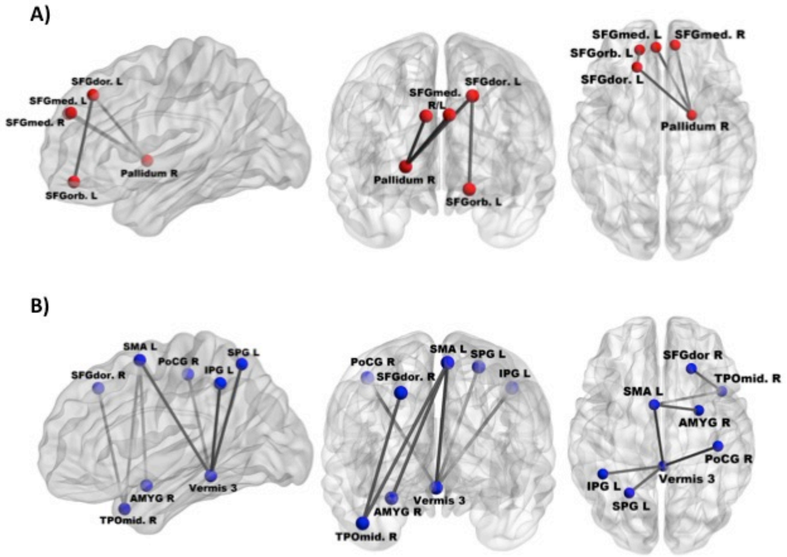


Figure 3. *Results of the network-based statistical analysis over the structural brain graph. Subnetworks showing increased structural connectivity in simultaneous interpreters as compared to translators (T-threshold=3, K= 10000 permutations, p < 0.01 FWE corrected). A) Subnetwork I: regions forming an individual component with 5 nodes/regions and 4 edges/connections. B) Subnetwork II: regions forming and individual component with 8 nodes/regions and 7 edges/connections. Abbreviations: L, left; R, right; SMA, supplementary motor area; SFGdor, superior frontal gyrus; SFGmed, medial superior frontral gyrus; SFGorb., orbital superior frontal gyrus, PoCG, postcentral gyrus; IPG, inferior parietal gyrus; SPG, superior parietal gyrus; TPOmid, middle temporal pole; AMYG, amygdala.*

DISCUSSION

We aimed to investigate whether SI may boost cognitive control, using a well-controlled longitudinal design in which SI experience was manipulated over time within the same participants. We included two highly similar groups of multilinguals with high levels of second (L2) and third (L3) language proficiency, but different language control needs. One group consisted of participants enrolled in a translator program, whereas the other group was following a simultaneous interpreting program (SI). As SI is often associated with extreme language control (Elmer et al., 2011; Woumans et al., 2015), we hypothesized that these students would show both behavioral and neural differences compared to translators after their nine-month training course. With regard to behavioral changes, we assumed that practicing SI would enhance domain-general cognitive control and verbal cognitive control. We also predicted that functional changes in activation of cognitive control related brain areas would occur, together with a modification of structural connectivity between brain regions that are involved in cognitive control of language.

Our expectations were, however, only confirmed at the functional and structural neural level, not at the behavioral level. We did not observe any cognitive behavioral advantages in SIs compared to translators. This finding replicates the majority of previous findings that failed to observe significant differences between SIs and other multilinguals on tasks relying on inhibition (Babcock & Vallesi, 2017; Dong & Xie, 1014; Morales, Padilla, Gómez-Ariza, & Bajo, 2015; Yudes, Macizo, & Bajo, 2011).

Analyses at the functional level revealed small but interesting differences after 9 months of training in SI or translation. Note however, that these differences did not survive the stringent threshold for multiple comparisons. Compared to the translators, the SIs showed an increase of activation in the right angular gyrus in the color-shape switch task, and an increase in activation in the left superior temporal gyrus in the Simon task. Increased activation in these areas in these tasks has been interpreted as a reflection of increased capacity of cognitive control functions (Rubia et al., 2006). Translators only showed an increase of activation in the right cerebellum in the color-shape switch task after nine months of training, relative to the SIs.

Interestingly, the left superior temporal gyrus, a region that is typically involved in a broad region of language processes, including the auditory perception of language switches (Abutalebi et al., 2007), appeared to show more activation in the non-verbal Simon task after nine months interpreting training than after nine months translating education. Furthermore, in previous literature, better interference suppression during incongruent trials of the Flanker task is also associated with higher activation in the superior temporal gyrus in bilinguals (Luk, Anderson, Craik, Grady, & Bialystok, 2010).

The functional increase of activation in the right angular gyrus during a task that relies on the inhibition of irrelevant information after 9 months of interpreting training supports the important role of the angular gyrus in the capacity to switch between languages. This was already highlighted in by Pötzl (1925), who revealed that lesions in the anterior angular gyrus lead to language-switching deficits. Additionally, the angular gyrus is not only reported to be connected to language control, but also to supramodal attentional control (J. J. Green, Doesburg, Ward, & McDonald, 2011) and supramodal semantic control (Noonan, Jefferies, Visser, & Ralph, 2013). Della Rosa et al. (2013) confirmed these findings at the structural level and did show that changes in gray matter values in the angular gyrus depend on the relationship between multilingual competence scores and attentional control scores. Therefore they concluded that the angular gyrus is a neural interactive location for multilingual talent (Della Rosa et al., 2013).

Most interestingly, at the structural level, we found a significant increase of connectivity for the SI's in two different subnetworks. This increment in FA values for the SI's are in line with our hypotheses, but opposite to the direction of connectivity effects in the previous study of Elmer et al. (2011a), who found lower FA values for SI's in comparison to their multilingual control group.

The first network consists of five interconnected nodes: the right pallidum, the left superior frontal lobe, the left superior orbital frontal lobe, and the right and left medial superior frontal lobe. The right pallidum, a substructure of the basal ganglia, seems to be a central node in this network, since all projections to the frontal regions seem to depart from this region. The second network consists of eight interconnected nodes: the right postcentral lobe, the Vermis 3, the left superior parietal lobe, the left inferior parietal lobe, the left SMA, the right amygdala, the right superior frontal lobe, and the right middle temporal pole. In this network, the Vermis (a substructure of the cerebellum) and the SMA seem to be the central nodes between all connections.

The central role of the pallidum and the connection with frontal regions in the first anatomical subnetwork confirms the inhibitory control function attributed to this network in previous research. For instance, Aron et al. (2007) showed that the pallidum was involved in stop and go processes, whereas Atallah, Frank, and Reilly (2004) also highlighted the importance of the pallidum in the suppression of competing responses. Atallah et al. (2007) even proposed a cognitive model (the cortico-striato-thalamo-cortical loops model) in which the basal ganglia and frontal regions work together as one cooperative system to obtain cognitive control. In this system, the basal ganglia act as a modulator of the frontal regions, by facilitating the appropriate responses and suppressing the competing responses that are being considered by the frontal regions. Lehtonen et al. (2005) additionally showed that the pallidum is not only important for the suppression of competing responses in non-verbal cognitive control, but also for verbal control. They found that the pallidum was specifically involved during translation. These findings confirm the idea that the basal ganglia and its interplay with frontal regions are essential for domain-general cognitive control and language control. Furthermore, this overlap in brain regions confirms the cross-talk between language control and domain general executive cognitive control as proposed in the inhibitory control model of Green (1998). Therefore, we can conclude that language control is a crucial mediator that may reshape the neural circuitry responsible for cognitive control. This recruitment of highly similar brain regions during tasks that rely on language control and tasks that rely on domain general cognitive control is also supported by De Baene, Duyck, Brass, and Carreiras (2013). They argued that the recruitment of similar brain circuits during language control and cognitive control provide powerful evidence that the challenges of language control can shape the brain regions on which cognitive control relies. This is a plausible explanation for the reported bilingual advantage on tasks that rely on domain-general executive cognitive control (Bialystok, Klein, Craik, & Viswanathan, 2004; Bialystok, 2006; Bialystok, Craik, & Luk, 2008; Costa et al., 2008).

