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Exploring the ventral language pathways of the brain through bilingualism: a Tractography study

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Abstract

The focus of the present PhD thesis is to compare the brain correlates associated to bimodal bilingualism with respect to unimodal bilingualism. The overarching aim is to identify which are the common neuronal substrates between signed and spoken languages, with respect to the neural substrates that are specific for each linguistic modality, i.e., signed versus spoken. This is a relevant issue as it allows to better explore (i) to what extent and for which function the two language modalities might interact; (ii) for which function they might interfere, and (iii) whether the two language modalities are supported by independent neuronal systems. In addition, this project explores the organization of the bilingual brain in a broader view, assessing whether the neural structures underlying the first language (L1) can be separated from structures mainly devoted at handling the second language (L2). Measures of diffusion magnetic resonance imaging tractography will be assessed in a group of unimodal bilinguals of Italian (L1) and English (L2) and in a group of bimodal bilinguals of Italian (L1) and Italian Sign Language (L2), with variable level of proficiency in the second language. Together with the tract-specific measures, both demographical and behavioral data will be collected in order to assess the level of performance for both L1 and L2. Tract-specific data will be correlated with behavioral data, revealing how the degree of expertise with signed or spoken language and the relative modality are capable of shaping the neural circuitry at the service of specific linguistic functions.

Synopsis

Part One. In the *first chapter* (Chapter 1) the evolution of the language system from Broca's/Wernicke's view up to the use of neuroimaging techniques will be outlined. Particular relevance will be given to the identification of the brain areas responsible for perception, production and object nouns processing. In the *second chapter* (Chapter 2) the basic principles of Diffusion Tensor Imaging (DTI) and DTI tractography will be provided. The description will mostly focus on the techniques used and on the contribution of DTI tractography in the definition of the white matter tracts composing both the dorsal and the ventral network of language. Then, a summary of the structural studies on the ventral pathway of language will be outlined. The *third chapter* (Chapter 3) is centered on the bilingual brain from both a functional and a structural perspective. Then, the focus will shift on bimodal bilingualism and sign language. The basic characteristics of sign language will be depicted trying to highlight possible differences and similarities across the sign and the spoken language brain. Finally, a summary of the most influential research concerned with the bimodal bilinguals' brain will be presented.

Part Two. The *fourth chapter* (Chapter 4) relates to my research work. In this section, the aims, the design, together with the materials and methods will be delineated. In the *fifth chapter* (Chapter 5) I shall describe the participant's sample, the statistical analysis and the report of the main findings. In the last and *sixth chapter* (Chapter 6), I shall draw the main conclusions on the basis of available literature and suggest future research directions.

Part One

CHAPTER 1

The language system

Introduction. Language ability has always been considered one of the major differences between humans and other animal species. For decades, research on language has been oriented in defining the origin of the linguistic function, viewed as an innate faculty and a unique characteristic the human beings have developed during the evolution. Diverse evolutionary theories have attempted to explain how this development, from monkeys to humans, may have occurred. One of the most popular theories was put forward by Aboitiz and Garcia (1997). According to these authors, the linguistic function has emerged as a gradual specialization of preexisting systems in the primate brain, through two main evolutionary phases. A first phase, in which the superior temporal lobe became increasingly connected with the infero-parietal regions, linking the auditory system with the parietal premotor loop, used to generate vocalizations. A second phase identified as the development of a direct connection between the superior temporal regions with prefrontal areas, a link used to connect the auditory information with the orofacial premotor regions. These two phases would have contributed to the development of the oldest components of what is now referred to as the posterior segment (PS) and the long segment (better known as arcuate fasciculus - AF) of the dorsal language stream (Catani, Jones, & ffytche, 2005; Catani & Mesulam, 2008). More recently, Arbib (2003) proposed that language would have emerged from the development of hand movements. A central focus in this theory is given to the mirror neurons system in monkeys. Recent studies on this system revealed the possibility to employ a common neural system when executing and observing actions (see also Chapter 2). According to Arbib (2003) the ventral premotor area F5, within which mirror neurons have been first uncovered, adapted to support pantomime (basic communication through hands) and then, through further modification, language in the human brain.

Most theories today agree with the idea of a constant collaboration between genes and environment, working together in the integration, shaping and translation of our daily experience into complex behaviors (e.g., Ottman, 1996). This cooperative interaction can be applied to the development of language as well as to the improvement of any other intellectual function.

In general, the literature of the past 30 years indicate that the neural system supporting language is far more complex and dispersed than what researchers might have imagined in the past.

Going back, the first studies on language were conducted in the 19th century. In such studies, a correlation between a specific symptom during life and a localized brain damage (viewed *post-mortem*) indicated the association of a specific brain area with a specific function (Mott, 1910). Through the analysis of patients with brain lesions, neurologists tried to distinguish the neural systems supporting language production and comprehension. In 1861, Pierre Paul Broca described the case of patient Leborgne, who after a stroke had completely lost the ability to speak. The patient could understand language but could produce only the syllable “tan”. After the patient’s death, through brain dissection, Broca localized the damaged area in a frontal region of the left hemisphere, now called Broca’s area, which corresponds to areas 44-45 in Brodmann’s nomenclature. He ascribed to this area the function of language production. The same correlation pattern was confirmed a few months later in another patient, called Lelong (Broca, 1861), and later in other patients (Broca, 1865), who all had the same frontal lesions.

With a similar approach in 1874, Carl Wernicke defined a temporal region of the left hemisphere that subserves the comprehension of speech (the so-called Wernicke’s area, which corresponds to area 22 in Brodmann’s nomenclature). This area adjacent to the auditory cortex, when compromised, leads to impairment in understanding both the written and the spoken language, but apparently leaves intact the capacity of sliding speeches, even if speeches are often meaningless. Based on the evidence from the *post-mortem* dissection, Wernicke elaborated the first language model. According to his model, Wernicke’s area would be the center where information would be transformed into a phonetic representation and transferred to the Broca’s area. Broca’s area was defined as the center where the syntactic structure of a sentence would be elaborated, before reaching the motor cortex area, the center of the articulation of tongue and mouth (motor-verbal area). A few years later following Wernicke’s ideas, Lichtheim (1885) formulated a three-component model of language, in which Broca’s and Wernicke’s areas were interconnected by a previously undefined “fiber link”, involved in semantic processing and passing through the external capsule, in the insula. The hypothesis of a direct connection between Broca’s and Wernicke’s areas would eventually be confirmed through studies by Von Monakow (Geschwind, 1967), who identified a long arch of white matter fibers, the AF. The presence of a connection corresponding to the AF has been then acknowledged by Reil (1809), Burdach (1822) and confirmed by Dejerine (1895) at the end of the 19th Century. The AF has been a crucial element for the development of an anatomically based model of language, the Broca-Wernicke-Lichtheim's model. For the first time, connections (and disconnections) among areas were considered critical for cognitive functions. Specific language deficits were not ascribed to lesions of the areas subserving the function impaired, but to the disruption of the connections between areas. Conduction aphasia, characterized by spared production and comprehension but poor repetition skills and difficulty in finding words, has been ascribed to a disconnection between Wernicke's or Broca's areas, i.e., to a lesion of the AF. Geschwind further elaborated this model in the 1960s, considering the inferior parietal region including the angular gyrus ("Geschwind's territory") as an additional area involved in language processing. The angular gyrus has been considered important for different reasons; first, due to its location in the brain, it might be particularly important for cross-modal association between vision and hearing. Moreover, it seems to be connected with the process of associating a heard name with the corresponding seen or perceived object (Geschwind, 1965). Geschwind's speculative idea (which has yet to be confirmed anatomically) regarding lesions to Wernicke's area was related to the fact that if the Wernicke's area and the angular gyrus are somewhat connected, Wernicke's aphasia could be due to a lesion on this specific area or in any other point of the connection between the two.

It is worth noting that all these lesion studies were conducted considering the left hemisphere of the brain, which has long been considered the "headquarters" of language processing.

Contribution of neuroimaging. The development of techniques for measuring the relationship between the activity of the brain and a specific behavior, has become a very hot topic since it develops the understands of the functionality of different areas and their connections. Through neuroimaging studies, it has been shown that language rests on a more distributed network in the brain, with respect to what was thought in the 19th century. The AF and its connections with Wernicke's and Geschwind's areas originally were considered the "core" of linguistic processing in the brain. More recently, this view has been replaced by the idea of a distributed network for language processing which involves a larger number areas and connections than initially thought. Evidence collected through functional and structural neuroimaging studies is consistent with this idea.

1.1. Functional studies on language comprehension and language production

In this section, some of the functional studies related to language comprehension and production will be summarized, emphasizing the associations between specific brain areas and the possible behavioral function(s). Speech comprehension processes will be described from the perspective of the dual stream model of language (Hickok & Poeppel, 2007). The Lemma Model (Levelt, 2001) will be used as the guideline for describing the brain regions associated with language production. Lastly, since an important part of the present research is dealing with objects representations and their retrieval mechanism, an overview of how the brain processes object nouns will be carried out.

1.1.1. Language comprehension explained by the Dual Stream Model

Speech perception occurs automatically. However, behind this process, a series of computational operations occur at different levels, engaging different brain areas. The stream of speech's sounds is segmented in meaningful units through mechanisms that are mostly unconscious and effortless. This process occurs taking into account the differences between speakers, so that the listener can be sensitive to the acoustic variability but, at the same time, he/she can recognize the target sound/word regardless of the talker's voice.

The Dual Stream model (Hickok & Poeppel, 2007), which is one of the most compelling models of speech perception, postulates that after the early stages of sound processing, the acoustic signal is elaborated through two separate pathways.

The early cortical stages of speech perception involve the Heschl's gyrus and project into the superior temporal gyrus (STG) and superior temporal sulcus (STS). More precisely, the thalamus sends the auditory signal to the Heschl's gyrus and to the close cortical areas (where also the STG's dorsal area is included) that operate spectrotemporal analyses in order to detect both the sound frequency and the sound rate. Then, the phonological network, identified as the STG and STS, receives the signal. The theory assumes that these stages of early speech perception are organized hierarchically (with lower levels which conduct elementary spectrotemporal analyses and higher levels extracting phonological patterns) and bilaterally. As for the hierarchical associations, various levels of neuronal architecture have been associated with speech perception processes. Studies on animals' tonal scream perception (e.g., Rauschecker & Scott, 2009) have given support to this view. However, the neural architecture underlying the human's phonological system, due to its complexity, is still foggy. Even if the neural circuitry for processing the auditory stimuli on humans still requires further investigation, evidence shows that the dorsal STG is involved in the analysis of the spectrotemporal properties of the sound. Then, both the ventral STG and the STS seem to be involved in higher level processing, detecting phonemes and syllables. It has been assumed that these hierarchical levels are bilaterally organized. Several fMRI studies have confirmed the contribution of both hemispheres in the perception of speech. For example, Binder and colleagues (2000) showed activation of both hemispheres during the perception of five different types of auditory stimuli. Specifically, participants had to judge whether an auditory stimulus was a word, a pseudoword, a reversed word, an unstructured noise or a frequency-modulated (FM) tone. Hearing of FM tones versus unstructured noise activated the dorsal and mid-lateral STG. Moreover, the mid-lateral STG and middle sector of the STS were more active with speech perception than tone perception, confirming the hypothesis of a bilateral and hierarchical organization of the early cortical stages of speech perception (e.g., Joanisse & Gati, 2003; Dehaene-Lambertz et al., 2005; Liebenthal, Binder, Spitzer, Possing, & Medler, 2005; Rimol, Specht, Wes, Savoy, & Hugdahl, 2005; Benson, Richardson, Whalen, & Lai, 2006, for similar conclusions). In addition to suggesting the same activation of critical area, the above studies used the same technique measuring activation through fMRI analyses. This method, despite being a very informative, non-invasive technique, has some important limitations. For example, it does not clarify whether the area activated during a task is playing a causal role for that specific task. In other words, the activation of both the left and the right temporal regions during speech perception may be not strictly necessary for the perception process. For this reason, further studies have been conducted to explore the contribution of the two hemispheres in speech perception.

Hickock et al. (2008) used the Wada procedure (Wada & Rasmussen, 1960) to anesthetize one of the two hemispheres (first one and then the other) while performing a linguistic task. The results showed that speech perception was fully preserved when the right hemisphere was put asleep. Crucially, however, even when the left hemisphere activity was "blocked", participants could correctly perform a word-picture matching task, showing that the right hemisphere alone can still perceive speech. In general, all the data coming from this study and other literature (see also Poeppel, 2001; Bauer & McDonald, 2006; Stefanatos, 2008) are in line with the idea that early stages of speech perception involve the superior temporal regions of both hemispheres, with a preference for the left hemisphere. Looking specifically at the hemispheres contribution in speech perception, there is evidence suggesting hemispheric specialization for the processing of specific types of auditory signals. In 1992, Rosen pointed out how different phonological structures have distinctive durations and, for this reason, they should be processed with different timing. Such idea has been further developed into the "asymmetric sampling in time" hypothesis by Poeppel (2003), which postulated a specialization of each hemisphere in relation to the size of the temporal window used to integrate sounds (Poeppel, Idsardi & van Wassenhove, 2008). According to this still debated hypothesis, the left hemisphere seems to be optimized for detecting fine and rapid phonemic distinctions (in the range of 20-80 ms), whereas the right hemisphere seems to be optimized for detecting longer sounds at the syllabic level (in the range of 150-300 ms). Aside from speech perception, the right hemisphere has also been associated with the perception and comprehension of visually presented words, suggesting that the same area processes words, regardless of the modality (visual or spoken). With specific reference to visually presented words, the right hemisphere carries out the visual feature analysis, while the left hemisphere supports the identification and the naming processing. This suggests that the comprehension of words is a multistage process (Pirozzolo & Rayner, 1977).

After the early cortical stages of speech processing, further processing occurs through two different streams, the ventral and the dorsal stream (Hickok & Poeppel, 2000; 2004; 2007). The existence of these two different channels is based on the studies of brain-damaged patients showing a "double dissociation" between comprehension and repetition tasks (Kümmerer et al., 2013, Miceli, Gainotti, Caltagirone, & Masullo, 1980 for evidence of a double dissociation in aphasic patients). The ventral stream connects the phonological representation with the lexical-semantic system (the "what" stream) and the dorsal stream links the phonological representation with the articulatory motor system (the "how" stream").

The ventral stream is involved in the comprehension of speech and it is considered more bilateral. Specifically, this stream links the phonological representation of the heard sounds to the corresponding semantic representation. It also plays a role in meaning integration, allowing the comprehension of complex sentences. It is composed of two different components: a "lexical interface" and a "combinatorial network". The lexical interface is located in the posterior portion of the middle temporal gyrus (MTG) and in the posterior portion of the inferior temporal sulcus of both hemispheres (with a left hemispheric preference). It connects the phonological representations stored in the STS with the semantic system. It is relevant to note that the model assumes that the semantic system is not located in this area, but this area has the function of linking the semantic network (see Paragraph 1.1.3.) with the phonological network. Even if the computational details of the lexical interface are still highly underspecified and its role debated (see Hickok and Poeppel, 2004), there is evidence supporting the neuroanatomical location of this component. Aphasia and fMRI studies on semantic processing (Boatman et al., 2000) as well as neuropsychological findings (Dronkers, Wilkins, Van Valin, Redfern, & Jaeger, 2004), suggest that the posterior MTG plays a critical role in auditory word comprehension.

The combinatorial network is located in the anterior portion of the MTG and in the anterior portion of the inferior temporal sulcus of the left hemisphere (Hickok & Poeppel, 2007). Several fMRI studies, but also studies with Positron Emission Tomography (PET), have shown that listening to semantically and syntactically coherent sentences versus lists of isolated words or other types of auditory stimuli, activate the left lateral anterior temporal lobe (ATL; Friederici, Meyer, & von Cramon, 2000; Humphries, Buchsbaum, & Hickok, 2001; Humphries, Love, Swinney, & Hickok, 2005; Humphries, Binder, Medler, & Liebenthal, 2006). Moreover, an interesting fMRI study by Rogalsky and Hickok (2009) used a sentence verification task in which incorrect sentences contained a violation at the semantic or at the syntactic level in two separated blocks. The analyses were focused just on the correct sentences. The results showed highly similar activation of the ATL when attention was directed either at the semantic and the syntactic level. Taken together, these data are congruent with the idea that the combinatorial network is located in the ATL and that both the semantic and the syntactic aspects of a sentence are computed by a highly interactive system and therefore not easily distinguishable.

Lastly, it should be taken into account the possibility that the ventral stream does not work alone in the auditory sentence processing, but it needs the support of the dorsal stream as pointed out in recent studies by Rolheiser, Stamatakis and Tyler (2011). They performed a whole-brain voxelwise correlation analysis (using neuropsychological inference, DTI and linguistic tasks) in 24 chronic stroke patients with left hemisphere damage, in order to assess whether language is more based on communication areas working together, rather than as a "segregation" of streams. From the results emerged that the comprehension of syntax involved in the same way both the AF and the extreme capsule; which is coherent with the idea that left frontal and middle temporal regions are engaged in syntactic comprehension (Rodd, Longe, Randall, & Tyler, 2010); while syntactic production seems to be linked to the AF. This finding appears to reflect cooperation among systems rather than a segregated dual-stream system, especially when processing morphological and syntactic aspects of language. In this respect, a similar conclusion of a dual stream synergic system has been advanced by Wilson and colleagues (2011).

The dorsal stream that maps perceptual representations of vocal sounds onto motor representations is strongly left lateralized and has two functional-anatomical components: the "sensorimotor interface" and the "articulatory network". The "sensorimotor interface" has feed-forward and feedback connections with the phonological network and is located in a parietal-temporal region termed as "area Spt" (Sylvian parietal-temporal). The Spt is responsible for the integration of auditory information (phonological representations) with the motor representations guiding the movements of the vocal tract. Given this function, the area Spt is involved not only in speech perception but also in speech production, regardless of whether or not the auditory feedback is present (Hickok, Buchsbaum, Humphries, & Muftuler, 2003; Hickok, Okada, & Serences, 2009; Buchsbaum, Hickok, & Humphries, 2001; Buchsbaum, Olsen, Koch, & Berman, 2005). Several studies have shown Spt activation not only when overt sentences or melodies have been presented to participants (Hickok et al., 2003; Pa & Hickok, 2008), but also when it was asked to participants to covertly repeat sentences or melodies (Pa & Hickok, 2008). Crucially, during the control resting phase condition, no activation has been seen in this area.

The "sensorimotor interface" is linked to the other dorsal stream component: the "articulatory network". This component is associated with some motor-related regions, located in the left posterior frontal lobe, such as Broca's area and premotor cortices of the vocal tract. We will better explore this system in the next paragraph focused on speech production. What is critical for the Dual Stream model is the role of the articulatory network for auditory short-term memory and speech perception. The model assumes that the interconnections between the sensorimotor interface and the articulatory network support the sub-vocalic articulatory processes of the phonological loop. So, this area has shown to be active during tasks of covert rehearsal in which participants were required to repeat the sound sequence they had just heard (Pa & Hickok, 2008). Opposite evidence has been provided by studies showing the activation of this area in different conditions as, for example, when visual stimuli with no auditory associations are presented (e.g., Meyer et al., 2007), or during the syntactic processing of auditory and written sentences (e.g., Raettig, Frisch, Friederici, & Kotz, 2010). Different explanations regarding the activation of the same area for different processing have been suggested (see Price, 2012). For example, the activation of the area Spt not only during covert articulation might suggest the existence of different and distinct cell populations for perception and covert production within the same area (Hickok et al., 2009).

Finally, the articulatory network seems to be also involved in the "perceptual analysis" of the heard sound. Evidence consistent with such assumption comes from Transcranial Magnetic Stimulation (TMS) studies which showed that under the stimulation of either the lip motor area or the tongue motor area, participants were facilitated in the perception of syllables that are either performed with the lips (/ba/) or with the tongue (/ta/), respectively (D'Ausilio et al., 2009).