The involvement of the second subnetwork is a bit more unexpected, because in previous research the cerebellum was mostly found to subserve the coordination of autonomic and somatic motor functions instead of language or cognitive control (Ackermann, Mathiak, & Riecker, 2007; De Smet, Paquier, Verhoeven, & Mariën, 2013; Fabbro, Moretti, & Bava, 2000; Mariën et al., 2014; Murdoch, 2010). However, most previous studies completely neglected this region and did not try to fit the cerebellum within the scan window. In contrast, Green and Abutalebi (2013) proposed a language control network, in which several areas of the second network (specifically, also the cerebellum, the SMA and the parietal lobes) also play a key role. In this model, the SMA initiates speech in language switching and the parietal lobes are connected to the maintenance of task representations.

Note, however that the structural and functional analysis revealed distinct findings. The cerebellum seems to be involved in both analyses, but unexpectedly in opposite directions, with an increased involvement of the cerebellum during the colour-shape switch task for the translators and an increased connectivity of the cerebellum for the SI's. Additionally, the increased involvement of the right angular gyrus during the color-shape switch task and the increased involvement of the left superior temporal gyrus during the Simon task was only apparent in the functional analysis, but not in the structural analysis. A possible explanation could be that translators and interpreters differ in the way they rely on the neural network. The connectivity between the cerebellum and other brain regions might for example become stronger for the interpreters. Therefore, a shift could occur from relying solely on the cerebellum to relying more on the exchange between the cerebellum and other regions.

It is important to emphasize the conservative approach adopted here, to compare SI students with a group of closely matched translators from the same Bachelor program, rather than a monolingual or less L2-proficient control group. As a result, the obtained differences between these two highly similar groups need to be attributed to control processes that are specific to SI. In SI, a one-time presentation of an utterance in a source language (SL) is instantly rendered into an utterance of similar meaning in a target language (TL). According to Christoffels and de Groot (2005) and de Groot and Christoffels (2006), inhibitory control plays a crucial role during this rendition. The authors describe possible inhibition accounts of SI, assuming (functionally) distinct input and output lexicons that can be separately activated and inhibited. These accounts state that both SL and TL input lexicons should be activated, to allow for input comprehension and output monitoring, while the SL output lexicon should be strongly inhibited. Other explanations for the observed differences between the SI and the translators are the development of a more efficient divided attention system or language switching system. This is because besides the proposed role of inhibitory control, an SI's attention is divided or switches rapidly between the different processes (Pöchhacker, 2004; Hiltunen, Pääkkönen, Gun-Viol, & Krause, 2016). Therefore, future studies are necessary to determine the specific processes that distinguish translating from SI.

The lack of behavioral differences between the two groups could similarly be explained by our conservative approach comparing two highly similar groups of SIs and translators, with the exact same prior education. Translating is not totally different from SI. Translators, too, have to render a source text into a target text, and when they are formulating this text in the target language (TL), they need to inhibit the source language (SL) at the output level, while keeping it activated at the input level. Essentially the process appears the same, but the amount of extreme language control is different between the two groups. SIs have to perform this process in real-time, i.e. immediately after or simultaneous with reception of the source text, making SI much more challenging (Babcock & Vallesi, 2017). Additionally, it is possible that further experience could create behavioral differences that did not yet appear after only nine months of SI training, especially because the amount of SI practice was still limited during this Master course. Another possibility is that SIs recruit brain regions in a more efficient way, resulting in the observed functional activation differences, but that there are no behavioral differences between SIs and translators, because both already perform close to individual ceiling. Note that the lack of behavioral findings within our longitudinal design may also have been influenced by the demonstrated low test-retest reliability for the Simon effect, and somewhat higher test-retest reliabilities for the switch cost and mix cost (Paap & Sawi, 2016).

The lack of behavioral group differences in the inhibition task replicates the longitudinal findings of Dong and Liu (2016) and Babcock et al. (2017) who used a similar conservative approach comparing SIs with translators. However, in contrast to our results and those of Babcock et al. (2017), in the study of Dong and Liu (2016) the SIs improved significantly more on switching than the translators. In future research, it may be interesting to also investigate tasks that tap into different types of inhibitory control (ex: ANT, flanker task, stroop task, go/no-go task) or switching-flexibility (ex: WCST) (Miyake & Friedman, 2012).

To conclude, given this longitudinal design with closely matched groups of SIs and translators, who received the same previous education, the observation of neural differences over the course of only nine months is really remarkable. Our results suggest that SIs undergo neural changes in specific control-related brain networks to handle the extreme language control that takes place during interpreting.

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CHAPTER 6
GENERAL DISCUSSION

The central goal of the current dissertation was to investigate the neural basis of bilingual language processing, assessing both linguistic representations and language control. At the linguistic level, the main question has been whether the representations of both languages are integrated in one system or rather rely on separate cognitive/neural representations for each language. In the three main psycholinguistic models outlined in the introduction, different predictions have been made about whether semantic and lexical representations are overlapping across languages or not (Dijkstra & Van Heuven, 2002; Kroll & Stewart, 1994; Van Hell & de Groot, 1998). Therefore, in **CHAPTER 2, 3 and 4** we explored the neural overlap of a first language (L1) and a second language (L2) in different language modalities and representational levels.

Additionally, if two languages are integrated at the representational level and a person only needs to use one language in a certain communicative setting, the second question is whether a language control mechanism is then required to prevent interference from the non-relevant language that might otherwise cause cross-lingual speech errors. Although, most psycholinguistic models agree that an inhibitory control mechanism is needed to achieve language control, it is not exactly clear how this language control mechanism is represented in the brain and whether this accounts for both production and comprehension.

Therefore, in **CHAPTER 5**, we investigated the neural substrate of extreme language control during simultaneous interpreting.

In this final chapter, the main empirical findings of this research project are summarized and the psycholinguistic models are evaluated in the light of these findings. Finally, the chapter is concluded with some limitations and directions for future research.

EMPIRICAL FINDINGS: AN OVERVIEW

Neural linguistic representations

Studies on bilingualism have investigated neural overlap of a first language and a second language in a wide variety of experimental tasks that tap into different modalities (comprehension and production) and language representational levels (semantic and lexical representational level). Hence, the different cognitive processes and neural structures that the different tasks recruit might explain the divergent results in the previous literature about bilingual language representations. Therefore, in the present dissertation the first objective was to disentangle the influence of the different language modalities and representational levels on the neural overlap of L1 and L2.

The second objective of the current dissertation was to apply a multivariate decoding approach to get a more fine-grained look at the results of previous literature that used univariate analyses approaches to investigate neural overlap across languages. In the univariate analysis approach the average activation over a set of voxels, that are all treated as similar, is used as an indication of whether or not a region is involved in a certain task or experimental condition (Mahmoudi, Takerkart, Regragui, Boussaoud, &

Brovelli, 2012). Hence, in the univariate approach it could be that the same brain region is activated across tasks in which different languages need to be used despite the fact that the pattern of voxel activity is in fact different for two languages. In contrast to the univariate approach, in a multivariate decoding approach it's only possible to predict or classify stimuli across different languages if overlapping neural populations are really involved across languages. Hence, only the observation of overlapping neural populations and not merely brain regions would be supportive of a real integrative view of L1 and L2 in bilinguals. Therefore, the time is right to apply a multivariate decoding approach to shed a different light on bilingual language representations in different modalities and representational levels, in order to examine to what degree such data support the assumptions of the most influential psycholinguistic models of bilingual language organization.

Until now, decoding was only applied in comprehension to investigate neural overlap across L1 and L2 semantic representations (Buchweitz, Shinkareva, Mason, Mitchell, & Just, 2012; Correia et al., 2014). Therefore, in **CHAPTER 2** we used decoding to investigate the neural overlap between L1 and L2 semantic representations during production in a group of mainly high proficient Dutch - French bilinguals with a mixed age of acquisition (AOA) of French. To tap into production, we used a picture naming task in which the participants had to name pictures in L1 and L2. More specifically, we tested whether brain activity during the production of individual concepts in one language allowed predicting the production of the non-cognate translation equivalent in the other language.

The results showed that significant decoding of individual concepts is possible in picture naming across languages. More specifically, brain activity associated with the activation of semantic representations of individual concepts during production in one language accurately predicted the activation of semantic representations of the translation equivalent. This provides evidence for neural overlap in bilingual semantic representations in production, because the non-cognate translation equivalents only shared the underlying semantic representation (sensory and lexical overlap was maximally excluded). The significant decoding accuracies for the semantic representations across languages were located in the bilateral occipito-temporal cortex and the inferior and the middle temporal gyrus. These findings replicate the importance of the posterior temporal regions not only for monolingual semantic representations (Indefrey & Levelt, 2000; Price, 2012; Rodd, Vitello, Woollams, & Adank, 2015; Van Doren, Dupont, De Grauwe, Peeters, & Vandenberghe, 2010), but also for common bilingual semantic representations in L1 and L2 production.