1.1.2. Language production and the Levelt Model

Just as in speech perception, speech production is a natural and effortless ability to produce spoken words, similarly consisting of several hierarchical processes. One of the most relevant models of language production is the Lemma Model, proposed by Willem J. M. Levelt (2001), which was developed from research studying speech errors (MacKay, 1970; Fromkin, 1971; 1973) and measures of production latencies. In particular, the model is based on results derived form the picture-naming task, where a word is generated on the basis of a picture. According to Levelt, Roelofs and Meyer (1999), this process includes two distinct stages: the "lexical selection" stage and the "form encoding" stage. When a picture is presented, first it is processed at the visual level and recognized as a known object. Once the corresponding semantic representation is accessed, activation is spread to the corresponding lexical node, the lemma. According to the model, at the semantic level, lexical concepts are organized according to semantic principles so that when the picture stimulus activates a lexical concept, also semantically associated concepts become active. At the lemma level, therefore, several units become active and compete for selection. At the lemma level, the morphosyntactic features of a given unit, such as its grammatical category, the grammatical gender of nouns, the transitivity/intransitivity of verbs are specified but the phonological form of the word is not yet available. This is retrieved during the Form Encoding stage. In the model, this latter process consists of three phases: (1) retrieving morphemic phonological codes, (2) prosodification/syllabification and (3) phonetic encoding. Despite the complexity of its functional architecture, the Lemma model has inspired a large number of studies aimed at providing consistent evidence at the neurobiological level. Among the most ambitious of these studies, is the seminal work by Indefrey and Levelt (2004). The study is based on a meta-analysis performed on 82 neuroimaging studies in which different word production tasks were used. The underlying logic was to compare the areas activated in common by different tasks and those activated uniquely by one task. The tasks used were word fluency, picture naming, word reading and pseudoword reading that share only some of the processes involved in speech production. By comparing which areas are active during fluency tasks and picture naming tasks with areas active during reading tasks, Indrefrey and Levelt identified the mid section of the left MTG as the region correlated to semantically driven lexical selection processes. Consistent with this conclusion, other studies have similarly shown the involvement of this area in lexical selection (Damasio, Grabowski, Tranel, Hichwa, & Damasio, 1996; Damasio, Tranel, Grabowski, Adolphs, & Damasio, 2004; Tranel, 2006; 2009). For example, Damasio et al., (1996) analyzed the lesion site of a large pool of patients showing category-specific deficits in object naming and confirmed that proper name retrieval deficits are associated with lesions in the left temporal pole; animals names retrieval deficits are associated with lesions in the anterior part of the left inferotemporal pole, and finally, deficits in the ability to name tools are associated with lesions in the posterior part of the left inferotemporal region, extending into the lateral occipital cortex. It is worth noting that nouns and action verbs retrieval seem to rest on independent processing circuits, to the point that the two processes can be independently impaired (Shapiro &

Caramazza, 2009). In particular, the retrieval of action verbs seems associated to activation in the left inferior frontal gyrus (IFG), the left inferior parietal lobe and the mid-posterior section of the MTG (Vigliocco, Vinson, Druks, Barber, & Cappa, 2011).

In order to identify the areas involved in the form encoding stage, Indefrey and Levelt (2004) compared the areas that resulted in activation during tasks requiring the retrieval of a known phonological code (i.e., word fluency, picture naming, and word reading) with the active areas during pseudoword reading, a task in which a "new" phonemic sequence must be computed through grapheme-phoneme conversion mappings. Activations have been found in Wernicke's area (specifically the left posterior STG/STS), the left posterior MTG, the left anterior part of the insula and finally the right supplementary motor area (SMA; Indefrey & Levelt, 2004). These same areas have also been identified as relevant in the perception of language (see Paragraph 1.1.1.), specifically in the "phonological network", one of the components of the ventral stream (Hickok & Poppel, 2000; 2004; 2007). Further research is needed to better understand the interactions between input and output processes and to establish whether the linguistic function is supported by a unique phonological lexicon or by separate but adjacent input and output ones. The involvement of left posterior STG and MTG in the retrieval of the phonological codes has been also confirmed by data on word production disorders showing that lesions of these areas bring about Wernicke's aphasia, which is mainly characterized by paraphasias and neologisms (e.g., Corina et al., 2010). Syllabification has been investigated by considering tasks requiring both covert and overt speech, assuming that in all these tasks syllabification processes should occur. The region that was commonly activated by these tasks was Broca's area and, more precisely, the left posterior IFG (Indefrey

& Levelt, 2004; but see also Papoutsi et al., 2009; Bohland & Guenther, 2006). The last stage of the Lemma model involves phonetic encoding and articulation, where the pre-existing units composing the syllabary are activated. After the application of the rules to combine them via the “articulatory score”, the selected syllabic concatenation can be finally projected into the vocal apparatus, in order to be articulated. The anatomical location related to all aspects of planning and performing speech gestures is still a matter of debate even if it has been suggested the involvement of both right and left cerebellum, the ventral primary motor cortices and primary somatosensory cortices, the right dorsal primary motor cortex, the right SMA, right midbrain and the thalamus bilaterally (Indefrey & Levelt, 2004). However, these results still require further in-depth study.

Garnham, Shillock, Brown, Mill and Cutler (1981) have shown that speakers usually make very few errors, about one error out of 1.000 words. It has been proposed that a self-monitoring system continuously checks the output of the language system during speech production in order to identify and correct "online" possible errors. The Lemma Model postulates two different self-monitoring feedback loops: the external loop and the internal loop. The external feedback loop monitors the acoustic signal during the utterance of the sentences. Its role can be shown in the following example “My car is the orange… the red one”, where the whole word (orange) is produced and the speaker corrects the error after hearing it. As for the internal feedback loop, usually, error detection occurs after the syllabification stage and before the articulation processes are fully accomplished. In this case, the speaker repairs the error monitoring covert processes of phonology computation. The role of the internal feedback can be exemplified in the following example: “I should check my or… my black bag”, where just the first syllable of the word “<u>or</u>ange” is produced before the speaker corrects the sentence with the appropriate word. Thus, the external feedback loop is based on monitoring the speaker's voice, whereas the internal feedback loop is based on monitoring the syllabification output. Indefrey and Levelt (2004) investigated external monitoring processes by comparing areas activated during tasks that required overt word production with areas activated during auditory word perception. They identified the posterior superior temporal regions for two-thirds, bilaterally, as a possible candidate area for the external feedback loop. The neural correlate of the internal feedback has been harder to investigate since such a mechanism operates at the subvocal level. Candidate areas engaged in this type of feedback can be derived from studies in which healthy participants were asked to create images of their voice (McGuire et al., 1996), or from studies on brain activation during "vocal hallucinations" in schizophrenic patients (Shergill, Brammer, Williams, Murray, & McGuire, 2000). The results of these studies seem to support the idea that the internal loop, when monitoring covert processes, may also include areas (or at least a part of the areas) engaged by the external loop (Indefrey & Levelt, 2004).

The Lemma Model has been largely investigated and it has been presented in this thesis since it represents one of the most complete and articulated accounts of speech production. There are, however, some challenging issues that have been raised in the literature, contesting some tenets of the model. First, the idea of lemmas as amodal units linking semantic and phonological representations has not been confirmed by neuropsychology studies. For example, A. Caramazza (1997; see also Caramazza & Miozzo, 1998) argued against the assumption of the existence of amodal units subserving the activation of phonological and orthographic representations. Research on brain-damaged patients performing a word production task has shown that there are patients making errors in the spoken output that were not extended to the written output and there are patients who exhibit the opposite pattern. For example, the patient named RGB, after having seen a picture of a clam said the word “octopus” but wrote the correct word “clam” (Caramazza & Hillis, 1990). A patient showing the opposite deficit has been described in a work by Hillis and colleagues (Hillis, Rapp, & Caramazza, 1999). This type of double-dissociation is contrary to the idea that lexical nodes are amodal. As a consequence, Caramazza (1997) abandoned the idea of lemmas and hypothesized direct connections between semantic, syntactic, orthographic and phonological representations. Another critical aspect of the model concerns the serial processing organization, which proceeds uniquely from the higher to the lower levels. Moreover, the model postulates that at the lemma level only one lemma must be selected, which in turn activates the corresponding phonological representation. The competitive lemmas will be active only during the selection process and activation is not spread to the corresponding phonological codes. This serial and modular organization is not consistent with studies that analyzed the pattern of speech errors made by brain-damaged patients and healthy subjects (e.g., Nooteboom, 2003; Roelofs, 2004a; 2004b). Many of these errors are mixed, in the sense that the incorrect uttered word is associated both at the semantic and the phonological level to the correct target word. These types of errors are frequent during both spontaneous and induced speech tasks (Rapp & Goldrick, 2006). This type of evidence does not support modular models and is in line with interactive activation models in which activation flows forward and backward among levels (e.g., Stemberger’s “interactive activation model of language production” or Dell’s “spreading activation theory of retrieval in sentence production”; Stemberger, 1985; Dell, 1986).

1.1.3. The meaning of words

Another important question is related to how and in which regions our brain represents and classifies concepts related to objects. During the 70's and the 90's, the prominent theory was the Amodal Symbolic Model which assumes that concepts are compositions of abstract amodal features that are processed and represented separately from the modality specific systems related to perception and action (Fodor, 1975; Smith, 1978). According to this model, a meaning of a concept is accessed through the activation of its semantic features (e.g., the object word "rose" is accessed through the activation of its elementary features "flower", "red", "thorns", "petals", etc.). The retrieval of past memories about the concept is not needed and not critical for meaning access. More recently, a theory called Grounded Cognition Model (also known as Embodied Cognition model) hypothesized that word comprehension is based on the activation of modality-specific representations of sensory, perceptual and motor features. The basic idea is that every brain region conserves its assignment and the meaning of a specific object is not stored in a specific "abstract" unit in the brain, but it is composed by fragmented activation of the cortical regions that process its perceptual/sensory/motor features (Barsalou, 1999, 2008).

Language representations, abstract or concrete?. Classical theories of cognition postulate that knowledge is coded within the semantic memory system in an abstract format and do not contain modality specific information. One of the main principles of the standard theories is that modal representations are converted in amodal symbols stored in the semantic system, which can represent knowledge about life and experiences. The Embodied Cognition model, which focused on the interaction between the mind and the body, became in recent years a new theoretical perspective within cognitive science. The traditional idea of mental representations as abstract, symbolic and amodal, is redefined by a new concept, which puts sensorimotor and perceptual experiences at the center of cognitive processes (e.g., Gibbs, 2006; Wilson, 2002). According to this view, word meaning is based on the "simulation" of the processes involved in perceptual and sensorimotor experiences, so that semantic features are not abstract properties of concepts stored in a autonomous module but are located in the very same areas related to the sensory and motor processing of those features. The embodied theory postulates that we understand the expressions of natural language through the activation of those brain areas dedicated to perception, action and emotion. For example think about the word "cat". In order to access to the corresponding meaning, areas of the brain dedicated to the perception of the cat, such as its "meow" or action, such as to pet it, need to be activated. In short, it seems that to understand the word "cat" or to think about cats we need to simulate the concrete experience of a cat. Even if the embodied approach has received much attention in literature, especially in the last 25 years (for behavioral findings see, e.g., Zwaan, Stanfield, & Yaxley, 2002; for findings on semantic deficits see, e.g., Beauvois, 1982; Varela, Thompson & Rosch, 1991; for findings on neuroimaging, e.g., Rueschemeyer, Brass, & Friederici, 2007), the assumptions of this approach are still a matter of debate, as it is shown by several recent papers (Wilson & Golonka, 2013; Goldinger, Papesh, Barnhart, Hansen, & Hout, 2016; Killeen, 2016).

Some of the features of the classical and the embodied theories of cognition have been incorporated in theoretical proposals such as the "Hub and Spoke Model" (Lambon Ralph, Sage, Jones, & Mayberry, 2010a).

Semantic processing and modality-specific systems. Several lines of investigations focused on specific semantic object features with the aim of revealing that the brain areas involved in the processing of semantic features are the same areas involved in the perception of such features. One of these features is color, which for some categories such as animals, vegetables and fruits, is a relevant aspect of the object's conceptual knowledge. Color perception seems to be mediated by two main areas: area V4, located in the lingual gyrus of the occipital lobe and area V4-alpha, located in the fusiform gyrus of the ventral temporal cortex. The former is involved in passive color perception, that is, when the perceiver simply looks at colored objects. The latter is involved in the active perception of colors that is when the perceiver actively discriminates colors (Zeki & Bartels, 1999). It has been shown that these areas are active also during the processing of words corresponding to "colored" objects, such as "carrot" or "zebra" (Simmons et al., 2007), supporting the idea that access to word meaning implies the activation of sensory information.

Visual aspects related to object shape seem to be processed by the ventral occipitotemporal cortex. It has been shown that this part of the cortex is organized to process the shape of specific categories of objects. For example, Chao Haxby and Martin (1999) during a silent picture-naming task, reported activation of different cortical areas for the perception of animals with respect to tools. The perception objects belonging to both these categories seem to activate the mid fusiform gyrus, but animals activate its lateral portion and tools activate its medial portion. Critically, the same activation was found not only when pictures were presented, but also during the presentation of words (Chao et al., 1999), suggesting that word processing recruits areas that are involved in perceptual processing.

Another relevant object feature is motion. It refers to the typical movement we associate to a specific entity and which constitutes part of the conceptual knowledge about the object (e.g., the meaning of "horse" is represented by the classical riding movement as well). It has been shown that the perception of moving stimuli activates the anterior occipital and lateral occipital sulci, and more precisely, an area called MT+ (Malikovic et al., 2007). This area by itself seems not to distinguish the motion of different objects but it is connected with a sector of the posterior STS, which seems to be selectively activated by biological motion patterns (Saygin, 2012) and with a sector of the posterior MTG, which is selectively activated by non-biological motion patterns (Beauchamp & Martin, 2007). Interestingly, it has been shown that the pSTS and the pMTG are selectively engaged in the processing of animal nouns with typical biological motions and of object nouns with typical nonbiological motion, respectively (Chao et al., 1999).

Some objects' concepts are also characterized by the information about the correct way to interact with them. This is the case of tools. So, the concept of a screwdriver also contains information about the movement associated with its use. It has been shown that tool use recruits the anterior intraparietal sulcus, the inferior supramarginal gyrus and the ventral premotor cortex. In right-handed people, these regions are more active in the left hemisphere during the effective use of the tool or when a pantomime of the gesture is performed. Different studies have shown that these areas are also more active when processing the meanings of tools than when processing the meaning of animals (Chouinard & Goodale, 2010) and, moreover, words corresponding to manipulable objects, activate these areas to a larger extent than words corresponding to non-manipulable objects (Saccuman et al., 2006).

Auditory features refer to the typical sound associated with an object. Several fMRI and electrophysiological studies confirm the idea that this feature is processed by the left hemisphere and precisely in the pMTG, pSTS and the pSTG (e.g., Kiefer, Sim, Herrnberger, & Hoenig, 2008). Kiefer and colleagues (2008) used a lexical decision task with words that differed for the relevance of auditory features, such as "telephone" versus "armchair". The results showed that words with semantic-auditory features activated the left pMTG, pSTS and the pSTG to a larger extent with respect to words without auditory features (see also Goldberg, Perfetti, & Schneider, 2006a; Lewis et al., 2004). Again, it seems that word processing automatically recruits areas related to the perception of the corresponding objects.

A similar conclusion can be drawn for gustatory and olfactory semantic features. Some objects are characterized by a particular smell or taste, like fruits or food in general. It has been shown that in a semantic similarity judgment task, the fruit category activates the bilateral orbitofrontal cortex, a region that has been associated with the perception of smell and taste (Goldberg et al., 2006a; Goldberg, Perfetti, & Schneider, 2006b).

In conclusion, these studies show that semantic processing is anchored to modality-specific brain networks and suggest that meaning comprehension involves the activation of high-level perceptual, spatial and motor representations of objects. To what extent the activation of modality-specific representation is necessary and sufficient to meaning representation, and to what extent the modality-specific representation activated in concept comprehension overlap with the representations used for perception and action is still a debated issue that needs further investigation.

The semantic hub for concept processing. A growing body of evidence shows that, in addition to the modality-specific systems mentioned above, concept processing involves an additional area in both hemispheres, the ATL. This region receives input and sends output through complex sets of connections. In particular, it has bidirectional connections with the systems involved in the activation of word phonology and orthography and the high-level modality-specific systems that subserve perceptual and motor functions distributed in the brain. Given these properties, ATL areas of both hemispheres (the “semantic Hub”; Lambon Ralph & Patterson, 2008) have been suggested as integrative regions containing modality-invariant aspects of semantic concepts. According to Patterson and Lambon Ralph, the semantic Hub seems to mediate the access to semantic representations that are independent from modality and are similar for all semantic categories (Patterson, Nestor, & Rogers, 2007; Lambon Ralph & Patterson, 2008). More recently, Lambon Ralph in 2014, proposed a new approach, called the “Hub and Spoke model”. This approach seems to put together some of the assumptions of the Amodal Symbolic model and the Grounded Cognition model. Indeed, from the one hand, the modality invariant representations of the ATLs might be seen as the “concepts” of the Lemma Model. On the other hand, similarly to what proposed by the Grounded Cognition model, semantic knowledge is derived from the activation of high-level modality specific systems since the Hub has the primary role of binding together the information derived from different modalities, extracting subtle distinctive concept features and then capturing statistical variations among features, without representing conceptual content itself.

There is in fact evidence consistent with a “semantic center” located bilaterally in the ATLs regions, which comes from both studies of patients with semantic dementia and from neuroimaging studies. Semantic dementia is a neurodegenerative condition in which the patient starts to lose gradually the ability to name objects, and of verbally recalling conceptual knowledge in general. Bright, Moss, Stamatakis and Tyler (2008) reported the performance of EK, a 60-year-old woman affected by semantic dementia on four different semantic tasks: object naming, word-picture matching, semantic fluency and property verification task. The patient was tested, longitudinally, in the three successive years. As expected from the progressive cortical damage, Bright and colleagues observed the performance of EK dramatically decline over the three years. However, when the damage was restricted to the ATLs during the initial testing sessions, EK performance was already quite impaired showing a large amount of semantic errors in all four tasks. This study is consistent with the idea that ATLs plays a critical role in object concepts processing (see also, among others, Lambon Ralph et al., 2010a; Mayberry, Sage, & Lambon Ralph, 2011).

Traditionally, fMRI has proved not to be efficient in detecting activation of the ATL area, because the BOLD signal is not sensitive enough near to the air-filler sinuses, adjacent to ATL localization. Recent improvements of the technique, however, allowed correcting the fMRI signal and pinpoint activation of ATL regions during the execution of semantic tasks (see Visser, Embleton, Jefferies, Parker, & Lambon Ralph, 2010). The fMRI results of Visser and colleagues are in line with the neuropsychological studies: the ATLs areas resulted more active when participants were asked to evaluate the semantic properties of a series of words, with respect to when the task required evaluating the identity and the case of letter sequences. The activation, even if bilateral, was leftward asymmetric and involved the anterior fusiform gyrus as well. To see the effective contribution of the right hemisphere, Lambon Ralph, Pobric and Jefferies (2009), performed a TMS study and asked participants to perform a synonym judgment task and a number judgment task. They found that the TMS stimulation interfered with the lexical task but not with the number task. The interference effect was the same, independently of whether the target TMS region stimulated was in the left or in the right hemisphere. This evidence is in line with the Hub and Spoke model that assumes that ATL areas of both hemispheres contribute to the implementation of the semantic hub. Even if this new proposed model may be considered in some way to be "less authoritarian" with respect to the modality of the representation, it still received some critics. The major criticism refers to the unitary nature of the ATL as an amodal convergence area in both hemispheres. Instead, it has been proposed that the ATL areas might have specific roles, according to hemisphere. From the one side, some authors propose that the left ATL supports a general conceptual knowledge system, whereas the right ATL subsumes a domain-specific social cognition system (Simmons & Martin, 2009; Simmons, Reddish, Bellgowan, & Martin, 2010). This hypothesis is based on studies showing that damage in the left ATL is associated to semantic deficits whereas damage in the left ATL is associated with disturbances at the social-behavioral level with no associated semantic deficits (e.g., Edwards-Lee et al., 1997; Perry et al., 2001; Thompson, Patterson, & Hodges, 2003; Chan et al., 2009). Other authors have proposed that while the left ATL stores language-mediated semantic representations, the right ATL stores embodied sensory-motor representations (e.g., Gainotti, 2011; 2012). This latter view is supported by studies reporting that semantic dementia patients with a major atrophy of the left ATL showed a prevalence of lexical-semantic deficits, whereas patients with a major atrophy of the right ATL showed a prevalence of deficits at the non verbal sensory-motor level (for a review see Gainotti, 2015). This evidence suggests that the right and the left ATL might store representation of different formats (verbal versus non-verbal). In conclusion, what is clear from the literature review is that further research is needed in order to fully understand the role of ATL in language.