Furthermore, in the within-language decoding analysis, we also found significant decoding accuracies in L2, but not in L1 in the pre_and postcentral gyrus, the inferior, middle and superior temporal lobe, the supramarginal gyrus, the cuneus and the superior partietal lobe. These results suggest that in addition to the shared neural populations representing semantics across languages, there are also neural populations that are recruited specifically by L2 lexical or semantic representations. The distinction between the semantic or lexical level is however not possible to make in the within language decoding analysis of this Chapter, because the design implies within-languages lexical overlap by definition (see Chapter 4 for a dissociation of lexical vs. semantic representations). Interestingly, the involvement of the neural populations in L2 semantic processing seems to be influenced by the AOA of L2. Our results seem to indicate that the later L2 was acquired, the more additional neural populations are involved in the semantic processing of L2. This might implicate a more efficient organization of conceptual knowledge in early bilinguals then in late bilinguals, as proposed in the reviews of Indefrey (2006), Perani and Abutalebi (2005) and Stowe and Sabourin (2005) who also suggested more widespread activation for L2 processing by late bilinguals, compared to L1 processing. They concluded that late learners might be more likely to draw on additional resources to aid them in L2 processing. Note however, that we can't dissociate AOA and L2 exposure in this paper, because AOA is highly correlated with the years of use of L2 in our sample. These effects could therefore be driven by both AOA or by the amount of exposure to L2.

To conclude, the results of **CHAPTER 2** provide evidence for at least partially overlapping neural populations for L1 and L2 semantic processing tapped into by word production.

In addition to exploring whether semantic representations overlap across languages, the other aim and innovative part of **CHAPTER 3** was to investigate whether semantic representations also overlap across modalities. This was investigated in the same group of mainly high proficient Dutch-French bilinguals as in Chapter 2. In this chapter we therefore used decoding to investigate the neural overlap between Dutch and French semantic representations of non-cognate translation equivalents, within and across production (picture naming), visual comprehension (word reading) and auditory comprehension (word listening). Hence, this is the first study to examine whether decoding of individual semantic concepts across languages was also possible across modalities, within the same individuals.

The results showed that encoding of semantic information was possible across languages, for each modality. It was possible to identify the picture or word named, read or heard in one language based on the brain activity in a distributed bilateral brain network while, respectively, naming, reading or listening to the picture or word in the other language. However, the brain regions that predicted language-independent representations differed across the tasks that tapped into the different modalities. As reported in Chapter 2, for picture naming, the decoding results across languages showed shared semantic representations in the occipital and temporal regions. In addition, shared semantic representations across languages were observed for word reading in the rolandic operculum, inferior frontal lobe, the middle temporal lobe, the precuneus, the calcarine and the inferior and middle occipital lobe. The decoding results for word listening only showed shared semantic representations across languages in the rolandic operculum. The observation of modality specific semantic representations might explain the varying brain regions identified in different studies, because depending on the experimental task, different aspects of semantics could result in the involvement of different brain regions.

Furthermore, we also applied a cross-modal decoding analysis to investigate whether the semantic neural representations are not only overlapping across languages, but also across modalities. The decoding results across modalities revealed shared language-independent semantic representations across production and word reading in the lingual gyrus. Hence, across modalities, it was possible to identify the concept the participant was naming in one language based on the neural activation patterns in the lingual gyrus observed during the presentation of the equivalent written word in the other language, and vice versa. However, no significant brain regions were observed in the semantic decoding across word reading - word listening and production - word listening. These findings are in accordance with previous studies that also provided evidence for the existence of amodal semantic hubs. Musz and Thompson-schill (2016) also argued that the lingual gyrus is important for semantic integration across different semantic contexts. The specific localisation was however dissimilar in the different studies. Bonner, Peelle, Cook, & Grossman (2013) for example argued that amodal representations are instead located in the angular gyrus. In contrast, Simanova et al. (2014) argued for the localization in inferior temporal and frontal regions, whereas, Fairhall and Caramazza (2013) argued for the localization in the precuneus and the posterior middle and inferior temporal regions.

To conclude, the results of **CHAPTER 3** provide evidence for the existence of a language independent distributed semantic network that includes both an amodal integrative component and modality specific representations that are widely distributed across the brain.

Although most research agreed that both languages of a bilingual are represented in at least partly shared neural semantic representations in production, it remains unclear whether also lexical representations are integrated neurally across languages. In **CHAPTER 4**, we therefore applied decoding to investigate the neural representation of 3 word categories (identical cognate translations, non-cognate translations and homographs) that differed on the amount of semantic and lexical overlap across languages. As in Chapter 2, we used a picture naming task in which the participants had to name pictures in L1 and L2 to tap into production. More specifically, we tested whether brain activity during the naming of pictures in one language allowed predicting the naming of the non-cognate translation, the cognate translation and the homograph pictures in the other language. Hence, this is the first study to examine whether decoding of lexical representations is possible across languages, within the same group of late proficient Spanish-English bilinguals.

First, the results showed that brain activation in the occipital and fusiform regions allowed non-cognate translations to be predicted across languages. Because both languages only share the underlying meaning in non-cognate translations (visual and lexical overlap was maximally avoided), this indicates that these regions share semantic representations across L1 and L2 production. The involvement of these regions are in line with the results of Chapter 2, in which we also applied decoding to investigate semantic neural overlap of non-cognate translations in production. The additional involvement of the left inferior and middle temporal regions was however not observed in Chapter 4. Note, however that in Chapter 2, Dutch-French bilinguals with a high proficiency and mixed age of L2 acquisition were investigated, whereas in Chapter 4, Spanish-English bilinguals with a high proficiency, but late age of L2 acquisition were investigated.

Second, brain activation in frontal, temporal, parietal, occipital and sensorimotor regions allowed homographs to be predicted across languages. Because homographs only share the underlying lexical form (orthography and associated phonology) across languages (visual and semantic overlap was completely avoided), this indicates that these regions share lexical representations across L1 and L2 production. The involvement of the left inferior parietal and the left superior frontal regions confirms previous research that showed significant slower reaction times and greater activation in these regions for inter-lingual homographs relative to control words (Heuven, Schriefers, Dijkstra, & Hagoort, 2008).

Third, the decoding results for cognates, which share both semantic and lexical representations across languages, showed neural overlap across languages in temporal, frontal, parietal, occipital, fusiform and sensorimotor regions. This observation of unique neural representations for cognates in the bilingual brain is in line with the view that cognates are unique word categories that are represented in a very specific way, rather that just being the sum of homographs and translation representations (Peeters, Dijkstra, & Grainger, 2013). Peeters et al. (2013) argued for example that at least for late bilinguals who acquired both languages in a different context (e.g. home vs. school), cognates are represented by language dependent morphonsyntactic representations and shared language independent orthographic and semantic representations. Hence, depended on the required context (target language, task), cognates could be processed in a different fashion relying on different morphosyntactic representations (with different plural markers, gender, etc). According to the two-morpheme view cognates are processed faster than control words as a consequence of faster retrieval of the word meaning. This view assumes that the shared orthographic representation in both language lead to a stronger semantic activation compared to control words. Although the two-morpheme view seems to account for the representation of cognates in late bilinguals, this view does not necessarily apply for early balanced bilinguals who acquired both languages in the same context. Hence, for early balanced bilinguals it could be that the processing of cognates is more influenced by the frequencies in both languages independent of the task context in accordance with the cumulative frequency hypothesis (Davis et al., 2010; Sánchez-Casas & García-Albea, 2005). According to this hypothesis cognates are processed faster than control words, because cognates are more often used than words that only exist in one language.

To conclude, the results of **CHAPTER 4** do not only confirm previous studies that provided evidence for overlapping semantic representations across L1 and L2, but also provide additional evidence for integrated lexical representations across languages. However, the specific brain regions involved differed across the homographs, cognates, and non-cognate translations. Therefore, we can assume that the brain regions involved depend on the language semantic or lexical representational level.