Category-specific impairment. Objects can be organized in categories and there are several neuropsychological studies describing patients with selective semantic impairments, or a deficit just in the retrieval of a specific category (the first study in this line was by Warrington & McCarthy, 1983). The three major categories have been more frequently described in this type of studies, animals, fruits and vegetables, and tools. The patients with specific deficits for the animal category (or for animate living things more generally) show bilateral lesions of the anterior ventral temporal cortex and medial temporal regions (Blundo, Ricci, & Miller, 2006; Sartori & Job, 1988). The brain injury in these cases is mostly caused by herpes simplex encephalitis or by a stroke.

There are also patients showing a specific deficit for inanimate living things, such as fruit and vegetables. With respect to the previous patients, lesions in this case are more often unilateral, involving only the left hemisphere and are localized more posteriorly including the left mid-fusiform gyrus (e.g., Samson & Pillon, 2003).

Tool concepts can be also be selectively impaired as shown by a number of neuropsychological studies (e.g., Warrington & McCarthy, 1987; Gainotti, 2006; Mahon et al., 2007). Patients showing this type of deficit often have lesions on the posterior lateral pMTG, on the inferior parietal region and inferior frontal region of the left hemisphere (e.g., Gainotti, 2006). Two main hypotheses have tried to explain the category-specific deficit data obtained by research (the Distributed Domain-Specific Hypotheses by Caramazza & Mahon, 2003, 2006; and the Differential Weighting Hypothesis by Warrington & Shallice, 1984), but it seems that the approaches available do not exhaustively explain how impairment of a certain domain of object concepts occurs.

CHAPTER 2

Introduction to Diffusion Tensor Imaging, DTI Tractography and its contribution in linguistic studies

In conjunction with the different structural MRI methods previously developed to investigate how experience shapes the brain, Diffusion Tensor Imaging (DTI) is currently offering new opportunities for the study of white matter connections of the human brain *in vivo* (Jones, 2008).

Basic principles. First discovered in 1999 DTI highlights white matter fibers connecting different brain areas in a non-invasive fashion. The white matter feature data is derived from an indirect measure of the water diffusivity inside tissues and permits the description of the microscopic structure of the brain matter, depicting its integrity and organization. Diffusivity is a specific event, which characterizes living cells, and can be describes as the random motion of particles resulting from thermal energy. The motion of water in tissues is defined by an index titled "Apparent" Diffusion Coefficient" (ADC). This is an essential measure in DTI, and in conjunction with temporal resolution, defines the displacement proportion of water molecules diffusion (Basser, Matiello, & Le Bihan, 1994). The diffusion tensor can be represented as the 3D probability of the displacement of water molecules, defined by an ellipsoid and the square root of its three eigenvalues. Normally in tissues like white matter, the diffusion of the water is highly restricted in the direction perpendicular to the fibers and unconstrained in the direction parallel to the fibers orientation. For this reason, white matter is generally considered anisotropic, whereas gray matter and cerebrospinal fluid are considered more isotropic (Alexander, Lee, Lazar, & Field, 2007). The tract orientation is given by the diffusion of the major eigenvector (which is the vector with the greatest diffusivity), which allows for the estimation trajectories of the white matter bundles using the tractography algorithm, a tool allowing the mathematical reconstruction of the main white matter pathways in 3D (Basser, Pajevic, Pierpaoli, Duda, & Aldroubi, 2000; Mori, Crain, Chacko, & van Zijl, 1999; Jones, Simmons, Williams, & Horsfield, 1999; Conturo et al., 1999). *Tractography algorithm* has become the most important tool for studying the anatomy and the connections of both the normal and the pathological brain (Catani, Howard, Pajevic, & Jones, 2002; Catani et al., 2011; Ciccarelli et al., 2005). It helps describe more precisely the microstructural changes in diffusion and, to resolve cases of individual crossing fibers within the same voxel, initially one of the primary limitations of the methodology (Dell'Acqua & Catani, 2012). Given the nature of the present dissertation thesis, the image acquisition method (e.g., the pulsed-gradient approach) will not be described, but we will proceed directly with the description of the measures that can describe the property of the brain's white matter. For a detailed account of the image acquisition method, please refer to the paper written by Alexander and colleagues (2007) and specifically in the section "Diffusion-Weighted Image acquisition".

Relevant DTI measures. Several scalar measures can be extracted to define the fibers diffusion characteristics. The most shared are the mean diffusivity (MD; sometimes called ADC), which describes the average motion of water molecules contained in a tissue (i.e., molecular diffusion rate) and the fractional anisotropy (FA), which reflects the preferential directionality of the diffusion of the water in the tissue. FA, the most widely used invariant measure of anisotropy, varies between 0 and 1, where 0 suggests isotropic diffusion (there is not a preferred direction of molecules) and 1 indicates infinite isotropic diffusion (Basser & Pierpaoli, 1996). Axial and Radial diffusivity are also suggested to be useful, particularly in relation to pathology. Radial diffusivity for example, which is the average of the two eigenvalues amplitude, is more associated to white matter myelination; whereas axial diffusivity is associated to axonal degeneration (Song, Sun, Ramsbottom, & Chang, 2002). Other relevant measures are the mean number of tracts, the mean volume of the tract.

Deterministic versus probabilistic tractography. Tractography algorithms can be divided into two different main groups, deterministic and probabilistic tractography. Deterministic approaches produce only one reconstructed trajectory per "seed point", assuming that the fiber orientation represents the best estimate to propagate streamlines. There is just one estimate of fiber orientation, which is the principal eigenvector. The output of this estimation is always reported as a binary form, which reflects if a point is connected with another point or not: 0 = there is no pathway; 1 = presence of a pathway (Jones, 2010).

Probabilistic approaches generate numerous solutions in order to propagate multiple streamline samples within every seed-voxel and to reflect the uncertainty of the fiber orientation estimated (Jones, 2010; Jbabdi & Johansen-Berg, 2011). At each point of the space, a distribution of the fibers orientation's estimate is given, and this same procedure is operated from one point to the next one in order to choose the following propagation direction. This process generates multiple pathways from a given point space and the result is a set of multiple pathways, also called streamlines, passing through a given seed-point. This pathway contains how many times (in percentage) each voxel in the volume of interest, is intersected by streamlines. This uncertainty may be caused by the noise produced by the resonance, the partial volume effects and the mistakes in deciding which diffusion model is more appropriate (Dell'Acqua & Catani, 2012). After the uncertainty has been derived, patterns of potential pathways are generated by the streamlining algorithm in order to get a specific index, which can vary between 0 and 1. An index of 0 means that none of the selected streamlines reached the other voxel; an index of 1 means that all the streamlines selected, have been able to reach the second voxel (Jones, 2010). This last approach, despite being very useful and informative (i.e., precision of the tracking and very closely correspondence to neuroanatomy), lacks in terms of its accuracy (e.g., kissing and crossing fibers).

Advantages and limitations. As already mentioned at the beginning of the chapter, DTI permits non-invasive measurement of the organization of white matter connections in the normal and pathological living human brain. Therefore, it offers the possibility to confirm *postmortem* neuroanatomical results (Lawes et al., 2008), but also to localize tracts damages and to effectively intervene pre- and post- surgery. Yet these are not the only benefits of its use. In fact, compared to the amount of data that can be obtained thanks to this technique, DTI is also quite time efficient in its acquisitions. Moreover, it can be used to study large population samples, to evaluate their anatomical differences and to correlate white matter data with behavioral and other functional measures (Dell'Acqua & Catani, 2012). Another contribution of DTI is related to the study of the brain asymmetry, which is an essential index especially when talking about the lateralization of the linguistic function (e.g., verbal memory performances; Catani et al., 2007), and also in consideration of handedness (Catani et al., 2012) and vision (Thiebaut de Schotten et al., 2011). Despite these powerful characteristics, some limitations are present. One of the major limitations is the fact that one of the two ways to extract the tract is the "operator dependent" technique.

This means that there must be a unique operator for definition and extraction of the tracts. The reason of this complex operation can be summarized by the fact that, especially among subjects belonging to the same research or in cases where a post-operative follow-up is planned, there is a need of consistency in the technique use and in the neuroanatomical references behind it. Automated techniques may be also applied, which are more time efficient but, in turn, have other disadvantages. Another limitation is the low specificity of the measures. In fact techniques and its measures are still matter of active research in order to reach a greater degree of specificity. Also important to consider, are the more "technical" limitations, such as the small perturbations in the image data, including acquisition noise, image distortions, head motion, physiological noise, scanner stability, partial-volume averaging (Alexander, 2011) and presence of subject's pathological processes, such as brain oedema, bleeding, and compression that could all affect tractography results. Last but not least, tractography algorithms may generate the so-called "false-positive" reconstructions when two adjacent tensors belonging to different pathways are joined together by the tractography algorithm. "False-negative" artifacts, on the other hand, occur when the tractography algorithm is unable to reconstruct pathways that truly exist. This usually happens in regions with crossing fibers, where the tensor assumes a planar or spherical shape and does not provide a clear indication of the directionality of the underlying fibers. Other algorithms can also be developed in order to solve some of the fibers orientation problems.

Spherical Deconvolution Approach. To resolve multiple fiber orientations of DTI Tractography and to calculate the proper fiber orientation distribution, Tournier, Calamante, Gadian, & Connelly (2004) proposed the Spherical Deconvolution approach. Spherical Deconvolution is a nontensor model that enables a more accurate estimation of multiple fiber directions in crossing fiber regions. Basically, it estimates a continuous 3D distribution of the possible fiber orientations within each voxel. An advantage of Spherical Deconvolution is that the acquisition time is close to that of DTI. Spherical Deconvolution gives information on the orientation of different fiber bundles within the same region. It can improve tractography reconstructions in regions containing complex white matter organization. An example of the advantage of Spherical Deconvolution tractography is the ability to identify trajectories in regions with crossing fibers such as the corpus callosum, the association pathways and the corticospinal tracts, where diffusion tensor tractography often produces false negatives or false positives. Specific of Spherical Deconvolution, is a newly proposed index of anisotropy, along individual groups of fibers within a single voxel, referred as Hindrance Modulated Orientation Anisotropy (HMOA). Changes in the HMOA have greater sensitivity, in respect to conventional FA values, in the detection of degeneration occurring only in one population of fibers, while the other crossing fibers remain intact. This new index allows for a more realistic measure of the microstructural properties of the fibers (Dell'Acqua, Simmons, Williams, & Catani, 2013). Given these advantages, Spherical Deconvolution approach was adopted for the present study.

The over mentioned techniques have allowed researchers to isolate the language white matter tracts, organized in a dorsal and in a ventral stream.

Dorsal white matter pathways. With the use of DTI tractography, it has become clear that the anatomy of the dorsal stream is more complex than previously described (Catani et al., 2005; Catani et al., 2007; Martino et al., 2013).

Three different main bundles have been primarily identified as part of the dorsal linguistic network. In addition to the AF, described as the direct pathway connecting Wernicke's region with Broca's region, two parallel pathways have been recently distinguished, composing the indirect pathway of the AF. It is worth noting that the discovery of these new segments has been confirmed by *postmortem* dissection studies, by functional studies, studies on animals such as monkey and intraoperative electrocorticography studies (Lawes, et al., 2008; Schmithorst & Holland, 2007; Deacon, 1992; Matsumoto, et al., 2004) and by other DTI studies (Eluvathingal, Hasan, Kramer, Fletcher, & Ewing-Cobbs, 2007; Lawes, et al., 2008; Maldonado, Mandonnet, & Duffau, 2012)

The indirect pathway is composed of an Anterior Segment (AS), linking Broca's region to Geschwind's region and a PS between Geschwind's and Wernicke's regions (Catani et al., 2005). Schulze, Vargha-Khadem and Mishkin (2012) suggested that the absence of these connections in non-human primates might explain our unique ability in learning new words. An historical note might help to better describe the dorsal stream. Reil and Autenrieth (1809) have first described the "superior longitudinal fasciculus" (SLF) as a bunch of bundles passing through temporal, frontal and parietal areas. Few time later, Burdach and Dejerine (Burdach, 1922; Dejerine, 1895), described this tract as the Fasciculus Arcuatus. Indeed, for a long time the SLF and the Fasciculus Arcuatus have been considered synonymous. This entanglement has occurred due to the proximity of the AF with the SLF-III, the sub-component described by Thiebaut de Schotten as the perisylvian component of the SLF, which connects the supramarginal gyrus with the ventral premotor and prefrontal regions (Thiebaut de Schotten et al., 2011). Other studies have considered the AF as the fourth subcomponent of the SLF (e.g., Makris et al., 2005), consistent with some nonhuman primate studies (Petrides & Pandya, 1984; 1988). Moreover, limitations in the DTI technique make very difficult to distinguish the AF from the SLF pathways in humans and in some studies the two terms are used as interchangeable (Martino, et al., 2013; Catani et al. 2005; for further discussion on the distinction between these pathways, see Dick & Tremblay, 2012 and Makris et al., 2005). Since the present thesis is focused on the extraction of the ventral stream, the dorsal stream will not be described with more-in-depth neuroanatomical detail.

Ventral white matter pathways. Three tracts mainly compose the ventral pathway of language: The inferior longitudinal fasciculus (ILF), the Uncinate Fasciculus (UF) and the Inferior Fronto Occipital Fasciculus (IFOF). All these three tracts are considered as association pathways because they connect regions within the same hemisphere and they have a direction going from anterior to posterior or vice versa. The anatomical description of the tracts is reviewed below.

The ILF (see Figure 1, green bundle) was firstly described by K. Burdach in 1822 and, since that time, its real existence caused debates within the scientific community (ILF viewed as a ventral portion of the geniculostriate pathway; e.g., Putnam, 1926; Polyak, 1957). Conversely, some studies considered this tract as the major occipitotemporal associative tract (e.g., Dejerine, 1895; Gloor, 1997). Thanks to the new techniques as the one described above, the debate about its presence in humans (even if evidence of a connection between occipital and temporal areas in humans has been already confirmed by Wilson, Babb, Halgren, & Crandall, in 1983) has been confirmed with very impressive results. It has been shown that this tract is formed by both long and short fibers: the short ones connect the occipital lobe with the temporal lobe; the long ones connect the visual area to the amygdala and hippocampus (Catani, Jones, Donato, & ffytche, 2003). In detail, its cortical projections originate from the extrastriate cortical regions on the dorsolateral surface of the occipital lobe, then go ventromedially from the posterior lingual gyrus and fusiform gyrus and dorsomedially from the cuneus. It is easily visible a bifurcation of the dorsal stream into medial and lateral branches, who start to go parallel to the fibers of the splenium and optic radiation. Then they join together in a single bundle at the level of the posterior horn of the lateral ventricle. The ILF terminates in the anterior temporal lobe, with some of the branches passing to the superior, middle and inferior temporal gyri of the lateral surface of the temporal lobe; some other fibers pass medially to the uncus-parahippocampal gyrus, close to the amygdala and hippocampus (Catani et al., 2003; Catani & Thiebaut de Schotten, 2008).

The second associative bundle corresponds to the UF (see Figure 1, yellow bundle). This tract connects the anterior temporal lobe with the medial and lateral orbitofrontal cortex (Catani et al., 2002) with a “hook-shaped” fascicle. There are still discussions about the exact origin and termination of its fibers, but a recent study shows the UF as composed by 5 different subcomponents, with more widespread cortical terminations compared to previous studies (Hau et al., 2016).

The last tract, the IFOF (see Figure 1, red bundle) connects the ventral occipital lobe (running parallel to the ILF), to the orbitofrontal cortex. When approaching the anterior temporal lobe, the fibers gather together in the external capsule, just dorsally to the UF. This tract is considered part of the mirror neuron system and is also probably the only direct connection between occipital and frontal cortex in the human brain (Catani, 2007).

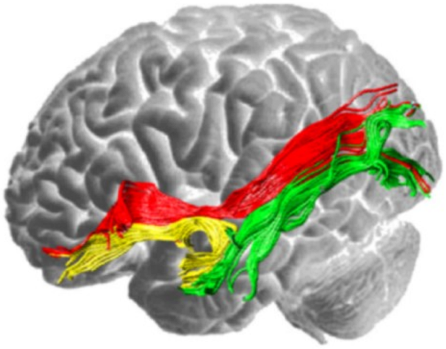

Figure 1. Three main bundles compose the ventral linguistic network. In red the IFOF, in green the ILF and in yellow the UF (from Catani & Mesulam, 2008).

Beyond the principal cited tracts, there some other tracts which has been hypothesized to be involved in language: the *Frontal Aslant Tract* and the *Extreme Capsule Tract*. The Frontal Aslant Tract connects Broca's area with the medial frontal area, the pre-SMA and the cingulate cortex. Since this tract seems to be left lateralized in most right-handed subjects, it has been hypothesized to have a role in language (Catani et al., 2005; 2012). Both studies on healthy and brain-damaged participants support this hypothesis. For example, Penfield and Rasmussen (1950) found that, when the pre-SMA and the anterior cingulate cortex are stimulated, healthy participants produce vocalization movements and have the arrest of speech states. Ackermann and Riecker (2010) have found that lesions of these areas led to speech impairment, both severe and mid-altered. Moreover, patients with deep lesions in the frontal periventricular white matter usually showed impaired fluency (Naeser, Palumbo, Helm-Estabrooks, Stiassny-Eder, & Albert, 1989), confirming the fact that the medial areas of the frontal lobe may contribute in the initialization of speech through direct connection to the pars opercularis and triangularis (inferior frontal gyrus). The Extreme Capsule Tract, which is considered a ventral pathway, seems not to be as specific as the other tracts passing through the extreme capsule (e.g., UF and IFOF). For this reason, and for its recent description in the human brain, further investigations are needed in order to see if direct links between Wernicke's and Broca's area passing from the external capsule do exist (Saur et al., 2008).

DTI tractography technique offers a straightforward method for the study of language as it allows for the investigation to what extent language processing is distributed within the brain. Moreover, several studies have recently tried to associate the bundles of axon fibers with specific linguistic functions. In the next paragraph, some of the most influential studies are summarized.

2.1. Contribution of DTI and the main neuroimaging tools for the understanding of language processing: the most relevant studies on the ventral pathways

Studies based on linguistic impairments, aphasia and on other clinical damages, allow for the identification of other brain areas beyond the canonical ones associated to language, and in particular the medial, inferior, and anterior temporal cortices (see Paragraph 1.1.). These areas seem to interact with the traditional perisylvian language network through the white matter tracts described above: the ILF, the UF and the IFOF (Catani & Mesulam, 2008).