Neural representation of language control

Chapter 2, 3 and 4 provided evidence for the idea that both languages of a bilingual are neurally integrated. Consequently, a strong language control mechanism is necessary to avoid unintended cross-lingual intrusions (which are relatively rare given constant dual-language activation). Therefore, a systematic assessment of the neural representation of bilingualism, as the current dissertation aspires, also implies an assessment of the neural representation of language control. In **CHAPTER 5**, we tackled the question of language control assessing the long-term anatomical and cognitive effects of simultaneous interpreting (SI), an expertise that requires extreme language control. To investigate this, we compared two similar training programs that only differed on the degree of language control (SI versus translation), in order to identify the cognitive and neural changes specifically related to SI. Translators have to read a written source text and convert it only afterwards into a written target text in another language, whereas SIs have to verbally listen to a spoken source message and immediately have to make a simultaneous verbal rendition into the target language (Christoffels and de Groot, 2009). Through all these simultaneous processes, it is generally assumed that SI's manage greater levels of language control in comparison to translators, which in turn may lead to greater cognitive gains and changes in underlying neural networks (Babcock & Vallesi, 2017). To our knowledge, this is the first study to examine longitudinal changes as a result of SI training, both in behavioural performance, using non-linguistic cognitive control tasks, as well as on a neural level, measuring both structural connectivity and functional differences. It is important to emphasize the conservative approach adopted here, comparing SI students with a group of closely matched translators from the same Bachelor program, rather than a monolingual or less L2-proficient control group. As a result, the obtained differences between these two highly similar groups need to be attributed to control processes that are very specific to SI.

The behavioural results did not reveal any non-linguistic cognitive control advantages after SI training compared to translator training. This replicates the majority of previous findings that failed to observe significant differences between SIs and other multilinguals on tasks relying on inhibition (Babcock & Vallesi, 2017; Dong & Xie, 1014; Morales, Padilla, Gómez-Ariza, & Bajo, 2015; Yudes, Macizo, & Bajo, 2011). Despite the lack of behavioural differences, neural differences were found at the functional and structural level.

Analyses at the functional neural level revealed small but interesting differences after 9 months of training in SI or translation. Compared to the translators, the SIs showed an increase of activation in the right angular gyrus in the color-shape switch task and an increase in activation in the left superior temporal gyrus in the Simon task. Increased activation in these areas in these tasks has been interpreted as a reflection of increased capacity of cognitive control functions (Rubia et al., 2006). Translators only showed an increase of activation in the right cerebellum in the colour-shape switch task after nine months of training, relative to the SIs.

Additionally, analysis at the structural level showed a significant increase of connectivity for the SI's in two different subnetworks. The first network consists of five interconnected nodes: the right pallidum, the left superior frontal lobe, the left superior orbital frontal lobe, and the right and left medial superior frontal lobe. The right pallidum, a substructure of the basal ganglia, seems to be a central node in this network, since all projections to the frontal regions seem to depart from this region. The central role of the pallidum and the connection with frontal regions in the first anatomical subnetwork confirms the verbal and nonverbal inhibitory control function attributed to this network in previous research (Aron et al., 2007; Atallah, Frank, and Reilly, 2004; Lehtonen et al., 2005). This recruitment of highly similar brain regions during tasks that rely on language control and tasks that rely on domain general cognitive control is also supported by De Baene, Duyck, Brass, and Carreiras (2013). They argued that the recruitment of similar brain circuits during language control and cognitive control provide powerful evidence that the challenges of language control can shape the brain regions on which cognitive control relies. The second network consists of eight interconnected nodes: the right postcentral lobe, the Vermis, the left superior parietal lobe, the left inferior parietal lobe, the left SMA, the right amygdala, the right superior frontal lobe, and the right middle temporal pole. In this network, the Vermis (a substructure of the cerebellum) and the SMA seem to be the central nodes between all connections. Although the involvement of the second network is more unexpected, the central role of the cerebellum within the second subnetwork is consistent with recent findings that suggest that the cerebellum might play an important role in the representation of semantics (Mariën et al., 2014; Xiang et al., 2003) and language control (Green & Abutalebi, 2013). These fMRI studies challenge the traditional view that the cerebellum is exclusively involved in the coordination of autonomic and somatic motor functions (Ackermann, Mathiak, & Riecker, 2007; De Smet, Paquier, Verhoeven, & Mariën, 2013; Fabbro, Moretti, & Bava, 2000; Mariën et al., 2014; Murdoch, 2010).

To conclude, the observation of neural differences over the course of only nine months of differential training is remarkable. The results of **CHAPTER 5** therefore suggest that SIs undergo neural changes in specific control-related brain networks to handle the extreme language control that takes place during interpreting.

CHAPTER 6

THEORETICAL IMPLICATIONS: EVALUATION OF PSYCHOLINGUISTIC MODELS

L1 & L2 in different representational levels

The results of **CHAPTER 2, CHAPTER 3** and **CHAPTER 4** provide evidence for overlapping semantic representations of concrete concepts across L1 and L2 as suggested by all three theoretical models of bilingual language processing: the BIA + model, the revised hierarchical model and the distributed feature model (Dijkstra & van Heuven, 2002; Kroll & Stewart, 1994; Van Hell & De Groot, 1998).

The results of **CHAPTER 4** furthermore provide additional evidence for integrated lexical representations across languages with language-independent lexical access in accordance with the Bilingual Interactive Activation + model (BIA+, Dijkstra & Van Heuven, 2002). This model argues that lexical representations in both languages are automatically co-activated during word processing in one language and therefore leaves open the possibility of cross-lingual influences. This observation of integrated lexical representations contrasts the architecture of earlier models of bilingualism such as the revised hierarchical model (Kroll & Stewart, 1994) and the distributed feature model (Van Hell & De Groot, 1998) that both assume distinct lexical representations across languages with language-selective lexical access.

Overall, we can conclude that the global results in the present dissertation are in line with the BIA+ model that assumes both integrated semantic and lexical representations across languages (Figure 1; Dijkstra & Van Heuven, 2002). The BIA+ model is developed based on its predecessor

BIA (Dijkstra & van Heuven, 1998) and the Interactive Activation model by McClelland and Rumelhart (1981). In this model a written word activates its sublexical and lexical orthographic and phonologic representations. These, in turn, activate the semantic representation and language nodes that indicate membership to a particular language. The BIA+ model did however only focus on bilingual word reading and the results of Chapter 4 specifically tapped into production. Therefore, the basic assumptions of this model should not only be applied to bilingual word recognition, but should also be extended to bilingual word production.

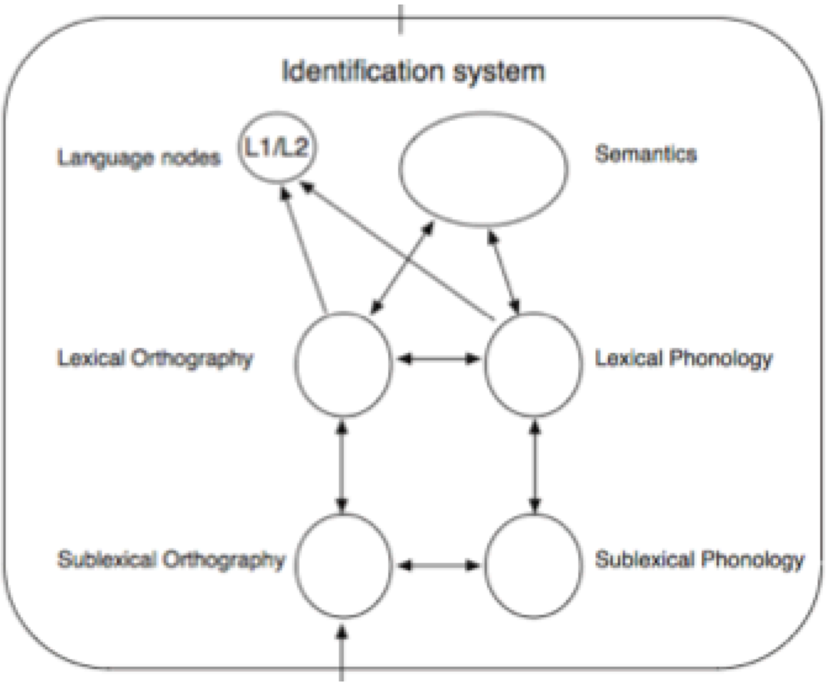

Figure 1. *The BIA+ model for bilingual word recognition (Dijkstra & Van Heuven, 2002)*

L1 & L2 in different language modalities

The results of **CHAPTER 3** provide evidence for both integrated amodal semantic representations and modality dependent distributed semantic representations. The integration of representations across comprehension and production is however not that obvious. Note that in production lexical access starts from semantic representations and ends with the identification of lexical representations, whereas in comprehension the opposite process does occur.

Evidence that separate neural systems serve comprehension and production was provided in the early aphasia literature that made the classical distinction between Broca's aphasia and Wernicke's aphasia (Rapp, 2001). More specific Broca's aphasia was defined as the specific impairment in the ability to produce language as a consequence of brain damage in inferior frontal brain regions. Whereas, Wernicke's aphasia was defined as the specific impairment in the ability to comprehend language as a consequence of brain damage in superior temporal regions. However, today this classical dissociation is left behind as it is currently well-known that brain damage in inferior frontal brain regions or superior temporal regions can cause both impairment in language production and language comprehension (Pulvermüller, 2012).

In addition, in modern neuroimaging literature more and more evidence has been accumulated for the existence of amodal semantic hubs in which information of multiple modalities converge to create a higher-level semantic representation (Bright, Moss, & Tyler, 2004; Buckner, Koutstaal, Schacter, & Rosen, 2000; Kircher, Sass, Sachs, & Krach, 2009; Pobric, Jefferies, & Lambon Ralph, 2010). In addition to the classical fMRI approach, Fairhall and Caramazza (2013) and Simanova, Hagoort, Oostenveld and Van Gerven (2014) applied a decoding approach to investigate semantic overlap across different modalities in L1 language processing. As in the classical fMRI studies, both studies supported the idea of amodal conceptual representations, although they didn't completely converge on the specific neural localization, which may of course also be stimulus dependent.

The results of Chapter 4 and the studies of Bonner, Peelle, Cook and Grossman (2013) and Price (2012) are furthermore consistent with both views assuming a distributed semantic network that include both amodal, integrative representations and modality-specific representations.

Although one generally assumes that comprehension and production at least partially overlap at the semantic level, this is less clear at the lexical level. Gollan et al. (2011) for example showed that lexical access occurred differently across production and comprehension. Therefore, future research should not only investigate whether semantic representations are overlapping across languages and modalities, but should also investigate whether lexical representations are integrated across languages and modalities within the same individuals.

Neural representation of language control

The results of **CHAPTER 5** confirm the idea that the basal ganglia and its interplay with frontal regions are essential for domain-general cognitive control and language control. Furthermore, this overlap in brain regions confirms the cross-talk between language control and domain general executive cognitive control as proposed in the inhibitory control model (Green, 1998; Abutalebi & Green, 2007, see figure 2). Similarly, Atallah et al. (2007) proposed a cognitive model (the cortico-striato-thalamo-cortical loops model) in which the basal ganglia and frontal regions work together as one cooperative system to obtain cognitive control. In this system, the basal ganglia act as a modulator of the frontal regions, by facilitating the appropriate responses and suppressing the competing responses that are being considered by the frontal regions.

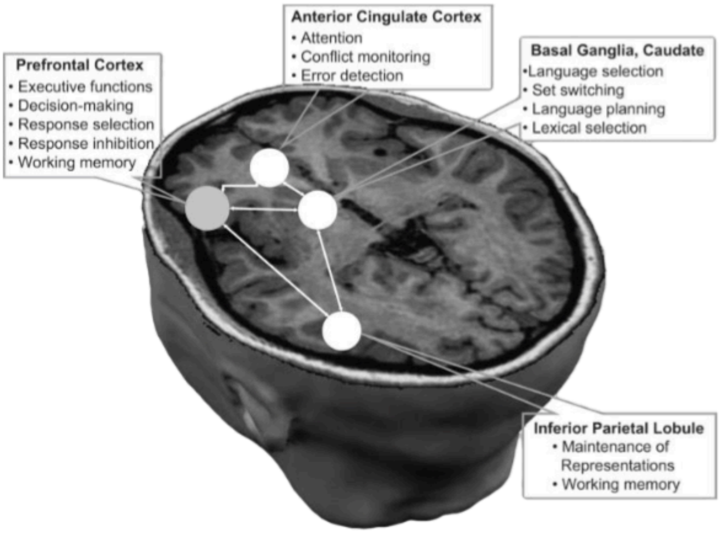

Figure 2. *Illustration of the neural devices that are responsible for both cognitive control as language control (Abutalebi & Green, 2007).*

Furthermore, In 2013, Green and Abutalebi proposed an adapted language control network (Green & Abutalebi, 2013; Figure 3), in which several areas of the second structural network that we observed in Chapter 5 (the cerebellum, the SMA and the parietal lobes) also play a key role. In this model, the SMA initiates speech in language switching and the parietal lobes are connected to the maintenance of task representations.

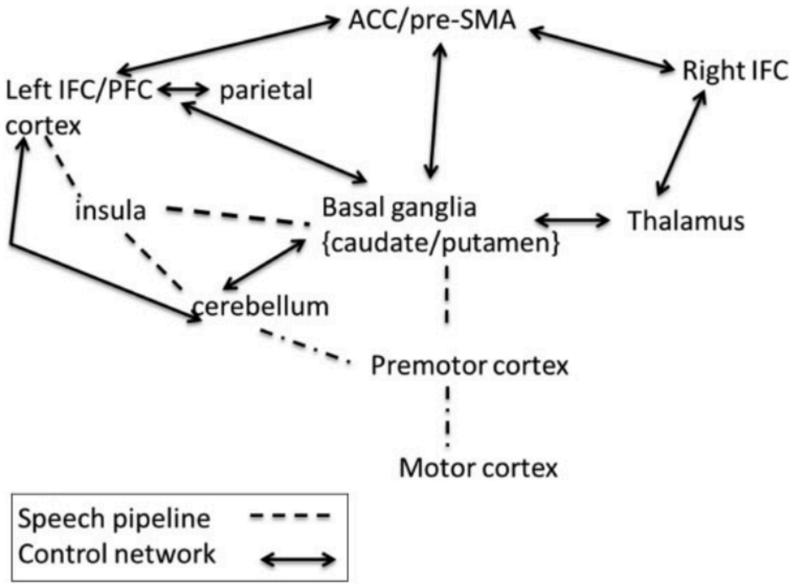

Figure 3. *Illustration of the adapted language control network proposed by Green and Abutalebi (2013).*

However, note that these inhibitory control models (Abutalebi & Green, 2007; Green & Abutalebi, 2013) are focused on speech production. Therefore, to investigate whether these models also apply for speech comprehension future research should compare the influence of language control in both production and comprehension within the same individuals. Especially because comprehension does not necessarily require a top down language control mechanism. For word recognition, bilinguals may just rely on bottom-up activation from the stimulus and proceed to lexical access without inhibition of any language. This is indeed why some models of word recognition, like the BIA+ model do not have top-down language inhibition (Dijkstra & Van Heuven, 2002).

LIMITATIONS & FUTURE RESEARCH

Although several factors such as the age of L2 acquisition, L2 proficiency, L2 exposure and language relatedness of L1 and L2 are likely to profoundly influence bilingual neural language representation, there is still no comprehensive evidence or view on the impact of these factors on the neural substrate of bilingualism. The review of Indefrey (2006) concluded that L2 age of acquisition (AOA), proficiency and exposure influence the neural representation during word level production, whereas word level comprehension is mostly influenced by proficiency. However, in **CHAPTER 2** we only saw an influence of AOA (or exposure that could not be disentangled from AOA in this chapter) and not proficiency, on the neural overlap of semantic representations in production. Hence, studies that specifically compare different (and therefore necessarily larger) subject groups with different AOA, proficiency levels and exposure levels are required to get a more detailed view on the influence of these individual difference variables on the neural overlap of semantic representations across languages and modalities. In addition, it would also be of added value to investigate the influence of the bilingual profile on the lexical representational level in both production and comprehension. Future research about bilingual organization in the brain should therefore investigate the semantic and lexical neural representations of L1 and L2 across all different combinations of individual difference variables in both comprehension and production tasks.

Similarly, the neural substrate for language control could also fluctuate depending on the language modality and the bilingual profile.

Hence, future studies should also investigate the influence of language modality and bilingual profile on the neural substrate of bilingual language control.