Inferior Longitudinal Fasciculus. As we already saw, the ILF is an associative white matter tract connecting the occipital and the temporal lobe. From neuropsychological studies, it emerges that the interruption of some connections between the visual and the temporal cortex can lead to diseases such as associative visual agnosia (Jankowian & Albert, 1994), prosopagnosia (e.g., Benson, Segarra, & Albert, 1974), visual amnesia and visual hypo-emotionality (e.g., Sierra, Lopera, Lambert, Phillips, & David, 2002). These studies suggest that the disruption of the fibers connecting the visual and the temporal areas causes visual deficits at the semantic, emotional and memory level. With DTI tractography, Catani and colleagues (2003), confirmed the neuropsychological findings and defined the ILF as a tract that carries visual information from occipital regions to the temporal ones (Catani et al., 2003). Generally, the findings on its role have been quite diverse among studies. In a research by Mummery and colleagues (1999), semantic dementia patients and control patients have been tested with PET in a semantic decision task relative to a visual decision task. They found that the ILF plays an important role in visual object recognition and in lexical phonological retrieval (in the process which concerns linking object representations to their lexical labels). Other works, mainly through electrical stimulation, have also suggested a role of the area corresponding to the location of the left ILF (together with the IFOF; Duffau et al., 2002; 2005) in semantics, hypothesizing that it serves as a transmission connection network, connecting occipitotemporal areas with the temporal ones. From here, the fibers of the UF further project to the frontal areas (Vigneau et al., 2006). The role of the ILF has been discussed by Mandonnet, Nouet, Gatignol, Capelle, & Duffau (2007), using intraoperative subcortical stimulation in awake patients. They did not find a correlation between the ILF and naming disturbances. The same results have also been found when parts of the ILF was resected, suggesting that it may not play a role in language processing (Mandonnet et al., 2007). Epelbaum and colleagues (2008), gathered together diffusion images and functional imaging data in a single case study. Using DTI tractography and Voxel-Based Morphometry they analyzed the brain of a patient who acquired pure alexia after a surgery in an area close to the visual word form area (left fusiform gyrus and surrounding cortex). From the images collected pre- and post- surgery, it was observed a progressive and selective degeneration of the ILF, suggesting the role of this tract in reading. Gaillard and colleagues (2006) have previously confirmed the involvement of the ILF in reading as well. A very recent DTI study, which examined 61 children at high/low risk of dyslexia before and two years after reading skills acquisition, found no strong correlation between the FA of the ILF and orthographic components, suggesting that this tract may have a role in pre-reading cognitive processes (Vanderauwera et al., 2018).

Since the damage to the gray matter of the ATL has been associated with semantic dementia (characterized by a progressive deterioration of semantic knowledge; e.g., Mummery et al., 2000; Rosen et al., 2002), Agosta and collaborators (2010) attempted to deepen the role of the other altered components of the linguistic network in dementia. Using DTI tractography in combination with cortical anatomical and functional magnetic resonance imaging data obtained during a series of language tests (i.e., irregular word reading task), the group analyzed 5 patients affected by semantic dementia. Semantic dementia was associated with lesions at the level of the left ILF, a finding that seems to suggest the involvement of the ILF in semantic and lexical processes (Agosta et al., 2010). Another study, with different findings, was conducted by Wong, Chandrasekaran, Garibaldi, & Wong (2011). The authors used DTI to assess the effect of a sound-to-word learning training paradigm in which twenty healthy adults learned to use a phonetic contrast proper of a foreign language in order to succeed in a task in which the novel speech stimuli (which has no syllables in common with the native language) had to be associated with pictures of objects presented in a computer screen. Results show a positive correlation between the FA index in the left parietal-temporal area (i.e., a bundle of the middle ILF which goes along the STG, a branch of the ILF which run along the MTG, a part of the SLF and the extreme capsule) and the participants' success in the sound-to-word learning paradigm. They also found that both the extreme capsule and the ILF mediate auditory comprehension (see Xing, Lacey, Skipper-Kallal, Zeng, & Turkeltaub, 2017 for consistent results). The last DTI study that will be described about the role of the ILF in language, examined 16 healthy adults when learning 12 letters from the Morse code alphabet. The learning session lasted six sessions, after which, participants had to perform a word recognition Morse Code decoding task. Learning Morse code resulted in an increase of association between the FA of the right ILF, suggesting that learning a new language affects the microstructure of fibers in this region. (Schlaffke, Leemans, Schweizer, Ocklenburg, & Schmidt-wilcke, 2017).

In conclusion, this overview gives an idea of what is the involvement of the ILF in language. What primarily emerges is the heterogeneity of the findings, which prompt researchers to conduct further investigation.

Uncinate Fasciculus. As already mentioned above, the UF is a "hook-shaped" bundle, which connects the anterior temporal lobe with the orbitofrontal area and the inferior frontal gyrus (Catani et al., 2002; Schmahmann et al., 2007). Similar to what was reported of the ILF, evidence of the role of the UF in language processing is still inconsistent and unclear. Some lines of research linked its cortical atrophy, caused for example by Alzheimer's disease, frontotemporal dementia and corticobasal degeneration, to impaired naming accuracy and, specifically, to the lexical retrieval component of naming, assessed with a classical semantic fluency task (Grossman et al., 2004). The deficit seems to be associated with atrophy of the left lateral temporal area, suggesting that this area may be involved in the selection of a name's abstract representation that matches to a concept in the semantic memory. The result obtained by Grossman and colleagues, assessing spatial functioning through a copy of geometrical designs with different spatial complexity, showed involvement of the right inferolateral temporal and right dorsolateral frontal cortices in the processing of the visual perceptual–spatial properties of a given stimulus (Grossman et al., 2004). Another study on patients with left or right anterior temporal lobectomy shows impairment in the retrieval of names for tools and in the appropriate actions for tools' use, indicating that the UF may mediate the activation of action-related information (i.e., movement plan and/or motor use), which also may facilitate the retrieval of tool names (Lu et al., 2002).

Among the studies investigating the role of the UF in language, and in particular in naming retrieval, Nomura and colleagues (2013) reported a single case study of a patient with astrocytoma (a type of glioma) near the left UF. The patient was asked to perform a picture-naming task, meanwhile an intraoperative electrical stimulation was carried out. The stimulation of the left UF induced picture naming deficits and semantic paraphasias. Mehta and colleagues (2016) and by Papagno and colleagues (2011) arrived at similar conclusions, but just for proper name retrieval.

In a longitudinal nine months follow-up study by Papagno and collaborators (2016), 17 patients in total, 8 with removed UF and 7 without removed UF, underwent to a DTI and MRI scanning pre- and post- surgery. The patients have been tested in a series of neuropsychological tests before the surgery and then every three months, at the time of the scanning session. The tests also included different production tasks such as the naming of famous faces, object picture naming and semantic verbal fluency (i.e., cued by a category). In the last follow up, all performances have been recovered but the famous faces naming ones, which recovered just in patients who had no UF removal. This result seems to show the importance of UF for retrieving names of unique entities as proper names.

Some studies propose the UF as not essential for language processing. For example, Duffau, Gatignol, Moritz-Gasser and Mandonnet (2009) used intraoperative cortical stimulation in 13 patients with left anterior temporal lobe glioma to investigate the role of the UF. The results show that the subcortical stimulation in the left UF site did not produce linguistic impairments. The authors hypothesized that the ILF (called in the Duffau et al.'s paper the "inferior occipito-temporal fasciculus"-IOF) could compensate the role of the UF (Duffau et al., 2009). Other results consistent with the idea of a limited involvement of the UF in the linguistic function come for a study using the conjunction of DTI and lesion maps in 30 patients with chronic stroke and with residual impairments in speech production. Spontaneous speech measures (i.e., the rate of speech) have been assessed and then correlated with lesions load in three main tracts (AF, UF and Extreme Capsule). The results have shown that UF (and the Extreme Capsule as well) lesion load, seems not to predict the efficiency in speech production, which was more related to AF lesion load (Marchina et al., 2011).

The UF has also been studied in relation to bilingualism (see Chapter 3.). For example, Luk, Bialystok, Craik, & Grady (2011) performed DTI in 14 bilinguals and 14 monolinguals, with the hypothesis that the bilingual condition preserves white matter integrity. The UF integrity, in terms of FA index, seems, in fact, to correlate with bilingualism. We anticipate in this section that, together with the UF, also the corpus callosum, the posterior areas of the bilateral SLF, and the anterior areas of the right IFOF seem to have higher FA values in bilinguals with respect to monolinguals.

The integrity of the white matter has been also studied with conjunction of DTI and resting-state fMRI in aphasic individuals with varying degrees of word comprehension deficits. Through the use of an auditory word-picture verification task, participants' single word comprehension and, indirectly, cognitive control processes in order to regulate semantic knowledge activation, were assessed (Harvey, Wei, Ellmore, Hamilton, & Schnur, 2013). Lower quality of the UF fibers has been associated with an inferior performance in the word-picture verification task. It generally emerged that the UF serves as a connection between regions specialized in cognitive control to areas that store word meanings, showing a possible role in cognitive control processes related to semantics during word comprehension (Harvey et al., 2013). Lastly, no deficit in fluency task has been associated with lower quality of UF fibers also in a recent study by Kljajevic, Dyrba, Kasper and Teipe (2016) where DTI was used to test 28 mid Alzheimer patients and the equal numbers of controls.

Inferior Fronto Occipital Fasciculus. The last ventral tract analyzed as being part of the ventral network is the IFOF, which is the only described direct connection between the frontal and the occipital areas in the human brain (Catani, 2007). Even though several studies attribute a role in reading and writing (e.g., Epelbaum et al., 2008; but also Vandermosten et al., 2012; Vanderauwera et al., 2018), the function of this fasciculus in language is still not clear. Some of the most relevant findings of approximately the last ten years will be mentioned. Several studies used intraoperative subcortical electrical stimulation to map language functions in patients with left glioma. During the stimulation, patients were asked to perform a picture-naming task. The stimulation of a region, which seems to correspond with a part of the IFOF, induced a significant higher number of semantic paraphrases (i.e., substitution of the target word with a word belonging to the same semantic field) in these patients (Duffau et al., 2005). These findings seem to attribute a role in semantics to the ventral stream including the IFOF (Duffau et al., 2005). Semantic paraphasias have also been detected, in concurrence with IFOF stimulation, in a work published some years later by Leclercq and others (2010). Similar results derived from work by Mandonnet and colleagues (2007), have found language disturbances (e.g., semantic errors) during the stimulation of the white matter corresponding to the IFOF (the bundle just above the roof of the temporal horn; Mandonnet et al., 2007).

Turken and Dronkers (2011) combined DTI with functional connectivity in healthy participants in order to assess the role of different regions (including also the IFOF) associated with sentence comprehension. The implication in comprehension processes has been confirmed by the authors (Turken and Dronkers) and then reaffirmed by the recent DTI work from Xing, where the white matter integrity was correlated with both word and sentence comprehension (Xing, Lacey, Skipper-Kallal, Zeng, & Turkeltaub, 2017).

The IFOF has also been studied in reading because of its brain location and function. Specifically, it crosses the pars triangularis and the visual word form area, regions that have been reported to be active during the recognition of visual word patterns (Jobard, Crivello, & Tzourio-Mazoyer, 2003). As for its involvement in reading, studies seem to show a modulation of the IFOF (in conjunction with the AF) as a function of reading acquisition. The left IFOF seems to be involved in some aspects of phonological processes in reading (assessed via various tests such as phonological awareness, rapid automatized naming and letter knowledge) in the time period before the reading onset and during the early stages of reading acquisition (Vandermosten et al., 2015). In participants with high reading abilities, this tract has been associated to orthographic knowledge (Vandermosten et al., 2012). Vanderauwera (2018) produced a more recent work on the role of the IFOF in orthography. In her study, 61 children at high and low risk of dyslexia have been tested with DTI. The results indicated that higher orthographic skills are associated with higher quality of the IFOF fibers. The

IFOF has also been largely studied in relation to bilingualism (see also Chapter 3). Mohades and colleagues (2015) performed DTI on 15 simultaneous bilinguals (L1 and L2 acquired at the same time), 15 sequential bilinguals (the L2 acquired after 3 years-old) and 10 monolingual children. Their findings showed a better quality of the white matter fibers in the left IFOF for simultaneous bilinguals when compared to monolinguals and sequential bilinguals, indicating the relevance of the time of exposition of the second language in the maturation of some white matter tracts related to language. Finally, the IFOF has been shown to be involved in semantic fluency task. Almairac and Herbet (2015) performed a voxel-based lesion-symptom analysis in 31 patients with a low-grade glioma. All the patients performed language tasks, with a prevalence of naming test, verbal fluency test, in different times pre- and post- surgery. The location of the voxel resulted as significant when considering the semantic fluency performance, have been located in the same areas, which anatomically corresponds to the IFOF, confirming the role and the importance of this tract in semantic processing.

CHAPTER 3

The Bilingual brain

Introduction. Neuroplasticity is considered a unique ability of the brain and it can be described as the capacity to organize and adapt both its functions and structures in response to behavior, environmental experiences and cognitive demands. The domains in which neuroplasticity have been studied are diverse. For example, some studies have been conducted to investigate brain modifications due to learning a musical instrument (Baeck, 2002); others have focused on the effect of enhanced topographic abilities (e.g., in London taxi driver's hippocampus; Maguire et al., 2000) and others on gray matter modifications as a result of motor trainings (e.g., juggling; Draganski et al., 2004). An increasingly common ability, learning a second language, constitutes another challenging approach to brain plasticity. Learning a second language it is a widespread experience, especially for new generations. Thanks to the environmental and social changes of the last century, more than half of the population is nowadays learning or speaking at least a second language, in addition to their native one and, for this reason, most of them can be considered in some ways bilinguals (Bialystok, Craik, & Luk, 2013). Research on bilingualism has been under the spotlight during the last twenty years not only because of its social and human interest, but also for the extraordinary effect that bilingualism has on the brain. One of the major issues for neuroscientists is how the brain can support and then represent more languages simultaneously, and, for example, two or more words for the same meaning.

Bilingualism has been investigated through behavioral, functional and structural studies (and their combinations as well), allowing examination of specific effects related to second language acquisition.

3.1. Understanding the bilingual brain: contributions from functional neuroimaging studies

As mentioned in Chapter 1 of the present dissertation, fMRI and PET are tools that offer the chance of mapping the language faculty in the human brain. These methods, in fact, can be considered as complementary (as well as a confirmation) to the classical lesion-based neuropsychological studies, allowing to precisely locate the areas involved in the behavioral tasks. The general findings of the principal functional studies on bilingual production and perception are here summarized. As it will be seen, the main focus of the research in this field was to investigate whether the processing of the second language recruits the same areas involved in the processing of the native language or whether there are specific areas devoted to the processing of the second language.

Early studies on language production and perception. The first functional studies on bilingual production date back to the beginning of the 1990, when Klein and coworkers (Klein, Zatorre, Milner, Meyer, & Evans, 1994; Klein, Milner, Zatorre, Meyer & Evans, 1995) published two PET studies aimed at understanding if the two languages in bilinguals shared the same brain regions for production (Klein et al., 1994; 1995). To respond to this question, a word repetition task for both English (L1) and French (L2) was adopted. The results revealed an overlapped activation across the two languages in the areas of the left frontal lobe (Klein et al., 1994). In addition, L2 production was associated to the activation of a subcortical structure belonging to the basal ganglia, defined as the left putamen. It is worth noting that no later studies have found the activation of this area associated to bilingualism. One year later, in 1995, the same team repeated the experiments with the same type of population but, this time, specific linguistic processes were investigated, using a number of production/generation tasks. These were a rhyme generation task, requiring a lexical search based on phonological cues, a synonym generation task, requiring a search at the semantic level, and a translation task, involving the retrieval of a word in the other language. Control tasks consisted in word repetition tasks in both the languages. The areas commonly activated during generation tasks in L1 and L2, irrespective of the semantic or phonological nature of the tasks, were all located in the left hemisphere (no common activations have been found in the right one). Specifically, a broader activation was observed in the inferior and dorsolateral frontal cortex (in the Brodmann's nomenclature known as the 8, 45, 9/46, and 47 areas). Moreover, the left infero-temporal regions (Brodmann's areas 20/37) and the left superior parietal cortex (Brodmann's area 7) resulted in activation, even if to a lesser extent.

Overall, to summarize Klein's findings, it emerged that L1 and L2 processes rely on the same brain areas, even when participants acquired L2 after having learned L1 (Klein et al., 1995). Some years later, Chee, Tan and Thiel (1999a) performed a fMRI study with early and late bilinguals (both highly proficient in the second language) using a cued word generation task and they found similar results. The literature is far more extended, but from the works cited as examples (as well as later studies; e.g., Isel, Baumgaertner, Thrän, Meisel, & Büchel, 2010), it seems that in proficient bilinguals the areas recruited for production overlap among languages, regardless of the age of L2 acquisition. Specifically, these data are in line with the idea that proficiency has a stronger impact on second language processing rather than the critical period of acquisition. The contribution of these two variables, age of acquisition and proficiency, has been largely discussed in literature. For example, conversely to Klein et al.'s findings, other fMRI and PET studies have found broader activation for the later acquired language, even when L2 proficiency was high (e.g., Yetkin, Yetkin, Haughton, & Cox, 1996; Perani et al., 2003; De Bleser et al., 2003).

As well as for production, perception of L1 and L2 was also investigated. For example in two PET studies, Perani and colleagues compared people with different levels of bilingualism, specifically: late low-proficiency bilinguals early high-proficiency bilinguals and late high-proficiency bilinguals (Perani et al., 1996; Perani & Cappa, 1998). In one study, participants were Italian-English late low proficiency bilinguals. They were instructed to listen to different stories in both languages and in an unknown language (Japanese) during a scanning session. Differences between L1 and L2 activations emerged. When performing the task in L1, the left perisylvian areas (comprising the angular gyrus; Brodmann's area 39), the superior and MTG of both hemispheres (Brodmann's areas 21 and 22), the left inferior frontal gyrus (Brodmann's area 45) and the temporal poles of both hemispheres (Brodmann's area 38) resulted in higher activation compared to the baseline condition. When performing the task in L2, the only common areas that resulted in activation among those found for L1 were the left and right superior and bilateral MTG (Brodmann's areas 21 and 22; Perani et al., 1996; see Dehaene et al., 1997 for similar results). There was also a minor activation of the parahippocampal gyri (Brodmann's area 36), which seems to suggest the involvement of memory related structures (Grasby, Frith, Friston, Frackowiak, & Dolan, 1993). Finally, when listening to Japanese, relative to the attentive rest condition, left and right superior and middle temporal regions (Brodmann's area 21 and 22) and the right mesial anterior temporal regions resulted in activation. Surprisingly, no regions where more active when listening sentences in English compared to Japanese, even if participants clearly understand just the first of the two languages. This last unexpected result suggested a high variability in the brain areas engaged for second languages as well as a weaker activation of those areas engaged during perception of second language.

In their second PET experiment, Perani and Cappa (1998) compared activations in high proficient late bilinguals (L2 acquired after the age of 10 years), and in high proficient early bilinguals (L2 acquired before the age of 4 years) while listening to stories in both languages. The results showed highly overlapping activation of the classical areas related to perception, in both groups when listening to stories in L1 and in L2. Taken together, these results further confirmed the critical role of proficiency, compared to age of acquisition, in the functional organization of the brain (Perani et al., 1998). In their fMRI study, Hasegawa, Carpenter and Just (2002) tested cortical activations in Japanese-English bilinguals (moderately fluent in the L2) with a sentence comprehension task. Despite the overlapping activation of some areas (i.e., the left temporal gyrus, the left angular gyrus, the left precentral sulcus and the bilateral Heschl's gyri), broader activation has been observed while processing sentences in L2 with respect to L1. This result was explained with the need of more cognitive effort when processing sentences in the less proficient L2.

These findings suggest that in consideration of the cortical activity during perception, proficiency is a more decisive index than age of acquisition. In fact, different brain activation amplitudes emerged only in low proficiency participants versus high proficiency participants, regardless of age of L2 acquisition (Chee et al., 1999b; Price, Green, & von Studnitz, 1999; Abutalebi, Cappa, & Perani, 2001, for a review).