Next, it would also be interesting to look at the influence of language relatedness on the neural substrate of bilingual language representations and language control, because the findings about neural overlap and language control do not necessarily generalise to all language combinations. Using decoding, neural overlap across languages has only been investigated in Dutch-English, Portuguese-English, Dutch-French and Spanish-English language pairs (Buchweitz, Shinkareva, Mason, Mitchell, & Just, 2012; Correia et al., 2014; **CHAPTER 2, 3 and 4**). Consequently, there is the need to systematically compare neural overlap in close related linguistic language pairs (e.g. Spanish-French) with more distant linguistic related language pairs and different writing systems (e.g. Spanish-Chinese).

Additionally, future studies should compare the neural overlap of concrete and abstract concepts within the same individuals using a decoding approach to test the detailed assumptions of the distributed feature model. In this model less neural overlap across languages is assumed for the semantic representations of abstract concepts in comparison to concrete concepts (Van Hell and De Groot, 1998). Similarly, Wang et al. (2010) argued that abstract concepts rely less on perceptual regions than concrete concepts because abstract concepts are less imaginable than concrete concepts.

In **CHAPTER 5**, it is possible that further experience could create behavioural and neural differences that did not yet appear after only nine months of SI training, especially because the amount of SI practice was still limited during this Master course. Therefore, it is important to longitudinally investigate the influence of SI and translating after a more extended period of experience.

In addition, the underlying specific cognitive process that SI relies on is still an unresolved question. Christoffels and de Groot (2005) and de Groot and Christoffels (2006) for example clamed that inhibitory control plays a crucial role during SI, whereas other accounts proposed that divided attention or language switching rather play an important role during SI (Pöchhacker, 2004; Hiltunen, Pääkkönen, Gun-Viol, & Krause, 2016). In Chapter 5, we however only used the Simon task and the Colour-shape switch task to investigate the underlying control processes during SI. Therefore, it is necessary to complementary employ a broad range of tasks that tap into different types of cognitive control (e.g.: Attention Network Task, flanker task, Stroop task, Go/no-go task, Wisconsin card sorting test, divided attention task) to determine the specific processes that distinguish SI from translating (Miyake & Friedman, 2012).

CHAPTER 6

CONCLUSION

The four empirical studies presented in the current dissertation contribute to both research on bilingual language representations (**CHAPTER 2, 3, 4**) and to research on bilingual language control (**CHAPTER 5**). Overall we can conclude that overlapping areas are used in L1 & L2 processing, but the amount of neural overlap and the specific brain regions involved seem to differ in specific subgroups of bilinguals and their influence seems to depend on the language modality and the language representational level. In addition, Chapter 5 confirms that these integrated representations seem to require a language control mechanism to prevent speech errors.

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CHAPTER 7

ENGLISH SUMMARY

The representation of language in the brain is a fundamental prerequisite to understand human nature and the creation of meaning. A part of this debate relates to how the language system is organized and recruited across different languages. Given the high prevalence of multilingualism in the world, the understanding of bilingual language processing is of high relevance for society. Hence, the central goal of the current dissertation was to investigate the neural basis of bilingual language processing, assessing both linguistic representations and language control.

At the **linguistic level**, the main question has been whether the representations of both languages are integrated in one system or rather rely on separate cognitive/neural representations for each language. In the three main psycholinguistic models different predictions have been made about whether semantic and lexical representations are overlapping across languages or not (Dijkstra & Van Heuven, 2002; Kroll & Stewart, 1994; Van Hell & de Groot, 1998). Therefore, in **Chapter 2, 3 and 4** we explored the neural overlap of a first language (L1) and a second language (L2) in different language modalities and representational levels.

An important objective of the current dissertation was to apply a multivariate decoding approach to get a more fine grained look at the results of previous literature that used univariate analyses approaches to investigate neural overlap across languages. In the univariate approach it could be that the same brain region is activated across tasks in which different languages need to be used despite the fact that the pattern of voxel activity is in fact different for two languages (Mahmoudi, Takerkart, Regragui, Boussaoud, & Brovelli, 2012). In contrast to the univariate approach, in a multivariate decoding approach it's only possible to predict or classify stimuli across different languages if overlapping neural populations are really involved across languages.

Until now, decoding was only applied in comprehension to investigate neural overlap across L1 and L2 semantic representations. Therefore, in **CHAPTER 2** we used decoding to investigate the neural overlap between L1 and L2 semantic representations during production. To tap into production, we used a picture naming task in which the participants had to name pictures in L1 and L2. More specific, using a decoding approach we tested whether brain activity during the production of individual concepts in one language allowed predicting the production of the non-cognate translation equivalent in the other language. Based on the brain activation for the individual concepts in one language in the bilateral occipito-temporal cortex and the inferior and the middle temporal gyrus, we could accurately predict the equivalent individual concepts in the other language. Because both languages only share the underlying semantic representation (sensory and lexical overlap was maximally avoided), this indicates that these regions share semantic representations across L1 and L2 word production.

In addition to exploring whether semantic representations overlap across languages, the other aim and innovative part of **CHAPTER 3** was to investigate whether semantic representations also overlap across modalities. In this chapter we therefore used decoding to investigate the neural overlap between L1 and L2 semantic representations of non-cognate translation equivalents, within and across production (picture naming), visual comprehension (word reading) and auditory comprehension (word listening). Hence, this is the first study to examine whether decoding of individual semantic concepts across languages was also possible across modalities, within the same individuals. The results showed that it was possible to identify the picture or word named, read or heard in one language based on the brain activity in a distributed bilateral brain network while, respectively, naming, reading or listening to the picture or word in the other language. The brain regions identified differed with task. During picture naming, brain activation in the occipital and temporal regions allowed concepts to be predicted across languages. During word listening and word reading, across language predictions were observed in the rolandic operculum and several motor-related areas (pre- and postcentral, the cerebellum). In addition, across language predictions during reading were identified in regions typically associated with semantic processing (left inferior frontal, middle temporal cortex, right cerebellum and precuneus) and visual processing (inferior and middle occipital regions and calcarine sulcus). Furthermore, across modalities and languages, the left lingual gyrus showed semantic overlap across production and word reading. These findings support the idea of at least partially language- and modality-independent semantic neural representations.

Although most research agreed that both languages of a bilingual are represented in at least partly shared neural semantic representations in production, it remains unclear whether neural lexical representations are also integrated across languages in production. In **CHAPTER 4**, we therefore applied decoding to investigate the neural representation of 3 word categories (non-cognate translations, homographs and identical cognate translations) that differed on the amount of semantic and lexical overlap across languages. The English word ‘grape’ and Spanish word ‘uva’ are for example non-cognate translation, because these words share meaning but not orthography. In addition, ‘pan’ (meaning pot in English) and ‘pan’ (meaning bread in Spanish) are for example homographs, because these are words that share orthography but not meaning across languages. Furthermore, the English word ‘piano’ and the Spanish word ‘piano’ are for example identical cognate translations because these are words that both share lexical form and meaning across languages. To tap into production, we used a picture naming task in which the participants had to name pictures in L1 and L2. More specific, we tested whether brain activity during the naming of pictures in one language allowed predicting the naming of the non-cognate translation, the cognate translation and the homograph pictures in the other language. Hence, this is the first study to examine whether decoding of lexical representations is possible across languages. The decoding results for the non-cognate translations showed shared semantic representations across L1 and L2 language production in the occipital and fusiform regions. Decoding results for the homographs showed shared lexical representations across languages in frontal, temporal, parietal, occipital and sensorimotor regions. In addition, decoding results for cognates, which share both semantic as lexical representations across languages, showed neural overlap across languages in temporal, frontal, parietal, occipital, fusiform and sensorimotor regions. Hence, the results of Chapter 4 do not only confirm previous studies that provided evidence for overlapping semantic representations across L1 and L2, but also provide additional evidence for integrated lexical representations across languages. However, the specific brain regions that predicted commonality in the across language representations differed across the homographs, cognates, and non-cognate translations. Therefore we can assume that the brain regions involved depend on the language semantic or lexical representational level.

Overall, we can conclude that the global results in the present dissertation are in line with the BIA+ model that assumes both integrated semantic and lexical representations across languages (Dijkstra & Van Heuven, 2002). In this model a written word activates its sublexical and lexical orthographic and phonologic representations. These, in turn, activate the semantic representation and language nodes that indicate membership to a particular language. The BIA+ model did however only focus on bilingual word reading and the results of Chapter 4 specifically tapped into production. Therefore the basic assumptions of this model should not only be applied to bilingual word recognition, but should also be extended to bilingual word production.