In order to further clarify the explanation of these ambiguous results, a recent work by Nichols and Joanisse (2016), combined fMRI and DTI data. The authors reported that some brain areas seem to be independently modulated by age of acquisition and/or proficiency in L2 speakers. Specifically, both gray and white matter changed as a function of age of L2 acquisition or proficiency in specific areas identified as: the STG, the middle and inferior frontal gyrus, the parahippocampal gyrus and the basal ganglia (for a complete description, see Nichols & Joanisse, 2016).

Another important distinction between bilinguals and monolinguals concerns hemispheric asymmetry. Hull and Vaid (2006) conducted a meta-analysis of 23 studies assessing laterality in relation to language experience. Studies using the same groups (i.e., monolinguals and bilinguals), same languages and same experimental paradigms (i.e., dichotic listening, visual hemifield presentation, and dual task) were compared in order to describe the contribution of L2 proficiency and L2 onset on laterality. What emerged was a left hemisphere dominance for the monolinguals and late bilinguals (L2 acquired after the age of 6 years); whereas bilinguals who acquired L2 early in life showed a more symmetrical hemispheric involvement. One year later, another meta-analysis corroborated these results, with late bilinguals showing greater left lateralization compared to early bilinguals (Hull & Vaid, 2007). Further confirmation of the contribution of early bilingualism in the laterality of perisylvian areas is suggested from more recent studies on DTI tractography (Hämäläinen, Sairanen, Leminen, & Lehtonen, 2017), where early exposure bilinguals have been associated with a more symmetrical organization of the AF and higher FA values in this tract when compared to late sequential bilinguals. What the study also shows is that early exposure did not show modifications in the IFOF, which was conversely associated to a decreased mean MD in late sequential bilinguals.

Looking at studies with direct electocortical stimulation, Bello and collaborators (2006) performed an intraoperative multiple language mapping in seven multilingual patients, which underwent to a surgery for tumor removal in the left hemisphere. The patients were tested in a battery of linguistic tests (with both production and comprehension tasks), which was performed at first in the dominant language and then in the other languages. Results shown, for every language, different pattern of cortical activation. Specifically, in some patients (n = 3) there was a specific site for the activation of L1 and a second common site for the other languages; whereas for some patients (n = 2), there were distinguished sites for all languages, regardless of the time of acquisition (Bello et al., 2006).

In general, the fact that the two languages rely on the same or very adjacent brain areas, leads to the question as to whether there exists a single lexical concept subserving all known languages, or conversely, there are as many representations as the languages one owns.

Cross language interference and object representation. Buchweitz, Shinkareva, Mason, Mitchell and Adam (2012), through the use of machine learning and a word-reading task, explored whether there exists a unitary semantic representation across languages. The main hypothesis is that proficient bilinguals should show a high degree of cross language brain activation, as already demonstrated by previous works (Isel et al., 2010; Illes et al., 1999). Participants had to read silently the words presented during the scanning session and think about the semantic properties of the words. The task was first performed in one language and in a separate session, in the other language. Based on the brain activation in one language, classifiers have been trained with machine learning methods to identify the noun (tools or dwellings) that bilingual Portuguese-English participants were thinking in the other language, showing a high degree of cross-language neural commonality of noun representations. The results confirmed that in high proficient bilinguals, patterns of neural words representations are independent from the language used (Buchweitz et al., 2012). Conversely, there are studies showing distinctive activations of words, in relation to the grammatical category. In fact, there is a growing body of evidence associating both nouns and verbs responses to different brain regions. For example, an fMRI study conducted with English-Chinese bilinguals found distinct neural patterns in bilinguals' responses to both nouns and verbs to a lexical decision task. English (L1) verbs activated prefrontal regions, while English nouns activated temporal-occipital regions. Conversely, there was no difference in the activation pattern in Chinese (L2) for verbs and nouns (Chan et al., 2008). Consistent with these results, a later work by Yang, Tan, and Ping (2011) found the same activation pattern for both nouns and verbs in late Chinese-English bilinguals (in L1 Chinese). An fMRI study comparing grammatical category organization in Spanish-English bilinguals found four regions which resulted to be more active when processing verbs compared to nouns in both languages; these regions were the left MTG, the left middle frontal gyrus, the pre-SMA and the right middle occipital gyrus. There were no regions in which nouns were more active than verbs, suggesting that verbs processing may rely on independent neural substrates (Willms et al., 2011).

The fact that in the high proficient bilingual brain conceptual representations are shared between two languages, raises another relevant issue: *cross-language interference*. Bilinguals need to instantly choose the appropriate word in relation to the context. Sometimes, when talking in one of the two languages, it can happen to have intrusions from words belonging to the other language (for example, saying the right word but in the “wrong” language). This phenomenon has been explained as a parallel activation and a general involvement of the non-target language when speaking (Spivey & Marian, 1999; Martin, Dering, Thomas, & Thierry, 2009; Kroll, Bobb, & Wodniecka, 2006). What may happen is that the language not in use is maintained in background and competes with the one in use (Costa, Miozzo, & Caramazza, 1999). This “joint activation” places the bilingual in the constant condition of selecting the language and the target words, and this could be the cause of the more effortful language processing for bilinguals than monolinguals. This likely explains some of the costs observed for bilinguals in psycholinguistic studies. For example, it has been demonstrated that bilinguals have lower verbal fluency skills (Gollan, Montoya, & Werner, 2002; Rosselli et al., 2000; Bialystok, Craik and Luk, 2008) and slower scores in picture naming tasks (Gollan, Montoya, Fennema-Notestine, & Morris, 2005) with more tip-of-the-tongue retrieval failures (Gollan & Silverberg, 2001) which may affect also the first language (Gollan & Acenas, 2004, Gollan, Bonanni, & Montoya, 2005; Ivanova & Costa, 2008; Ransdell & Fischler, 1987). Interference from the non-target language is controlled by a mechanism known as “inhibitory control”, which is responsible for the suppression of the non target language and for the monitoring of the target language (Green, 1998). The inhibitory control has effects not only for language processing, but may have an impact on non-linguistic processing as well (Abutalebi et al., 2012), especially after long life experiences with two or more languages.

Differences in the level of activations due to the degree of bilingual experience should receive confirmation at the neuroanatomical level. The main structural research, with particular reference to DTI studies, is summarized in the next paragraph.

3.2. Structural white matter modifications due to bilingualism

When speaking about "structural changes", we usually refer to all the modifications occurring at the level of the gray and/or white matter within the brain. The investigation of bilingualism via structural imaging techniques is quite recent compared to functional studies and might represent the anatomical confirmation of daily experiences and/or trainings contribution. White matter is mainly composed by axons and support cells (see Chapter 2), while gray matter comprises neuronal cell bodies. The latter has been largely considered the most common measure when detecting brain modifications. The first evidence of the effects of bilingualism on the structural development of the brain dates back to the beginning of this century, when Mechelli and collaborators (2004) show higher gray matter density value in the inferior parietal cortex in bilinguals, when compared to monolinguals. The inferior parietal cortex is implicated in phonological working memory, lexical learning, semantic integration and vocabulary knowledge (Della Rosa et al., 2013; Baddeley, 2003; Lee et al., 2007). Moreover, Mechelli et al. (2004) found that gray matter density of the inferior parietal lobe of both hemispheres, was negatively correlated with age of L2 acquisition, and only the left one seemed to be positively correlated with L2 proficiency. The gray matter differences between monolinguals and bilinguals were correlated with age of L2 acquisition, such that they were larger when L2 was acquired earlier in life. According to the authors at least part of these differences may be due to the experience (and the use) of a second language and thus, indirectly, with the performance in L2.

This work provided for the first hint of a proliferation of studies on the neuroanatomical organization of the perisylvian linguistic areas when acquiring a second language. Luk and colleagues (2011) expanded the research from the detection of differences on gray matter areas to white matter tracts, and specifically to the axons' bundles connecting different regions of the brain. The authors performed both DTI and resting-state functional connectivity analysis in order to measure white and gray matter volume in a group of monolinguals and a group of bilinguals. Their principal hypothesis was that the enhanced cognitive abilities and the better executive performances in bilinguals might also be reflected in more solid white matter connections. White matter integrity (assessed with FA index values) in bilinguals was higher in the corpus callosum, in the SLF bilaterally, in the right IFOF and right UF. Moreover, when compared to the monolinguals, bilinguals showed stronger anterior to posterior functional connectivity. The presence of white matter differences in bilinguals versus monolinguals has been reported to exist in childhood (Mohades et al., 2012; 2015), in adulthood (Cummine & Boliek, 2012; Pliatsikas, Moschopoulou, & Saddy, 2015), and in old age (Gold, Johnson, & Powell, 2013a; Luk et al., 2011).

In a DTI study, Cummine and Boliek (2013) compared the white matter connections of adult Chinese-English bilinguals and English monolinguals, in relation to some reading skills (specifically, participants have to perform a word reading tasks). Differences in the FA values appeared at the level of the right IFOF and the anterior thalamic radiations (right superior and bilateral inferior). However, these results should be cautiously considered, since the two groups were not matched for age. For this reason, results may have been driven by the still immature white matter in the bilingual group, which was composed by younger participants compared to the monolingual one. In order to assess whether white matter can be modified early in life as a consequence of L2 learning, Mohades et al. (2012) performed a DTI study on 15 simultaneous bilinguals (L2 acquired before the age of 3), 15 sequential bilinguals

(L2 acquired after the age of 3) and 10 monolingual children. Overall, the results indicated that the groups of bilinguals have higher FA values in the left IFOF, when compared to age matched monolinguals. Additionally, the more the bilingual was exposed to L2, the larger the difference was with the monolingual group, suggesting that age of acquisition (or proficiency) could predict white matter changes. Differences between the groups emerged also in the corpus callosum, a white matter tract connecting the two hemispheres, which size has been put in relation with the lateralization of language (Josse, Seghier, Kherif, & Price, 2008). Specifically, differences appeared in the bundle connecting the anterior corpus callosum with the orbital lobe. In this case, monolinguals had larger FA values than bilinguals. The authors explained this findings taking into account the left hemisphere dominance in monolinguals (and in late bilinguals; see Hull & Vaid, 2006), which may be the cause of differences in this tract.

Brain modification as a consequence of bilingualism seems to persist also later in life, as reported by Luk and colleagues (2011). These results are consistent with the hypothesis that bilingualism has a protective experience against cognitive decline (Bialystok, Craik, & Freedman, 2007; Gold, Kim, Johnson, Kryscio, & Smith, 2013b; Grant, Dennis, & Li, 2014; for evidence in bimodal bilinguals see Li et al., 2017). Even if this pattern has been confirmed by gray matter studies (e.g., Abutalebi et al., 2014), not all research analyzing bilingualism in aging is consistent with Luk and colleagues pattern (see Gold et al., 2013 for a study showing greater FA values of the ILF, IFOF, fornix and various portions of the corpus callosum in monolinguals with respect to bilinguals).

Garcia-Penton, Pérez Fernández, Iturria-Medina, Gillon-Dowens, and Carreiras (2014) combined DTI with network analysis and graph theory in order to compare the connectivity degree in early Spanish-Basque bilinguals and Spanish monolinguals. In bilinguals, a higher degree of connectivity was found, likely reflecting the experience with another language (Garcia-Penton et al., 2014). Larger connectivity involved mainly two networks: (1) In the left hemisphere, areas associated with language, attention and control processes as: the insula, the STG, the supramarginal gyrus, the inferior frontal gyrus and the medial superior frontal gyrus. (2) Brain areas that include the left superior occipital gyrus, the right superior frontal gyrus, the left superior parietal gyrus, the left superior temporal pole and finally the left angular gyrus, which have a role in reading, word recognition and lexical semantic processing. The results, taken together, suggest a major involvement of the frontal cortex in bilinguals, likely reflecting the larger engagement of control processes in the mastering of two languages. (Abutalebi & Green, 2007).

When talking about the "bilingual status", we usually refer to people who have known the second language for a long time. As a consequence, we imagine their brain as sensitive to modifications, which occurred over extended period of time. In current literature, the "bilinguals" category also includes people that learned the second language later in life such as work travelers or people moving to another country. In these cases, a new language needs to be acquired in few months and through intensive training. In this regard, recent studies showed that short-term L2 training might result into structural brain changes. In order to detect these short-term changes, Schlegel, Rudelson and Peter (2012) performed a longitudinal DTI study, which allowed monitoring neuroanatomical modifications due to L2 learning. A group of monolinguals participated to an intensive Chinese language class. Participants were tested each month, for a total of 9 months. This group was compared with another group of monolinguals peers who did not follow any language class. The results showed differences in the FA values for the group who participated to the Chinese classes, specifically in the frontal tracts of the brain that cross the genu of the corpus callosum. These modifications were proportional to the amount of L2 learning (the higher the proficiency in Chinese, the higher the FA values). Moreover, the same tracts showed a decreasing of RD, which in combination with the increased FA values, has been interpreted as an index of increased myelination. The interested areas were the classical areas associated to language in the left hemisphere, and the analogous areas in the right, like the transverse frontopolar gyrus and sulcus, Brodmann's area 45 (pars triangularis), anterior superior temporal gyrus, which resulted in increased activation in language learners over controls. Specifically, the caudate nucleus has been reported to be the end point of many of the tracts analyzed, suggesting an involvement of this area in language and in control functions, as already reported by fMRI (e.g., Zou, Ding, Abutalebi, Shu, & Peng, 2012a) and by lesion data studies (Abutalebi, Miozzo, & Cappa, 2000): the damage of the left caudate nucleus in fact, may produce pathological language switching or interferences among languages (as well as difficulties in the selection of the right language in relation to the external o specific request) during production tasks (Abutalebi, Rosa, Tettamanti, Green, & Cappa, 2009; Marien, Abutalebi, Engelborgh, & De Deyn, 2005; Aglioti, Beltramello, Girardi, & Fabbro, 1996; Aglioti & Fabbro, 1993).

Hosoda, Tanaka, Nariai, Honda, & Hanakawa (2013) through the use of a training paradigm, asked a group of Japanese people who learned English at the age of around 11, to participate to a training session lasting 16 weeks, aimed at enlarging L2 vocabulary. After 4 months, the training group showed increased levels of gray matter density in the right inferior frontal gyrus and, specifically, in the pars opercularis with respect to the control group. Moreover, increased reorganization of white matter connections has been found in the inferior frontal gyrus-opercularis-caudate and in the inferior frontal gyrus-STG/SMG of the right hemisphere. These modifications seem to be maintained over time only in people who keep learning new words also after the training (Hosoda et al., 2013). From the literature, it seems that in order to see brain changes, several months of intensive vocabulary training are needed. The shorter training period is three months as reported in a study by Mårtensson and colleagues (2012) on cortical thickness. For studies analyzing other functions not involving language (e.g., motor skills), the “training period” needed to produce brain modifications may be even shorter (few weeks but also few days; e.g., Ilg et al., 2008; May et al., 2007), suggesting a different contribution of linguistic and non-linguistic faculties in the reorganization of the brain.

Several DTI studies aimed at comparing monolinguals and bilinguals reported differences in the brain structure between the two groups. However, the direction of the difference is not always congruent among studies. For example, while Cummine and Boliek (2012), and Gold and colleagues (2013a) converged on the idea of higher FA values in monolinguals, studies by Luk and collaborators (2011), Mohades and colleagues (2015) and Pliatsikas et al. (2015), have found the opposite pattern, with higher FA in bilinguals when compared to monolinguals.

Kuhl and colleagues (2016) used DTI to compare monolinguals and Spanish-English bilinguals. Anatomical differences in both hemispheres were found, involving tracts associated with (a) the linguistic function (i.e. IFOF, SLF, SLF temporal, all bilaterally), (b) the executive functions (i.e. anterior temporal regions, forceps minor, cingulum), (c) the motor function (corticospinal tract), (d) social cognition and emotion (UF and cingulum). In these areas, higher FA values appeared in the group of monolinguals with respect to bilinguals. The DTI data were also analyzed as a function of duration of residence in the US. Results showed that the longer time spent living in the US, the higher the FA values in the posterior regions of the brain, as well as in the posterior regions of the SLF, and in the left IFOF. Decreased MD and RD values (associated with higher density and packing of fibers) in the anterior regions, including the left UF and left IFOF were associated with increased experience in L2 listening. These data, despite suggesting the contrary of previous literature, have received some confirmation. For example it has been shown the activation of regions involving production in children learning their L1, when listening to other's speech (Kuhl, Ramirez, Bosseler, Lin, & Imada, 2014). Moreover, FA in the ILF and in the corpus callosum were positively correlated with the duration of US residence, corrected for the amount of time speaking the L2, so that the more the speaking, the higher the FA in these two tracts (Kuhl et al., 2016). These increased FA values (which are synonym of processing efficiency) with in increased L2 speaking experience may indicate that the environment gives a decisive contribution for the improvement of efficiency in the perception of speech.

Further evidence about the differences on white matter fibers between monolinguals and bilinguals, is provided by Bakhtiari, Boliek and Cummine, (2014). These authors isolated, for each hemisphere, four white matter tracts, in order to understand their role in reading: the dorsal ones were the AF and the SLF, whereas the ventral ones were the UF and the ILF. FA and MD values for every tract have been correlated with the RTs required for reading a list of regular and exception words. The reading task was performed in L1 and also in L2 for bilinguals. The results showed a significant correlation between DTI measures of ventral white matter tracts (i.e. ILF and UF) and reading performance for both bilinguals and monolinguals; dorsal white matter tracts (i.e. SLF) seemed to be associated to reading performance only for the bilingual participants. More precisely, in both the groups (bilinguals and monolinguals), RTs in the reading task were positively correlated with MD of the right UF; in the bilinguals group a positive correlation emerged between RTs and the MD of the right AF and between RTs and the MD of the left and right SLF. A trend close to a positive correlation was also observed with the right ILF in the bilingual group, although not significant in this study.

To summarize, bilinguals, when compared to monolinguals, have larger gray matter volume in motor and perceptual areas. Several white matter regions seem to be engaged in bilingual processes; the left IFOF (Mohades et al., 2012, 2015; Gold et al., 2013a; Pliatsikas et al., 2015) and the left SLF (Luk et al., 2011; Pliatsikas et al., 2015). These two bundles connect the occipital with the frontal areas and, according to Hickok and Poeppel model (2004), are both cortical regions involved in language processing; the former has been associated with speech comprehension and the latter to sensorimotor language integration. Differences between bilinguals and monolinguals emerged also in the ILF (Luk et al., 2011; Gold et al., 2013a) and in the corpus callosum (Luk et al., 2011; Gold et al., 2013a) In this case the results are conflicting: Luk and colleagues (2011) reported greater FA values in older adult bilinguals when compared to monolinguals (higher FA values were found also in the corpus callosum and the SLF bilaterally). Gold and colleagues (2013a) reported the opposite pattern for all three tracts. To account for these opposite results, several hypotheses have been proposed, involving participant characteristics (e.g., mid cognitive impairments in older adult bilinguals), linguistic factors (e.g., the amount of code-switching within the environment) and DTI limitations (e.g., crossing fibers; Grundy, Anderson, & Bialystok, 2017). Globally the findings suggest the involvement of the ventral tracts in bilingualism, but still further investigation is needed in order to define their specific contribution.

3.3. Bimodal Bilingualism and sign language

Looking at studies of bilingualism and the consequences of knowing more than one language for the brain, what emerges is that not all bilinguals are the same. In fact, as already discussed in Paragraph 3.1. there are bilinguals who acquired their L2 early in childhood at the same time of their first language (simultaneous bilinguals); bilinguals who acquired the second language later in life but during childhood, as for example at school (sequential bilinguals), and also bilinguals who acquired the L2 during their adulthood (late bilinguals). Other important factors characterizing the bilingual status are the amount of time in which bilinguals have been exposed to the L2 and the context in which the L2 has been learned (at home, at the school, in the society, a combination of those contexts, etc.). Another distinction among bilinguals is the linguistic modality employed by the two languages. In the case of unimodal bilinguals the two languages share the same input-output modality whereas bimodal bilinguals employ different input-output channels, one involving spoken language (auditory-vocal) and the other involving sign language (visual-manual). At the peripheral level, spoken and signed languages have to recruit different sensory and motor systems to support linguistic processes. The crucial, much more interesting, question is whether spoken and signed languages rest also on a amodal neural substrate, sharing mechanisms for lexical, morphological, and syntactic processing. The current findings will be summarized in the next sections.