Additionally, if two languages are integrated at the representational level and a person only needs to use one language in a certain communicative setting, the second question is whether a **language control** mechanism is then required to prevent interference from the non-relevant language that might otherwise cause cross-lingual speech errors. Although, most psycholinguistic models agreed that an inhibitory control mechanism is needed to obtain language control, it is not exactly clear how this language control mechanism is represented in the brain and whether this accounts for both production and comprehension. Therefore, in **CHAPTER 5**, we investigated the neural substrate of extreme language control. We tackled the question of extreme language control assessing the long-term anatomical and cognitive effects of simultaneous interpreting (SI), an expertise that requires extreme language control. To investigate this we compared two similar training programs that only differed on the degree of language control (SI versus translation), in order to identify the cognitive and neural changes specifically related to SI. Translators have to read a written source text and have to render it only afterwards into a written target text, whereas SIs have to verbally listen to a spoken source message and immediately have to make a simultaneous verbal rendition into the target language (Christoffels and de Groot, 2009). Through all these simultaneous processes it is generally assumed that SI's manage greater levels of language control in comparison to translators, which in turn may lead to greater cognitive gains and changes in underlying neural networks (Babcock & Vallesi, 2017). However, to our knowledge, this is the first study to examine longitudinal changes as a result of SI training, both in behavioural performance, using non-linguistic cognitive control tasks, as well as on a neural level, measuring both structural connectivity and functional differences. It is important to emphasize the conservative approach adopted here, to compare SI students with a group of closely matched translators from the same Bachelor program, rather than a monolingual or less L2-proficient control group. As a result, the obtained differences between these two highly similar groups need to be attributed to control processes that are specific to SI.

Despite the lack of behavioral differences between the two groups over time, functional and structural neural differences did arise. At the functional level, interpreters showed an increase of activation in the right angular gyrus and the left superior temporal gyrus in two non-verbal cognitive control tasks (the Simon task and a colour-shape switch task), relative to the translators. At the structural level, we identified a significant increment of the structural connectivity in two different subnetworks specifically for the interpreters. The first network, the frontal-basal ganglia subnetwork, has been related to domain-general and language-specific cognitive control (Green, 1998; Abutalebi & Green, 2007; Atallah et al., 2007). The second subnetwork, in which the cerebellum and the SMA play a key role, has recently also been proposed as an important language control network (Green & Abutalebi, 2013). These results suggest that interpreters undergo plastic changes in specific control-related brain networks to handle the extreme language control that takes place during interpreter training.

However, note that these inhibitory control models (Abutalebi & Green, 2007; Green & Abutalebi, 2013) are focused on speech production. Therefore to investigate whether these models also apply for speech comprehension future research should compare the influence of language control in both production and comprehension within the same individuals. Especially because comprehension does not necessarily require a top down language control mechanism. For word recognition, bilinguals may just rely on bottom-up activation from the stimulus and proceed to lexical access without inhibition of any language. This is indeed why some models of word recognition, like the BIA+ model do not have top-down language inhibition (Dijkstra & Van Heuven, 2002).

CONCLUSION

The four empirical studies presented in the current dissertation contribute to both research on bilingual language representations (**CHAPTER 2, 3, 4**) and to research on bilingual language control (**CHAPTER 5**). Overall we can conclude that overlapping areas are used in L1 & L2 processing, but the amount of neural overlap and the specific brain regions involved seem to depend on the language modality and the language representational level. In addition, Chapter 5 confirms that these integrated representations seem to require a language control mechanism to prevent speech errors.

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CHAPTER 8
NEDERLANDSTALIGE SAMENVATTING

Hoe taal gerepresenteerd wordt in de hersenen is een fundamentele onderderzoeksvraag om beter menselijke betekenisgeving te kunnen begrijpen. Door de hoge prevalentie van meertaligheid in de wereld gaat een deel van dit debat over hoe het taalsysteem georganiseerd en gerekruteerd wordt in verschillende talen. Het centrale doel van dit doctoraat was dan ook om de neurale basis te onderzoeken van tweetaligheid zowel op het linguïstisch representatieniveau als op het niveau van taalcontrole.

Op het **linguïstisch representatieniveau** was de hoofdvraag of de taalrepresentaties van twee talen geïntegreerd zijn in één systeem of eerder vertegenwoordigd worden door afzonderlijke cognitieve/neurale representaties in beide talen. De drie dominerende psycholinguïstische modellen verschillen m.b.t. de assumpties die ze postuleren omtrent het al dan niet overlappen van semantische en lexicale representaties tussen verschillende talen (Dijkstra & Van Heuven, 2002; Kroll & Stewart, 1994; Van Hell & de Groot, 1998). Om hier meer duidelijkheid in te verkrijgen, werd de neurale overlap van een eerste taal (L1) en een tweede taal (L2) in verschillende modaliteiten (productie en comprehensie) en verschillende representationele niveaus (lexicale en semantische representaties) onderzocht in **HOOFDSTUK 2, 3** en **4**.

Een belangrijk doel van dit doctoraat was het hanteren van een multivariate decoding analyse om meer inzicht te verkrijgen in de resultaten van voorgaande literatuur die univariate analyse methodes hanteerden om de neurale overlap tussen talen te onderzoeken. In de univariate benadering kan het zijn dat dezelfde hersengebieden geactiveerd zijn in taken die beroep doen op andere talen, ondanks het neurale patroon van voxel activatie eigenlijk verschillend is voor beide talen (Mahmoudi, Takerkart, Regragui, Boussaoud, & Brovelli, 2012). In de multivariate benadering is het daarentegen enkel mogelijk om de stimuli te gaan voorspellen in de verschillende talen indien overlappende neurale populaties betrokken zijn tussen talen. Het is dan ook belangrijk dat de multivariate benadering gehanteerd wordt ter aanvulling van de univariate benadering om zo meer inzicht te verkijkgen in de integratie van L1 en L2 in de hersenen.

Tot op heden was decoding echter enkel toegepast om de neurale overlap tussen L1 en L2 semantische representaties te onderzoeken in comprehensie. In **HOOFDSTUK 2**, werd decoding daarom gebruikt om de neurale overlap tussen L1 en L2 semantische representaties te bestuderen tijdens productie. Om productie te onderzoeken hebben we een taak gebruikt waarin de proefpersonen afbeeldingen moesten benoemen in L1 en L2. We onderzochten of het mogelijk is om op basis van het patroon van hersenactivatie tijdens de productie van individuele concepten in één taal, het patroon van hersenactivatie te gaan voorspellen van de geproduceerde niet-cognaat vertalingen in de andere taal. De resultaten toonden aan dat dit mogelijk was in de bilaterale occipito-temporale cortex en de inferieure en midden temporale cortex. Omdat enkel semantiek overlappend was tussen beide vertalingen (sensorische en lexicale overlap werd maximaal gereduceerd), kunnen we concluderen dat deze regio's gedeelde semantische representaties omvatten tussen L1 en L2 productie.

Naast het bestuderen van de onderzoeksvraag of semantische representaties al dan niet overlappen tussen talen, was het tweede en meer innovatieve luik van **HOOFDSTUK 3** te onderzoeken of semantische representaties ook overlappen tussen modaliteiten. In dit hoofdstuk hebben we daarom decoding toegepast om de neurale overlap tussen L1 en L2 semantische representaties van niet-cognaat vertalingen te onderzoeken, zowel binnen als tussen de verschillende modaliteiten (productie, lezen en luisteren). Dit is dan ook de eerste studie die onderzocht of decoding van individuele semantische concepten tussen talen, ook mogelijk was tussen modaliteiten bij dezelfde individuen. De resultaten toonden aan dat het mogelijk was om het gelezen, gehoorde of geproduceerde concept te voorspellen in een verspreid bilateraal neuraal netwerk dat geactiveerd werd tijdens het lezen, het luisteren of het benoemen van het concept in de andere taal. De betrokken hersengebieden verschilden echter van taak tot taak. In de productietaak, liet hersenactivatie in de occipitale en temporale regio's toe om concepten te voorspellen tussen talen. In de lees- en luistertaak was significante decoding mogelijk in het rolandische operculum en motor gerelateerde gebieden (pre- en postcentrale regio's en cerebellum). Daarnaast was significante decoding in de leestaak ook nog geobserveerd in regio's die typisch geassocieerd zijn met semantische informatieverwerking (linker inferieure frontale cortex, midden temporale cortex, rechter cerebellum en precuneus) en visuele informatieverwerking (inferieure en midden occipitale regios en calcarine sulcus). Daarenboven toonde het vernieuwende aspect van deze studie aan dat decoding ook mogelijk was tussen modaliteiten en talen. Deze analyse toonde namelijk aan dat de linker linguale gyrus betrokken is bij semantische overlap tussen L1 en L2 productie en lezen. Deze bevindingen ondersteunen het bestaan van op zijn minst gedeeltelijke taal- en modaliteitsonafhankelijke semantische neurale representaties.