3.3.1 Basic aspects of sign language

Sign languages arose primarily as a communication system for deaf people. Nowadays, sign languages have been recognized as full-fledged languages, with the same degree of structural complexity and expressivity as spoken languages (Stokoe, Casterline, & Croneberg, 1965; Sandler & Lillo-Martin, 2006; Pfau, Steinbach, & Woll, 2012). The phonological parameters characterizing signs are hand-shape, location, orientation and movement and allow distinguishing signs among each other and signs from non-signs (some examples in Meir, Padden, Aronoff, & Sandler, 2007). At the level of morphology, sign languages have complex signs, formed by basic ones by applying compounding, derivation, and inflection processes (an example of inflexion is shown in Perniss, Thompson, & Vigliocco, 2010). At the syntactic level rule-governed processes are used for combining discrete signs with each other and create infinite numbers of propositions (for further discussion, see Neidle, Kegl, MacLaughlin, Bahan, & Lee, 2000). Additional articulatory elements are non-manual actions. Sometimes manual signs are expressed simultaneously with the help of body-parts (as head, cheeks, eyebrows, lips etc.). To date, more than 120 different types of sign languages have been identified in the world each with language specificity, meaning that just as in spoken languages, signers of different sign languages cannot understand each other.

Given the evident differences in the communication effectors between spoken and signed languages, one should expect their processing relying on different brain networks. Conversely, it has been shown that sign language processing is left lateralized and involves the large part of the neural regions employed for spoken languages (Broca, 1861; Emmorey, Mehta, & Grabowski, 2007). The most significant evidence comes from the main language connections: Broca's area, the core system for verbal production, is functionally activated during sign production. On the contrary, the area usually associated to verbal comprehension (i.e. the Wernicke's area), is colonized by sign comprehension (MacSweeney, Capek, Campbell & Woll, 2008; Emmorey, 2002). Specifically, the overlapping areas are the inferior frontal gyrus and some areas located in the posterior superior temporal regions as the inferior parietal cortices, the middle temporal gyri and basal temporal areas (Braun, Guillemin, Hosey & Varga, 2001). Confirmation of the similarities between the brain regions engaged for sign and spoken language processing come from studies that used the Wada technique (Damasio, Bellugi, Damasio, Poizner, & Van Gilder, 1986; Corina et al., 1999). For example, in the study by Damasio and colleagues (1986), the Wada procedure was applied to an epileptic bimodal bilingual woman. When her left hemisphere was "blocked" with Wada, her fluency in a picture-naming task was impaired when performed both in English and in American Sign Language (ASL). This result shows that both sign and spoken language production are based on areas of the left hemisphere. Critically, this may suggest that there are brain regions involved in language that are independent from the modality in which the language is expressed or perceived.

Sign language specificity. Despite the consistent overlap in the processing of signed and spoken languages, modality-specific differences have also been described (Emmorey et al., 2003, 2007; Corina, San Jose-Robertson, Guillemin, High, & Braun, 2003; Kassubek, Hickok, & Erhard, 2004). Considering language production, Emmorey and collaborators (2007) analyzing PET data collected from signers and hearing participants, identified three brain regions showing overlap during overt object naming in spoken and signed language (compared to the baseline condition, which was a facial orientation judgment). The first region goes from the mesial occipital cortex to the lateral occipitopariental cortex. This activation was mainly attributed to the higher attention required for the naming task relative to the baseline condition (Emmorey et al., 2007). The second region is located anteriorly in the Broca's area and has been associated with Brodmann's area 45. The activation in this area represented the modality independent processes of language production. More specifically, this region has been associated to lexical selection processes (see also Paragraph on language production 1.1.2.). Finally, the third region showing common activation was the middle-inferior temporal cortex. This region has been associated with lexical retrieval processes and more specifically, with the processes involved in the retrieval of a phonological representation after a conceptual unit has been selected. (see Paragraph 1.1.2.; Indefrey & Levelt, 2004). Emmorey and colleagues also found areas that were more active during sign language than oral language production. One of these regions was the left superior parietal lobule and its activation has been associated to the proprioceptive feedback of the movement of hands and arms. In fact, given that signers tend not to look at their own signs during signing, they may recruit other types of information rather than visual in order to monitor their production (Emmorey et al., 2007). The other region that was significantly more activated for signs than for oral language production was the supramarginal gyrus. This area has been associated with the integration of the phonological aspects of signs. In fact, in order to correctly produce a sign, arms and hands actions should be coordinated both at the spatial and temporal level. This is a unique feature of sign language, therefore activation of this area is specific for sign languages. Confirmation of the involvement of this area in sign language phonology comes from the results of a study showing that the intracranical stimulation of the left supramarginal gyrus in a deaf participant produced sublexical phonological errors such as a wrong hand-shape with the correct hand orientation and movement, or an incorrect movement with the correct hand-shape (e.g., Corina et al., 1999). Moreover, a study by Poizner, Klima, & Bellugi (1987), described a very similar pattern of phonological errors in a deaf patient with lesions of this area.

Considering language perception, the overlap between signed and spoken languages is well confirmed in literature. Several studies showed that the brain areas involved in language perception are mostly shared between oral and signed languages (Neville et al., 1998; Petitto et al., 2000; MacSweeney et al., 2002, 2004; Capek et al., 2008, 2010; Emmorey et al., 2011b). Even in this case however, there are some brain areas that are engaged only in sign perception. A seminal fMRI study by MacSweeney and colleagues (2004), showed this outcome. Their study was aimed at examining whether the areas recruited for sign perception were the same recruited for the perception of hand gestures that do not contain linguistic meanings. They compared the perception of simple sentences in British Sign Language (BSL) with the perception of gesture sentences in Tic Tac, which is a sort of manual code used by bookmakers during horses races bets in three different groups: deaf native signers, hearing non signers and hearing native signers (i.e. bimodal bilinguals). In hearing non-signers, the contrast between BSL and Tic Tac perception with respect to the baseline did not show the activation of the classical areas devoted to the perception language. For deaf signers and bimodal bilinguals this comparison showed activation of several cortical areas, both anteriorly and posteriorly. When comparing BSL with Tic Tac, results showed greater activation in a region corresponding to a part of the Wernicke's area, specifically the posterior STG/STS when participants were exposed to BLS with respect to Tic Tac. As described in Paragraph 1.1.1., this region is involved in the auditory speech perception. These results seem to suggest that STG/STS is involved in the processing of phonological information regardless of the modality of the language (Emmorey et al., 2011b; MacSweeney et al., 2002). MacSweeney et al. (2004) showed that the activation of this region was broader for the deaf group if compared to the bimodal bilinguals group. Moreover, only deaf and not hearing signers showed activation of the supramarginal gyrus and the frontal region superiorly to the posterior part of Broca's area (Brodmann's nomenclature 44).

Right-hemisphere involvement. A number of fMRI studies seem to indicate that the right hemisphere is more involved in sign than in speech comprehension, even if the different fMRI studies showed different levels of right hemisphere recruitment (Neville et al. 1998; MacSweeney et al., 2004; Capek et al., 2004). The reason of this right hemisphere involvement is still controversial, but it has been hypothesized that it is due to the processing of spatial information, mostly required for signed languages. In particular the right parietal lobe seems to be maximally involved in the processing of classifiers, a special class of iconic signs that convey the spatial/topographical information about object location or movement (Emmorey, Corina, & Bellugi, 2013).

3.3.2. Bimodal bilingualism

If regions that control the two languages are almost overlapping between unimodal bilinguals and monolinguals (see Paragraph 3.1.), for bimodal bilinguals a lower degree of convergence of the neural network that processes the two languages has been described (MacSweeney et al., 2002; Neville et al., 1998). Despite this statement, studies analyzing the functional and structural organization of bimodal bilingualism are still scant, and mainly focused on the comparison of bimodal bilingualism with deaf people or monolinguals. According to Poarch (2016), a very interesting way to understand how the bilingual brain organizes and shapes its connections during both language production and perception is to compare bimodal bilinguals and unimodal bilinguals. However, to date, there have been very few studies aimed at analyzing the differences both at the functional and structural level, between the two groups (e.g., Allen, Emmorey, Bruss, & Damasio, 2013).

Among the studies that compared bimodal bilinguals with unimodal bilinguals, Söderfeldt and colleagues (1997) showed unimodal bilinguals employ auditory regions when perceiving both the languages. In bimodal bilinguals the bilateral superior temporal cortices resulted in greater activation when perceiving spoken language versus signed language, whereas the occipitotemporal visual regions bilaterally resulted in more activation when perceiving signed than spoken language. In addition, Emmorey, McCullough, Mehta, and Grabowski (2014) found that the parietal cortex in both hemispheres was more engaged when perceiving sign language than speech. A similar pattern, in terms of activation's overlap and intensity, has been obtained in studies analyzing production processes. While in unimodal bilinguals both the languages engaged the same regions in production of speech, in bimodal bilinguals there is a higher recruitment of the parietal and the left posterior middle temporal cortex in both the hemispheres, when signing compared to speaking (e.g., Zou et al., 2012b). Thus, the data seem to confirm that the main difference between bimodal bilinguals and unimodal bilinguals with respect to the brain regions engaged for production and comprehension is the different degree of cross-language overlap (spoken/spoken - signed/spoken).

Because of the engagement of different effectors, bimodal bilingualism provides a fascinating chance to investigate the mechanisms of control and management of one language while the other one is ongoing. In fact, one of the characteristics of bimodal bilinguals is the unique ability to produce one of the two languages without any interference coming from the language not in use at the output level. This is due to the fact that the two languages, as already mentioned, employ different output systems, and can be used simultaneously (a phenomenon called *code-blending*; see Emmorey, Petrich, & Gollan, 2012). This “cost-free” mechanism cannot be applied to unimodal bilinguals, who have to focus on the target language and avoid interferences from the non-target one. For this reason, the amount of executive control engaged in these two populations seems to suggest different mechanisms (e.g., Bialystok, Craik, Green & Gollan, 2009).

Do bimodal bilinguals co-activate the non-used language when speaking/signing with the other one? Studies seem to suggest that they do, even if not in the same way as unimodal bilinguals. For example, Zou and colleagues (2012b) reported in bimodal bilinguals the activation of regions usually recruited for sign language production, when naming pictures in the spoken language. When bimodal bilinguals (compared to unimodal peers) were performing a picture-naming task in their L1 spoken language, they showed a greater engagement of the supramarginal gyrus, of the temporal gyrus and the superior occipital gyrus (visual area), all in the right hemisphere. Since these areas are also activated when producing sign language, the authors hypothesized an automatic activation of sign language when performing the production task in the spoken language. A confirmation of this hypothesis came from Emmorey and colleagues (2005). In their study, bimodal bilinguals and monolinguals were tasked with a production task consisting in naming spatial relations in English. With respect to monolinguals, bimodal bilinguals showed a stronger activation of the right parietal cortex, area usually engaged in the expression of spatial relationships for classifier constructions in sign language (Emmorey et al., 2005).

Hemispheric laterality in bimodal bilinguals. Allen, Emmorey, Bruss, & Damasio (2008) compared the gray matter volume in bimodal bilinguals with respect to deaf participants. They found differences at the level of the posterior insula, with increased volume in the posterior insula for deaf. In a most recent study (Allen et al., 2013), the authors also investigated the effect of congenital auditory deprivation on three main cortical regions that corresponded to the calcarine sulcus (occipital lobe, location of the visual cortex), pars triangularis and pars opercularis (inferior frontal gyrus, associated with language areas) and the precentral gyrus (motor hand area). From the comparison between deaf, bimodal bilinguals and hearing controls, they found a difference at the level of the calcarine sulcus and the pars triangularis, with a greater volume of these areas in deaf participants and no differences between hearings signers and hearing non-signers. Regarding the motor region of the precentral gyrus, there was a difference in the left-right symmetry degree, with a left asymmetry for deaf participants, a symmetrical pattern for hearing signers and a right asymmetry for hearing controls. These differences have been attributed to respectively auditory deprivation and sign language experience; specifically the volume modifications of the calcarine sulcus and pars triangularis seems to be associated with the deaf group, while the lateralization differences in the motor region, to an effect of sign language practice. Other differences between these populations have also reported in specific gray matter regions. The most influential structural studies are reported below.

Gray matter modifications. Zou and colleagues (2012a) analyzed structural plasticity in late but highly proficient bimodal bilinguals focusing on the role of the caudate nucleus in cognitive control. Voxel Based Morphometry and a language-switching task were used to assess if there were anatomical differences in the left caudate nucleus and if these differences were supported by the functional activation during a language-switching task. Bimodal bilinguals had to alternatively name pictures in the spoken or signed language (compared with a non-switching condition, which was naming pictures just in the spoken language). Voxel based morphometry in the two groups showed that bimodal bilinguals had greater gray matter volume in the left caudate nucleus, compared to a control group of monolingual peers. Moreover within the bimodal bilinguals, there was a correlation between the magnitude of the switching effect and the gray matter volume, so that the larger the effect, the larger was the volume of the left caudate. At the functional level, a greater activation of the head of the left caudate nucleus was also found in the switching condition with respect to the non-switching condition. These results replicated those collected with unimodal bilinguals (Abutalebi et al. 2008) and suggest an involvement of the head of the left caudate nucleus in bilingualism, regardless of the language modality. Abutalebi and collaborators hypothesized that the greater volume of the caudate nucleus might be the neurocognitive response to the increased processing demands associated to bilingualism.

White matter modifications. If we look at studies on white matter characteristics in bimodal bilinguals, to date there is only one study comparing the volume of the insula in deaf, hearings and bimodal bilinguals. The insula has been shown to play a role in multimodal sensory integration and to be involved in auditory processing of speech, speech articulation and motor planning (Augustine, 1996; Noesselt, Shah, & Jäncke, 2003; Dronkers, 1996; Ackermann & Riecker, 2004). Using MRI data, Allen and colleagues (2008) have found both changes in the gray matter (already presented previously at the beginning of this paragraph) and in the white matter volume. As for white matter differences, signers, both deaf and bimodal bilinguals, show a higher volume of the right insula with respect to hearing bilinguals. The authors interpreted this finding in the light of the higher cross modal sensory integration required for sign language with respect to spoken language. The connectivity of the insula was greatly enhanced in the signers who had acquired sign language early in life.

From this brief review of the literature it emerges that the study of white matter structure in bimodal bilinguals requires further development in order to investigate a series of factors such as, among others, understanding what are the core structures involved in language processing and to what extent these are modality independent. In the present thesis, and for the first time in the literature, white matter tracts and specifically, those included in the ventral pathway, have been compared in two very special populations: bimodal and unimodal bilinguals. Moreover, the DTI measures extracted from these tracts have been correlated with the performance in some behavioral tasks traditionally used for investigating language production and comprehension processes. In this way, the differences and commonalities that have emerged, could be ascribed to specific linguistic functions.

Part Two

CHAPTER 4

The Research: Exploring the ventral language pathways of the brain through bilingualism: a diffusion magnetic resonance imaging tractography study

4.1. Aims and experimental overview

The aim of the present research is to explore, for the first time, whether the ventral linguistic pathways of the brain can be modulated by the modality of a language. We do that by using diffusion magnetic resonance imaging tractography, in two populations of bilinguals: unimodal and bimodal bilinguals. The unimodal bilingual is a bilingual who knows two spoken languages, while the bimodal bilingual is a bilingual who knows one spoken and one signed language. A critical difference between these two populations is the fact that while unimodal bilinguals employ the same sensory modality channel for the two spoken languages, bimodal bilinguals employ different input-output channels for the two languages.

Most of the research that has explored white matter changes caused by bilingualism has been focused on unimodal bilinguals. It is documented that learning a second language may profoundly change both the gray and the white matter of the brain (see chapter 3.). The extent to which these modifications are language specific and not modality specific is still largely unknown. Comparing unimodal and bimodal bilinguals will allow us to understand which are the core brain structures involved in language processing and to what extent these are dependent to the modality of the language used. Adding this relevant piece of the puzzle in the understanding of the brain architecture, may allow to shed light on a debated issue, that is, whether language is based on abstract representations, as traditionally thought, or whether representations in language are strongly interconnected with sensory modality. No published work has examined so far these differences, at the level of white matter, between these two populations. Moreover, no studies have tried to correlate the anatomical characteristics of the white matter connections with behavioral measures of proficiency both in L1 and in L2.

In the present study, specific measures of neuroanatomical characteristics have been extracted from tractography data. Specifically, a series of white matter tracts associated with language have been dissected through the use of Spherical Deconvolution Tractography. In particular, as a first step of a larger project, for the present thesis I concentrated the work to three specific tracts of the ventral language system: the ILF, the UF and the IFOF. As described in Chapter 2, these tracts form the ventral pathways of the linguistic network (Catani & Mesulam, 2008; Catani & Thiebaut de Schotten, 2008). In order to understand how white matter organization is influenced by proficiency in language production and comprehension according to language modality, behavioral data have also been collected. Tractography data were then correlated with the behavioral data for the two groups of bilinguals in order to describe the pattern of differences observed across groups and across tasks. This approach has the high potential to contribute to the research of language in different respects. First, and most importantly, we will be able to investigate whether there are language modality effects by exploring whether a specific language process (task) in spoken and signed L2, are associated by differential brain tracts. Second, we will be able to better describe the role of the ventral tracts in each of the behavioral tasks used by exploring the correlation between performance in L1 and the tracts. Finally, we will be able to highlight the general effects associated to bilingualism by comparing L1 and L2 over and above the differences between the two modalities.

The whole project underlying this work is aimed at analyzing the white matter tracts of the whole linguistic system, however in the present dissertation, the focus will be given to one of the two language streams: the ventral one. This choice has been based on both theoretical and practical reasons. At the theoretical level, if we consider the studies on bilinguals investigating the plasticity of the language system in terms of white matter connections, it emerges that most of the studies focused on the dorsal stream and, in particular, on the AF, the tract that have identified at the "core" of the language function (see Chapter 1). Conversely, as seen in Chapter 1, the role of the ventral tracts in language processing has been more recently identified and it is still largely unknown. This is testified also by the fact that the scant number of studies aimed at exploring the role of the ventral tracts in language processing, have often produced inconsistent findings (see also Paragraph 2.1.). The practical motivation is related to the duration of the data extraction processes. As seen in Chapter 2, MRI acquisition is quite time efficient since it permits to acquire neuroanatomical images relatively quickly. On the other hand, the images processing and the variables extraction, which in our case is an operator-dependent procedure, is highly time consuming. For each tract and for each participant's brain, the operator has (a) to delineate the Regions of Interests (ROIs), (b) to perform the visual representation in 3D of the white matter tract and (c) to extract the corresponding measures. These steps usually take several months to be accomplished and the time required extends as a function of the number of both tracts and participants analyzed.

Recruiting a group of bilinguals with a range of proficiency in L2, we were able to increase the variability of the performances of participants in L2, and increase the probability of finding a correlation between the measure of white matter and L2 expertise. The level of proficiency varies from the status of *simultaneous bilinguals* (for unimodal bilinguals) or *CODA* (Children Of Deaf Adults; for bimodal bilinguals) which means that the two spoken languages have been acquired early in life and mostly at the same time, to *late bilinguals*, i.e. people who learned the second language later in life. In addition, in order to address different language processes, three different behavioral tasks have been used, specifically: a verbal fluency task, a picture-naming task and a sentence verification task.

The behavioral tasks used to assess language performance were aimed at testing both production and comprehension processes. For production, both fluency and picture-naming tasks have been chosen. For comprehension, a sentences verification task was used. The tasks were performed both in L1 and in L2. Performance in L2 allowed us to investigate both the role of the ventral tracts in L2 processing and to highlight eventual differences associated to the spoken and signed modality.

Verbal fluency task. The verbal fluency task is a verbal production test where the participant has to produce as many words as possible within one minute of time. We collected both semantic and phonological fluency data. The semantic fluency test asks the participant to retrieve the words belonging to a specific category (for example, the “animal” category). The phonological fluency test requires retrieving the words, beginning with a specific phoneme (for example, the “F” phoneme). This type of task is widely used in the literature to measure lexical retrieval, cognitive ability and executive control (see Roher, Wixted, Salmon, & Butters, 1995).

It has also been used in research on bilingualism since bilinguals seems to have an advantage in cognitive control skills compared to their monolinguals peers. Since verbal fluency is a test that measures not only linguistic competence (vocabulary knowledge) but also cognitive control, applying it to bilingualism allows for the validation of the interaction between these two variables (see Luo, Luk, & Bialystok, 2010). The fluency task seems to be interesting also with regard to bimodal bilingualism since it has been reported that bimodal bilinguals do not differ regarding cognitive control skills compared to unimodal bilinguals. Given that unimodal bilinguals employ for both languages the same output channel (which is the vocal tract), they are constantly faced with a “forced choice” as it is not possible, physically, to produce two different languages at the same time. This means that the unimodal speaker needs always to select between two (or more, depending of the languages known) possible alternatives for the same word. Conversely for the bimodal bilingual, since the channel for producing the languages are separate (vocal tract-hands), does not need to inhibit one language or the other, since the two languages may be produced at the same time (a phenomenon called code-blending). Moreover, bimodal bilinguals can produce both languages effortlessly, because cognitive control is not required when speaking/signing (see Emorrey, Borinstein, Thompson, & Gollan, 2008).

As for the differences between the semantic and the phonological fluency task, it has been suggested that the semantic fluency task is easier in term of words access than the phonological task. Semantic fluency task is reported to be easier in term of words access than the phonological task. In fact, during the retrieving of words belonging to the same semantic category, for example "animals", all the semantically associated words become automatically active. So, for the animal category, the activation of "cat" will also automatically activate "dog", "rat", "duck" and so on. This automaticity is explained by the fact that we usually represent words using semantic associations, and this interconnected association among semantically related words happens to an early level, even before moving to the phonological level, which is more elaborated (Levelt, 1989). For this reason, semantic fluency when compared to the phonological one, results as a more automatic and "effortless" process. Differentially, in the task of phonological fluency the process of retrieving the words on the basis of the first phoneme is much more effortful. The words are not semantically correlated and the automatic semantic links must be inhibited, in order to favor the production of words similar at the phonological level. This process likely requires higher executive control resources, since does not represent a common strategy used when organizing words representation. From this production task, we extract two main measures (for type of fluency), which represent valid indexes of proficiency/vocabulary and executive control: the mean number of words produced within the minute and the rate of production. The rate of production is defined as the slope of the function generated plotting the number of words against the time (Luo et al., 2010). The rate of slope ranges between 0 and -1, where 0 means a constant retrieval of words along the one minute, and can be considered synonym of higher general proficiency, and -1 indicating that some words are produced at the beginning of the minutes but then the number of words produced decreases rapidly or stops. With this measure, the retrieval speed, the vocabulary knowledge and executive control in verbal fluency performance can be assessed. These two measures will be finally correlated with the measures extracted from every white matter tract (see materials and method section for details).

In the *picture-naming* test, participants were asked to retrieve as quickly and accurately as possible the correct word of the object presented in a picture. This test dates back to Cattell (1886) and it is used ubiquitously in psycholinguistic research. It allows for the investigation of the retrieval processes as a function of the properties of the name of the picture. Even if this task seems quite simple to accomplish, it envisages a series of complex operations. First of all, the object needs to be visually recognized, and on the basis of the computed visual information the corresponding semantic representation should be activated. Finally, the correct lexical label should be retrieved form the entire pool of known words and a motor plan activated in order to allow articulation (Levelt et al., 1999; Barry, Hirsh, Johnston, & Williams, 2001; Johnson, Paivio, & Clark, 1996). Evidence shows that naming times in the picture-naming test are slowed down in bilinguals with respect to monolinguals (Gollan et al., 2011; Gollan et al., 2005; Martin et al., 2012). Based on this type of confirmations, the psycholinguistic literature introduced the idea of a "bilingual disadvantage" in language production. This disadvantage has been recently proposed by Geizen & Emmorey (2017) also for bimodal bilinguals.

Literature report several explanations for the bilingual disadvantage theory (Ivanova, & Costa, 2008). For example bilinguals' lowest performance versus monolinguals in tests requiring lexical retrieval could derive from an effect due to the frequency of use of the first language (see word frequency effect; Mägiste, 1979, Ransdell & Fischler, 1987). Bilinguals on average may use their dominant language less often compared to monolingual peers. For this reason, it is possible that the frequency values of lexical representations are lower, compared to those of monolinguals who only experience one language and so it can affect the availability of the lexical items in these types of task. Another explanation of this disadvantage may be the cross language interference, in the way that the two languages compete for the selection, slowing down lexical access processes (see Paragraph 3.1. of the present dissertation thesis).

We used two measures from picture-naming test as predictors of the two tract-specific measures. One measure, which is RT, highlights the lexical access speed. RTs are calculated from the point the object picture appears at the center of the monitor until the participant vocally produce the corresponding word (for Italian and English) or lifts the fingers from the keyboard (for LIS) in order to produce the corresponding sign. Accuracy, which is more a measure of vocabulary amplitude, was also collected (see materials and method section for details).

Sentence verification task. In order to collect measures sensitive to the comprehension processes in the two groups of bilinguals we set up an auditory/visually sentence verification task. With neuropsychological patients or with children, comprehension is usually tested through Peabody-test like measures, in which participants are asked to match sentences with pictures. This test is based on accuracy and in our study, run with proficient adults, it would have likely given a rough measure of proficiency or a ceiling effect. Therefore we devised a new task in which we asked participants to evaluate the acceptability of a series of short sentences. It has been shown that the ability to recognize whether a sentence is acceptable is one of the basic abilities of native speakers of a language. Indeed, the ability to recognize sentence-level violations has been widely used to determine how the human brain processes language. Following this literature we devised three sets of sentences in each of the three languages used, L1 (Italian), L2 (English) and L2 (LIS). In all cases the violation was present in the last word of the sentence. In order to tap different comprehension processes three types of violations were analyzed. Lexical violations aimed at investigating the processes involved in lexical access, semantic violations aimed at investigating semantic processing and syntactic violations aimed at investigating syntactic processes. The sentences were presented auditorily in Italian and in English and visually in LIS. This task allowed us to collect both accuracy and RTs and therefore provided sensitive measures of performance both in L1 and L2. We collected both accuracy and RT measures from the sentence verification test as predictors of the tract-specific measurements. Accuracy corresponds to the average of the correct responses for each condition, whereas RTs corresponds to the time (in millisecond resolution) for the participant to identify if the sentence is correct or incorrect (see materials and method section for details).

Statistical Analyses. Statistical analyses were performed using RStudio software (Version 1.1.383; https://www.rstudio.com/). Given that (a) there are no studies investigating the role of the ventral tracts in bimodal bilinguals, (b) the evidence about the role of the ventral tracts in L1 processing is quite inconsistent, (c) there are no past studies that have considered a whole set of behavioral tasks to asses language performance both in L1 and in L2, in the present study we adopted a data driven approach. Data analyses have been performed separately for each language and for tract and task, following a series of interrelated steps. First, we explored the relation between tract-specific measurements and behavioral measures through correlational patterns. For each task, we computed Pearson's correlations between tract-specific measures and the behavioral measures. We considered r > .30 as the cut-off and further explored only those correlations higher than the cut-off. For such correlations, regression analyses have been run, in which the behavioral measure was included as predictor and the tract-specific measure as the dependent variable. In the case than more than one behavioral variable correlated higher than .30 with the same tract measure, in the regression analyses we corrected the p value using Bonferroni. Given the prominent role of "age" and "age of L2 acquisition" in the development of white matter tracts, all models included also these variables as predictors (e.g., model=lm(DTI_Measure~Behav_Predictor+Age, data=d1)). In the cases in which the regression model was significant, we compared it with a further model including the interaction with the factor Group (e.g., model=lm(DTI_Measure~Behav_Predictor*Group, data=d1)). Significant interactions with the factor "Group" would indicate modality specific effects.

4.2 Materials and Methods

4.2.1 Participants

A total of 25 bimodal bilinguals and 29 unimodal bilinguals took part to the study, for a total of 54 participants. The participants' selection has been carried out through brochures placed at the universities where LIS/English are usually taught and learned, through meetings at the ENS (National Deaf Organization) based in Padova, thanks to the word of mouth of students, LIS interpreters, thanks to the contribution of the Convitto Statale per Sordi "Antonio Magarotto" in Padova and associations such as CODA Italia and MPDF Onlus (Mason Perkins Deafness Fund Onlus). The basic criteria were the participant's age, (18-42 years) and the right-handedness (which has been verified through the Edinburgh Handedness Inventory Test; Oldfield, 1971). Criteria for L2 knowledge were the different for English and LIS. We used the "*Quadro comune europeo di riferimento per la conoscenza delle lingue*" (QCER) for establishing the level of English knowledge and only selected people with a certified linguistic level equal to or greater than C1. Alternatively we selected people who lived in an English speaking country (for a minimum time of six month). For LIS we select people having a level 3 or above the level 3 of LIS knowledge. Generally, after the 1st level (level A1 of the European framework) an individual who learns LIS is able to express himself/herself with basic communication, which touches certain aspects of daily life and the person and also includes the meaning of a basic interaction in LIS, as: understanding, at least in part, the meaning of a conversation in sign language; expressing in the language by elaborating a message that is sufficient for mutual understanding. The purpose of the 2nd level can be summarized in increasing and improving the knowledge acquired with the 1st level through a lexical and structural enrichment of LIS skills. The 3rd level is a refresher course of LIS, therefore all the topics covered in the two previous levels must be taken up and deepened, with a greater focus on: lexicon, morphological structures, syntactic structures. The goal is to achieve complete mastery of the language, in all its aspects. This screening was based on a questionnaire exploring L2 learning and knowledge. A second screening phase was based on a second questionnaire, which verified the eligibility to take part in magnetic resonance examination. No participants with a history of neurological illness were included. Finally, two groups of right-handed adults bilinguals were selected to take part in the study. They all participated voluntarily. They received, read and signed a written informed consent. Participants that completed the entire research sessions received a monetary fee contribution, which amounted to 40 euros. The Ethical Committee for Psychological Research of the University of Padova has approved the research procedure and methods.

4.2.2 Acquisition and Processing of MRI Data

Information about how the acquisition of MRI data will be carried out has been given to participants. Then, a forced choice response questionnaire was answered in order to assess if every participant falls within the criteria for being subjected to the examination (e.g., if she/he suffers from claustrophobia, if she/he has a pacemaker or prosthesis of any type, etc.). In addition, a further informed consent form, specifically related to the MRI session, was completed before the examination.

MRI acquisition. Measures of diffusion imaging data were acquired in a single session per participant, using a magnetic resonance scanner Siemens Avanto 1.5 Tesla housed in the Padova University Hospital with actively shielded magnetic field gradients (maximum amplitude $45 mT/m^{-1}$).

The body coil was used for radiofrequency transmission, and an 8-channel head coil for signal reception. Protocol consisted of a localizer scan, followed by a single- shot, spin-echo, EPI sequence with the following parameters: TR=8500, TE=97, FOV=307.2×307.2 mm, matrix size=128×128, 60 slices (no gaps) with isotropic ($2.4\times2.4\times2.4 mm^3$) voxels. The maximum diffusion weighting was 2000 sec/mm^2, and at each slice location 7 images were acquired with no diffusion gradients applied ($b=0$ s/mm^2), together with 64 diffusion-weighted images in which gradient directions were uniformly distributed in space and repeated 3 times, in order to increase signal to noise ratio (SNR). Gains and scaling factors were kept constant between acquisitions.

MRI data preprocessing and processing. Every participant's raw image data has been carefully examined to detect abnormalities, any outliers in the data, including signal drop-outs, poor signal-to-noise ratio, image artifacts such as ghosts and subject motions. The participants (n = 4; see Paragraph 5.1. under "Final participants' sample"), with raw data containing volumes with significant image quality issues, were removed from further analyses.

Final DWI datasets were concatenated and corrected for subject motion and geometrical distortions using Explore DTI (http://www.exploredti.com; Leemans, Jeurissen, Sijbers, & Jones, 2009).

The Spherical Deconvolution approach (Tournier et al. 2004, 2007) was then chosen to estimate multiple orientations in voxels containing different populations of crossing fibers (Alexander, 2005). Spherical Deconvolution was calculated applying the damped version of the Richardson-Lucy algorithm with a fiber response parameter α =1.5, 400 algorithm iterations and η = 0.15 and ν = 15 as threshold and geometrical regularization parameters (Dell'Acqua et al., 2010). Fiber orientation estimates were obtained by selecting the orientation corresponding to the peaks (local maxima) of the FOD profiles. To exclude spurious local maxima, we applied both an absolute and a relative threshold on the FOD amplitude (Dell'Acqua et al., 2013). The first "absolute" threshold corresponding to a HMOA threshold of 0.2 was used to exclude intrinsically small local maxima due to noise or partial volume effects with isotropic tissue. This threshold was set to select only the major fiber orientation components and exclude low amplitude spurious FOD components obtained from gray matter and cerebro-spinal fluid isotropic voxels. The second "relative" threshold of 5% of the maximum amplitude of the FOD was applied to remove remaining unreliable local maxima with values greater than the absolute threshold but still significantly smaller than the main fiber orientation (Dell'Acqua et al., 2013).

Tractography Algorithm. Whole brain tractography was performed selecting every brain voxel with at least one fiber orientation as a seed voxel. From these voxels, and for each fiber orientation, streamlines were propagated using a modified Euler integration with a step size of 0.5 mm. When entering a region with crossing white matter bundles, the algorithm followed the orientation vector of the least curvature. Streamlines were halted when a voxel without fiber orientation was reached or when the curvature between two steps exceeded a threshold of 45°. All spherical deconvolution and tractography processing was performed using StarTrack, a freely available Matlab software toolbox developed by Flavio Dell'Acqua (NatBrainLab, King's College London), based on the methods described in Dell'Acqua et al. (2013).

ROIs delineation and tract dissection. We used TrackVis Software (http://www.trackvis.org; Wang, Benner, Sorensen, & Weeden, 2007) to operate a virtual dissection of white matter bundles in order to visualize the tracts of interest and quantify tracts specific measures. The approach used has been previously validated (Catani & Thiebaut de Schotten, 2008). Each of the tracts was defined using a two Region Of Interests (ROIs) approach according to the method provided by Catani and Thiebaut de Schotten (2008). To identify the tracts we used 3 ROIs in total: "Temporal" (T), "Occipital" (O) and "External/Extreme Capsule" (E) drawn, on average, in 5 consecutive slices of the brain's fractional anisotropy (FA) map. The "O" and "T" ROIs are needed for dissecting the ILF, the "T" and "E" for the UF and, finally, the "T" and "E" ROIs for the IFOF. The not ROIs have been used to exclude undesired streamlines.

This following procedure was performed manually for every participant. The "T" ROI, created from the axial view, was located in the anterior temporal lobe, all around the white matter and usually in 5 or 6 slices, depending on the anatomy of the single brains. It initiates three slices below the fronto-temporal junction of the anterior floor of the external capsule. It is important to exclude the most posterior part of the temporal lobe in order to avoid contaminations coming from other tracts. To define the "O" ROI, its border was first traced from the lateral view of the brain, medially, superiorly along the parieto-occipital sulcus and inferiorly along all the occipital lobe. Then, from the axial view, a ROI was drawn on the 13-15 slices around the occipital white matter, following the borders already defined. The lowest slice contains the white matter of the lingual and fusiform gyrus, the dorsal one always posterior to the cingulum. The "E" ROI was defined from the coronal view, tracing just the most anterior part of the external capsule for usually 5 slices. Every tract was manually corrected in case of false positive fibers wrongly included as part of the bundle with "not_ROIs". Finally, an expert in Tractography performed a double check of some of the tracts. An example of the final dissection, for each white matter tract, is shown in Figure 2.

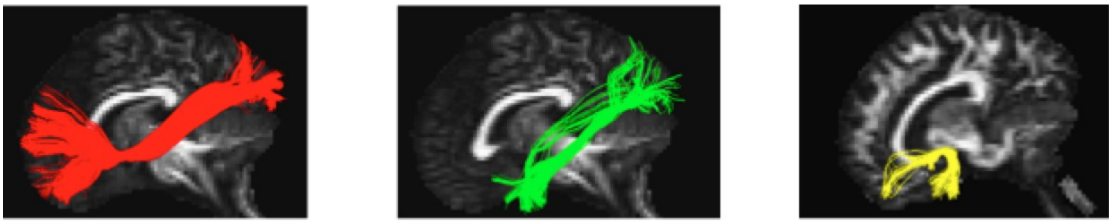

Figure 2. An example of the tractography dissection, performed on the left hemisphere in one participant. Higlighted, the three main tracts composing the ventral language network: in red, the white matter bundle which composes the IFOF, in green the ILF and in yellow the UF white matter tract.

Data extraction. After the dissection of the three tracts, the data had been extracted. In addition to the total number of fibers and total volume, other tract-specific measures had been extracted such as volume and HMOA.

The mean HMOA, calculated for each of the three tracts in each participant, is defined as the absolute amplitude of each lobe of the Fiber Orientation Distribution (FOD), and represents an index of the degree of tract anisotropy. HMOA was chosen over Fractional Anisotropy (FA, the measure which is usually adopted measure in most of the tractography study) because it is considered to be a tract-specific index, more sensitive to axonal myelination, fiber diameter, and axonal density (Dell'Acqua et al., 2013; see Chapter 2. of the present dissertation thesis). The volume was chosen arbitrarily over the number of streamlines since, from our analyses, it emerged that both the measures are highly correlated between each other.

4.2.3. Behavioral tasks

In a separate second session the participants performed the behavioral tasks and filled out the language questionnaire. Furthermore, a series of motor non-linguistic tests were administered to participants for purposes separate from the present thesis. Every linguistic test was performed in a fixed order of language, first in the L1 (Italian) and then in the L2 (English or LIS), and task order. This procedure was decided in order to ensure that both groups had the same level of "attentional cost" before performing the behavioral tasks in their respective L2. Behavioral tests were performed in the following order: (a) verbal fluency (b) Picture-naming (c) Sentence verification. The non-linguistic tasks were performed between the two language sessions, while the linguistic questionnaire were compiled at the end of the whole behavioral session. This second session was carried out in a quiet room at the Department of Developmental Psychology of the University of Padova after about 56 days (SD = 56.09), on average, from the first MRI session.

In addition to the behavioral linguistic tasks, motor measures (fine motor skills and spatial awareness data) were also collected. Specifically, the Purdue Pegboard Test (Tiffin & Asher, 1948) and Line bisection Test (see Cattaneo, Lega, Cecchetto, & Papagno, 2014) were used to extract indexes of fine motor skills for other purposes not related to the present study. Participants performed the tasks during a break between the two linguistic L1 and L2 sessions. In APPENDIX A the procedures are reported.

- Verbal Fluency Task

Procedure. The participant was seated in front a computer Acer Intel Core i7, display 17”. The participants were instructed to produce, as quickly and accurately as possible, all the words that come to their mind while trying to avoid repetitions, derivatives, personal and geographical names, all of which were considered errors. When tested in L1 (Italian) and L2 English participants received a pair of Microsoft LifeChat LX-3000 earplugs with a built-in microphone to record voice production. The entire minute of production was recorded using Audacity software. For recording the Verbal Fluency task in LIS, we used a camera in order to record the signs produced. We asked participant to place both the hands on the table placed in the front and to raise their hands each time they had to produce a new sign, and then put them back on the table. The starting point of every sign was calculated starting from the moment they raise the hands.