De meerderheid van het onderzoek is akkoord dat twee verschillende talen gerepresenteerd worden door ten minste gedeeltelijk overlappend neurale semantische representaties in productie. Desondanks blijft het onduidelijk of lexicale representaties ook geïntegreerd worden tussen talen in productie. In **HOOFDSTUK 4** hebben we daarom decoding gebruikt om de neurale representatie van 3 woordcategorieën (niet-cognaat vertalingen, identieke cognaten en homografen) te onderzoeken die verschillen in de mate waarin lexicale en semantische representaties al dan niet overlappen tussen talen. Het Engelse woord ‘grape’ en het Spaanse woord ‘uva’ zijn bijvoorbeeld niet-cognaat vertalingen omdat deze woorden semantiek, maar geen orthografie delen tussen talen. ‘pan’ (wat pot betekent in het Engels) en ‘pan’ (wat brood betekent in het Spaans) zijn daarentegen homografen omdat deze woorden orthografie, maar geen semantiek delen tussen talen. Daarnaast zijn het Engelse woord ‘piano’ en het Spaanse woord ‘piano’ voorbeelden van identieke cognaten omdat deze woorden zowel orthografie als semantiek delen tussen talen. Om productie te onderzoeken hebben we zoals in Hoofdstuk 2 een taak gebruikt waarin de proefpersonen afbeeldingen moesten benoemen in L1 en L2. We onderzochten of het patroon van hersenactivatie tijdens de productie van de concepten in één taal, het toelaat om de niet-cognaat vertalingen, de identieke cognaten en de homografen te gaan voorspellen die geproduceerd worden in de andere taal. Dit is dan ook de eerste studie waarin decoding werd gebruikt om de neurale overlap tussen L1 en L2 lexicale representaties te bestuderen tijdens productie. De decoding resultaten van de niet-cognaat vertalingen boden evidentie voor gedeelde semantische representaties tussen L1 en L2 productie in de occipitale en fusiforme regio’s. De decoding resultaten van de homografen boden evidentie voor gedeelde lexicale representaties tussen talen in frontale, temporale, pariëtale, occipitale en sensorimotorische regio’s. Daarnaast liet hersenactivatie in temporale, frontale, pariëtale, occipitale, fusiforme en sensorimotorische regio’s toe om cognaten te voorspellen die zowel semantische als lexicale representaties delen tussen talen. De bevindingen van Hoofdstuk 4, bevestigen niet alleen voorgaande studies die evidentie boden voor overlappende semantische representaties tussen L1 en L2, maar bieden ook extra evidentie voor de integratie van lexicale representaties tussen talen. Doordat de specifieke gebieden die overlap vertoonden verschilden tussen de homografen, identieke cognaten en niet-cognaat vertalingen kunnen we besluiten dat de hersengebieden die betrokken zijn in de representatie van L1 en L2 afhankelijk zijn van het semantisch en het lexicale representationele niveau.

Als we de resultaten van hoofdstuk 2, 3 en 4 samen nemen kunnen we concluderen dat dit doctoraat evidentie biedt voor het BIA+ model dat zowel gedeelde semantische als lexicale representaties verondersteld (Dijkstra & Van Heuven, 2002). Volgens dit model zal een geschreven woord de sublexicale en lexicale orthografische en fonologische representaties activeren. Deze zullen dan op hun beurt de semantische representaties en taalknopen activeren die aangeven tot welke taal de woorden behoren. Het BIA+ model focuste echter enkel op tweetalige woordherkenning en de resultaten van Hoofdstuk 4 gaan enkel over woordproductie. De basisassumpties van dit model lijken daardoor niet enkel relevant voor comprehensie, maar ook voor productie.

Als twee talen overlappen op het representationele niveau en we enkel één van de twee talen moeten gebruiken in een bepaalde communicatieve situatie, hoe komt het dan dat er zo weinig versprekingen gebeuren? In het tweede luik van dit doctoraat probeerden we daarom meer inzicht te verwerven in het **taalcontrole** mechanisme dat toelaat om interferentie van de niet-relevante taal te voorkomen. De meerderheid van de psycholinguïstische modellen gaan akkoord met het idee dat een inhibitiemechanisme noodzakelijk is om taalcontrole te handhaven. Desondanks is het nog steeds niet duidelijk hoe dit taalcontrole mechanisme gerepresenteerd wordt in de hersenen en of dit geldig is voor zowel productie als comprehensie. In **HOOFDSTUK 5** onderzochten we daarom de neurale basis van extreme taalcontrole. Om hier meer inzicht in te verkrijgen onderzochten we de lange termijn anatomische en cognitieve effecten van tolken, een expertise die extreme taalcontrole vereist. Als controlegroep werden vertalers genomen die een overeenkomstig niveau van talenkennis en dezelfde educatieve achtergrond hadden. Omdat deze twee groepen enkel verschilden in de mate van taalcontrole (tolken > vertaler) die moet worden uitgeoefend kunnen de resultaten dan ook toegeschreven worden aan taalcontrole processen die uniek zijn voor het tolken. Ondanks we geen longitudinale gedragsverschillen konden observeren tussen de twee groepen, waren er wel functionele en structurele neurale verschillen tussen beide groepen over tijd. Op het functioneel neuraal niveau vertoonden tolken in vergelijking met de vertalers een grotere toename in activatie in de rechter angulaire gyrus en de linker superieure temporale gyrus in twee non-verbale cognitieve controle taken (de Simon taak en de kleur-vorm switch taak). Op het structureel niveau, konden we daarnaast een significante toename in structurele connectiviteit observeren voor de tolken in vergelijking met de vertalers in twee verschillende subnetwerken. Het eerste subnetwerk, het frontale-basale ganglia subnetwerk is in voorgaande literatuur gerelateerd aan verbale- en non-verbale cognitieve controle (Green, 1998; Abutalebi & Green, 2007; Atallah et al., 2007). Daarnaast is het tweede subnetwerk, waarin het cerebellum en de SMA een centrale rol speelden ook voorgesteld als een belangrijk taalcontrole netwerk (Green & Abutalebi, 2013). Deze resultaten suggereren dat training in het tolken plastische veranderingen creëert in specifieke controle gerelateerde neurale netwerken om zo de extreme taalcontrole te kunnen handhaven die plaats vindt tijdens het tolken.

Deze taalcontrolemodellen zijn echter gericht op productie en niet op comprehensie. Om te onderzoeken of deze modellen ook geldig zijn voor comprehensie is toekomstig onderzoek vereist dat de invloed van taalcontrole onderzoekt tijdens zowel productie als comprehensie bij dezelfde individuen.

CONCLUSIE

De vier empirische hoofdstukken die in dit doctoraat zijn uitgewerkt dragen zowel bij tot het onderzoek naar L1 en L2 linguïstische representaties **(HOOFDSTUK 2, 3, 4)** als taalcontrole (**HOOFDSTUK 5**). We kunnen concluderen dat overlappende neurale gebieden gerekruteerd worden voor L1 en L2, maar dat de hoeveelheid neurale overlap en de specifieke neurale regio's afhankelijk zijn van de modaliteit en het representationele niveau. Daarnaast lijken deze geïntegreerde representaties een taalcontrole mechanisme te vereisen om taalfouten te vermijden.

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In compliance with the UGent standard for research accountability, transparency and reproducibility, the location of the datasets used in this dissertation are added below. For each of the empirical chapters (i.e. Chapter 2 to 5) a separate Data Storage Fact Sheet is completed, detailing which data and analysis files are stored, where thery are stored, who has access to the files and who can be contacted in order to request access to the files. In addition, the Data Storage Fact Sheets have been added to my public UGent Biblio account.

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% Author: Eowyn Van de Putte
% Date: 1/12/2017

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===

1a. Main researcher

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% Date: 1/12/2017

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% Author: Eowyn Van de Putte
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