Stimuli. The semantic categories used in the Semantic Fluency task, were “Animali” (animals) and “Mezzi di Trasporto” (transports) in Italian and “Food” and “Clothes” in English and LIS. For the Phonological Fluency task, participants were asked to retrieve all the words beginning with the letter “F” and then with the letter “L” in Italian. For English we used the letters “S” and “P” and for LIS the hand configurations “1” and “B” (see Figure 3 below).

Figure 3. Configuration “1” and configuration “B” in LIS.

Scoring. As for the verbal fluency task, we adopted the same approach used by Sandoval, Gollan, Ferreira and Salmon (2010). For the after-test scoring, every audio (or video, depending on the second language assessed) was listened to/viewed and every word was manually recorded. To assess Accuracy, one point was given for every correct word retrieved within the minute; for each error (e.g., proper names, repetitions, etc.), a score of zero was assigned. For each response given the Response Time (RT), that is the millisecond (within the minute) corresponding to the beginning of each word, was also collected.

- Picture-naming Task

Stimuli. We selected, from pre-existing databases (Alario, & Ferrand, 1999; Dell’Acqua, Lotto, & Job, 2000; Bonin, Peerman, Malardier, Méot, & Chalard, 2003), 50 colored pictures of concrete objects. Based on the *Corpus e Lessico di Frequenza dell'Italiano Scritto* (CoLFIS) for Italian and LIS and CELEX *Lexical Databases of English* for English, we selected 25 high frequency (HF) object names and 25 low frequency (LF) object names for Italian and 25 HF picture names and 25 LF picture names for English and LIS. Despite the CoLFIS database corresponds to the Italian corpus of frequency, it has been shown to be sensitive to the frequency in LIS as well (see Navarrete, Caccaro, Pavani, Mahon, & Peressotti, 2015). For this reason, the word frequency values for Italian and LIS were derived form the same database. For Italian, the mean frequency of HF words was 339.4 (Standard Deviation, SD = 570.86). The mean frequency of LF words was 12.8 (SD = 11,18). For L2 LIS, the mean frequency of HF words was 266 (SD = 285,02), whereas for LF it was 14 (SD = 7,70). Lastly for English, the HF words had a mean frequency as 28943 (SD = 24541,98), the LF words instead has a mean frequency that corresponds to 3587 (SD = 4830,09).

Items' category was also balanced across languages and the categories used were selected to be as varied as possible (fruits, tableware, body parts, objects, clothes, furniture, tools, animals, transportation etc.). The phonological length of every word was also checked (for the details see the APPENDIX B).

The same set of 50 pictures was presented twice, in distinct blocks, with a different randomized order for each participant. The two blocks were separated by a brief pause lasting not more than few seconds, according to participants' personal decision. The colored pictures were presented on the monitor of the computer at the center of a white 400x400 mm template, which appears in the center of a white screen. Before proceeding with the test, a trial session containing 6 items was performed in order to assure the participant understands the task instructions.

Procedure. The pictures were presented twice via DMDX software (Forster & Forster, 2003) for Italian and English and via E-prime (Schneider, Eschman, & Zuccolotto, 2002) for LIS. In the Italian and English conditions, participants were seated in front a computer and were provided by earplugs with a sensitive built-in microphone to record voice sound (adjusted to optimal distance from the participant's mouth) that were connected to the computer. Every picture was presented for 2000 ms or until the participant produced the response. Between every picture, a fixation point "+" appears for 500 ms. The vocal response of the participant was also recorded and checked posteriorly for accuracy.

When the task was performed in LIS at the beginning of each trial participants were instructed to press the "Z" and "M" keys on the keyboard with the left and right hand indexes respectively. A fixation cross "+" was presented for 500 ms and then the target figure appeared on the screen until the participant removed the fingers from the keyboard to sign for a maximum time of 3000 ms. A camera recorded the performance in LIS in order to check for accuracy. For both first and second language, six training trials were presented to participants before the experimental session in order to familiarize with the task.

Scoring. Mean RTs and accuracy scores were calculated for every language. In Italian and English, the RT interval between the appearance of the target picture and the beginning of the response given by the participant was checked manually through Check-Vocal software for every trial (Protopapas, 2007).

In LIS we measured the interval between the presentation of the target picture and the release of either the Z or M key. Incorrect naming of the figure and verbal disfluencies (stuttering and corrections after a previous incorrect name) were considered errors and not included in the RTs analysis. Response latencies faster than 200 ms or slower than 4000 ms were considered outliers and not included in the RTs analysis.

- Sentence Verification Task

Stimuli. Ninety correct sentences and 90 incorrect sentences, for a total of 180 sentences per language (Italian, English and LIS), were created *ad hoc*. Every sentence was composed by a minimum of 4 words/signs and a maximum of 9 words/signs and all of them share the same syntactic structure (see APPENDIX C for the list of the sentences used). The sentences for Italian and English were designed as follows. The 90 correct sentences were not ambiguous sentences composed by a noun and a verb phrase, for example the sentence "*The birthday party begins in the afternoon*". The incorrect sentences contained one of three types of violations always presented in the last word of the sentence. Thirty sentences contained a semantic violation. In this case the last word did not fit with the preceding context such as "*The cheerful carpenter builds a innovative sarcasm*". Thirty sentences contained a lexical violation. In this case the sentence ended with a pseudo-word, such as: "*The black piano is played by the gloost*".

Thirty sentences contained a syntactic violation. For English and Italian a morphological violation was related to number or grammatical gender, such as "*The rich taxi driver has a fast cars*".

The LIS sentences have been created following the same structure adopted for Italian and English.

For the semantic violations, sets of 30 sentences without a possible meaning were created (the last sign was not coherent with the rest of the sentence meaning).

For the lexical ones, 30 sentences with a non-sign placed at the end, were created. To generate the non-signs, we checked across sign language dialects to assure there were non-signs, which may have a meaning for some participants.

Lastly, for the 30 syntactic ones, different types of violations were generated:

(1) The spatial object-verb / action location concordance was controlled. For example, in the sentence "The kid takes a flower" (which is in Italian "Il bambino il fiore prende", written following the structure used in LIS), the verb "takes" referred to the flower was signed in a different location and not in the same location where the sign corresponding to "grass" has been signed (see Figure 4).

(2) The position of a negation placed at the end in phrases where there is an action already finished or completed (usually labeled with "done", in Italian "fatto"), as in the example "The biology test has been done not", (which is in Italian, LIS adapted "L'esame di biologia passato fatto non").

Figure 4. An example of a syntactic violation, where the spatial location where the flower should be taken is not respected. In order, the sign for "garden" (1); the sign for "flower" (2); the action of "takes the flower" in a different spatial location, where the garden was not signed before (3). The images are taken from our comprehension task as example.

The sentences in Italian and English were read by a female Italian-English bilingual and audio-recorded. The sentences in LIS were signed by a native deaf speaker and video-recorded.

The 180 sentences of each language were presented in a randomized order. After a block of 30 trials, there was a break in stimuli presentation allowing participants to take a rest. They restarted the experiment by pressing the space bar.

Procedure. The sentences were presented auditorily in Italian and English and visually in LIS, using DMDX Software (Forster & Forster, 2003). Participants were positioned in front of a computer screen. At the beginning of each trial a fixation cross "+" appeared on the center of the screen for 1500 ms. Before the experimental task, six training trials not included in the experimental list (three correct and three incorrect, one for each type of violation), were presented to participants in order to familiarize them with the task. Participants were instructed to press the "B" key of the computer keyboard when the sentence was correct and press "N" key when the sentence was incorrect.

Scoring. For the analysis of the sentence verification task, both RT and accuracy were collected. The sentences varied in their duration and therefore participant's response depended on the duration of the stimulus. To control for this source of variability, we operated a transformation of the RTs so that each RT was divided by the duration of the sentence (RT/Duration). Besides RT, the accuracy was also recorded.

Lastly, qualitative data and non-verbal intelligence were also recorded.

- Language proficiency and demographic data questionnaires

The participant completed a questionnaire created *ad hoc* in order to collect some L2 qualitative data. Among the various questions, a Likert scale (1–10) was adopted to measure participants' L2 proficiency, which is widely used in bilingual research and is significantly correlated with objective measures of language proficiency (Marian, Blumenfeld, & Kaushanskaya, 2007). The collected data about L2 production and comprehension, percentage of L2 daily use and other proficiency details are shown in table 1, Chapter 5. The complete questionnaire with the relative scale can be found in APPENDIX D.

In addition, language proficiency was further tested through the Multilingual Naming Test (MINT) by Gollan Weissberger, Runnqvist, Montoya and Cera (2012). This test is composed by 68 pictures presented with a fixed order of frequency (from the more, to the least frequent). We translated the picture names in Italian Sign Language and we administer this test to both the bilingual groups (see APPENDIX E for the test administration).

-Non-verbal intelligence test (Raven, Court, & Raven, 1977; Italian version 2008)

This test is composed by a series of matrix (with a rectangular design in which a part is missing). In the second part of the sheet, a series of alternative drawings are presented. The task the participant needs to perform is a forced choice to choose the only piece among the six alternatives, which correctly completes the figure. The cards become progressively more difficult giving an idea of the degree of development of non-verbal skills.

Procedure. Four of the five sections were administered (A, B, C and D). Every section was composed by 12 matrixes each. Two different RTs were also collected: the total RT and the RT for each section. The test book was placed in front of the participant on an empty table. After the instruction, the first matrix of the first group (matrix 1, section A) was completed together to ensure that the task was correctly understood. Furthermore, the participant was told not to rush and to think about the responses carefully. The RT was taken but not to assess the participant speed. On another sheet the experimenter wrote the answers given during the test session.

Scoring. To ensure the participants that the two groups were matched for non-verbal intelligence and were included within the average of the population distribution, both Accuracy and RT (in milliseconds) were collected. One point was given for every corrected matrix. The total maximum score was 48 points, indicating that the participant completed every item of the four sections correctly.

CHAPTER 5

Statistical analyses and results

5.1. Final participants' sample

Four unimodal bilingual participants were excluded due to artifacts (i.e., motions and signal drop-outs) in the MR images, and one bimodal bilingual participant was excluded due to technical problems during the behavioral tests. The group of unimodal bilinguals was composed by 25 participants (8 males; mean age = 25.4 years, SD = 4.93), the group of bimodal bilinguals by 24 participants (1 male, mean age = 27.79 years, SD = 6.01). All participants were Italian native speakers. See Table 1 for information regarding L2 history in the two groups.

	Italian-English Unimodal Bilinguals	***Italian-LIS Bimodal Bilinguals***
L2 knowledge in years	18.56	11.08
	(5.20)	*(10.14)*
Age of first L2 exposition	6.04	16.7
	(1.54)	*(7.84)*
Self-report proficiency in comprehension	7.8	7.29
	(1.19)	*(1.92)*
Self-report proficiency in production	7.2	7.08
	(1.22)	*(1.88)*
% of daily use	47.92	42.08
	(20.79)	*(24.88)*

Table 1. Mean and standard deviation (in brackets) of the main linguistic details extracted from the language background questionnaire.

The two groups were matched for non-verbal intelligence skills, tested by the use of the Raven Standard Progressive Matrices (unimodal bilinguals: mean = 41.61, SD = 2.68; bimodal bilinguals: mean = 40.12, SD = 5.39). Overall, the two groups of participants did not differ in terms of age, non-verbal intelligence skills, and in the self-report proficiency in L2 both in production and in comprehension (ps < .14).

5.2. Statistical analysis

Two levels of analyses were performed on the final pool of 49 participants. In a first step, we focused the differences on white matter measures. In order to check for morphological changes due to type of bilingualism, we looked for significant overall differences between the two groups of bilinguals in two depended variables, HMOA and Volume. Then, we explored whether age had some effect on the HMOA and Volume values trough regression analyses. All these analyses were performed on HMOA and Volume measures and in the left in the right hemisphere of each of the three ventral tracts, separately. For all analyses, the level of statistical significance was set at p < .05.

In a second step, we aimed at exploring whether language modality (signed versus spoken) affected the microstructural characteristics of the ventral white matter tracts, through correlations with behavioral measures. In order to identify which one of the three white matter tracts analyzed is sensitive to language modality, we adopted the following approach. Correlations between the tract-specific measurements and performance in behavioral tasks were calculated across all participants. Since each of these behavioral tasks addresses specific linguistic processing, we assumed that each task would engage specific brain circuits; for this reason analyses were performed separately by task. Pearson correlations higher than .30 were further explored in regression analyses, testing for the interaction with the factor “Group” in order to identify language modality effects. The same analyses were conducted considering L1 behavioral measures in the whole sample of participants. In this case, the interactions with the factor “Group” would indicate differences in L1 processing likely due to L2 language modality. Note that for L1 the likelihood of finding strong correlations is lower, given that all our participants were native Italian speakers and their performance in L1 is not so variable as in L2.

Overall, such an approach allows us investigating language modality effects and it could also give interesting hints on the role of the ventral tracts in linguistic processing.

5.2.1. Overall group differences on tract-specific measures

Gaussian distribution was confirmed for the white matter measures using the Shapiro–Wilk test (ps > .15). Means and Standard Deviations (SD) are reported in Table 2. Analyses of Variance were performed with a within-subject factor, Hemisphere (two levels: left and right) and a between-subject factor, Group (two levels: Bimodal and Unimodal).

As for the Volume, the ANOVA on the ILF tract did not report significant effects, Fs < 1. In the UF tract, the main effect of Hemisphere was significant, $F = 5.95$, $p = .019$, $\eta^2 = .112$, while the effect of Group and the interaction between these factors were not significant, Fs < 1. For the IFOF, no significant effects were found, ps > .14.

As for the HMOA measure, the analyses showed a significant effect of Hemisphere in all three tracts: ILF, $F = 28.73$, $p < .001$, UF, $\eta^2 = .379$; UF, $F = 14.06$, $p < .001$, UF, $\eta^2 = .230$; and IFOF, $F = 9.079$, $p = .004$, $\eta^2 = .162$. The effect of Group (ps > .19) and the interaction between these two factors (ps > .25) were not significant. Overall, the results suggested that the two groups of bilinguals do not present differences at the level of tract-specific measures in any of the three tracts analyzed. It is worth remarking here that this result is not surprising, given the variable L2 proficiency level within each of the two bilinguals groups.

	Italian-English Unimodal Bilinguals				***Italian-LIS Bimodal Bilinguals***			
	Left Hemisphere		*Right Hemisphere*		*Left Hemisphere*		*Right Hemisphere*	
	Volume	*HMOA*	*Volume*	*HMOA*	*Volume*	*HMOA*	*Volume*	*HMOA*
ILF	2425	0.072	2396	0.065	2296	0.070	2353	0.065
	(522.91)	*(0.01)*	*(493.28)*	*(0.00)*	*(451)*	*(0.01)*	*(554.75)*	*(0.01)*
IFOF	2413	0.088	2443	0.084	2232	0.086	2256	0.084
	(487.11)	*(0.01)*	*(499.43)*	*(0.01)*	*(511.18)*	*(0.01)*	*(446.26)*	*(0.01)*
UF	606	0.046	704	0.049	528	0.043	643	0.047
	(381.52)	*(0.01)*	*(174.60)*	*(0.01)*	*(248.09)*	*(0.01)*	*(193.06)*	*(0.01)*

Table 2. Mean and standard deviation of Volume and HMOA values in the three tracts, divided for each hemisphere and for group.

The regression analysis did not show effect of Age for the variable Volume in any of the three tracks. By contrast, participants' Age modulated HMOA value in the left ILF, β= - 0.01382; SE = 0.00485; t = - 2.849; p = 0.0065, showing that the younger was the participant, the higher was the HMOA (see Fig. A1). No other effect of Age was found.

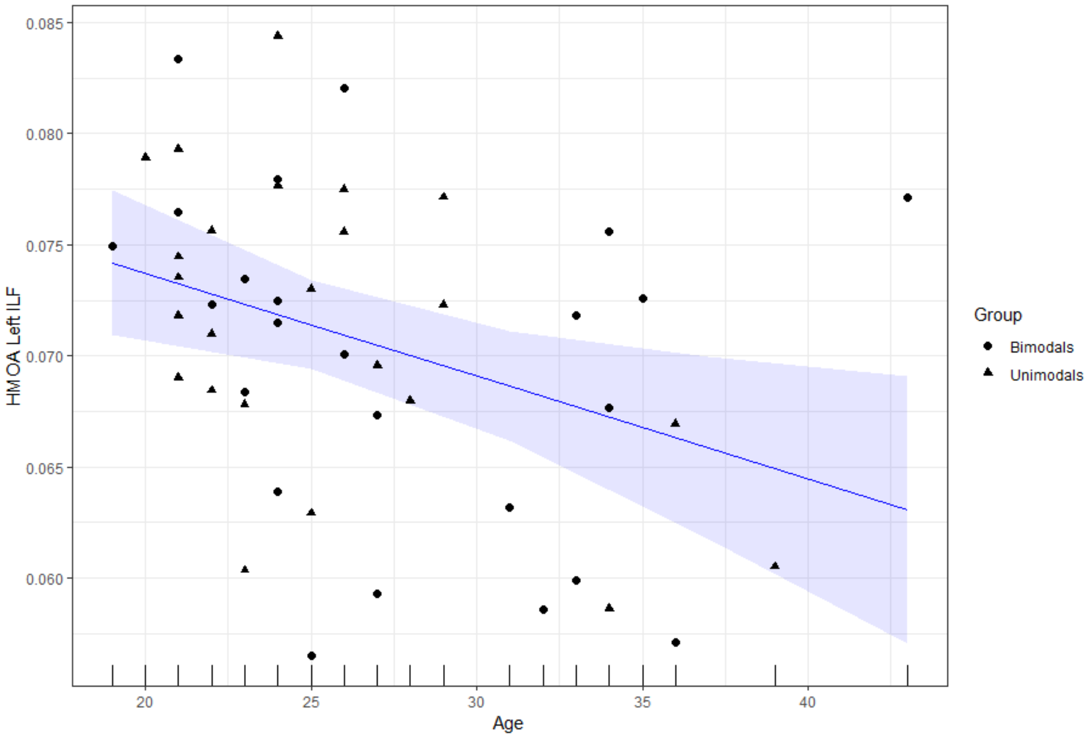

Fig. A1. The effect of Age of participants on the HMOA values in the left ILF.

5.2.2. Correlations between behavioral measures and tract-specific measures

As detailed above, analyses were performed separately by behavioral task (verbal fluency, picture-naming and sentence verification). In the first part, correlations were performed between Volume and HMOA and L1 performance measures. Then, the same diffusion measures were correlated with L2 behavioral tasks.

5.2.2.1. Verbal Fluency task

In this task, participants were required to retrieve all the words they could in a minute of time. In the semantic condition they have to retrieve the words according to a cued semantic category and in the phonological condition they have to retrieve the words beginning with a given letter (in Italian and English) or signed with a given hand configuration. From this task we extracted two behavioral measures: the number of words retrieved in the minute and the slope of the time-course retrieval curve. More negative slope values indicate that the large majority of the words were produced in the initial part of the minute, whereas values near to zero indicate that the rate of word production was nearly constant throughout the minute. In general, the closer is the slope to zero, the higher can be considered the performance in this task.
Table 3 reports the mean and the standard deviation of the number of word retrieved in each condition and for each group. Table 4 reports the slope of the retrieval curve.

	L1		L2	
Fluency Type	Bimodal	Unimodal	Bimodal	Unimodal
Semantic	17.1 (3.4)	18.2 (2.8)	14.4 (3.5)	15.1 (2.9)
Phonological	14.2 (2.9)	14.1 (3.2)	8.9 (1.9)	13.3 (2.3)

Table 3. Mean number of words retrieved in the semantic and phonological task for each group.

	L1		L2	
Fluency Type	Bimodal	Unimodal	Bimodal	Unimodal
Semantic	-1.22 (0.41)	-1.27 (0.37)	-0.61 (0.22)	-0.9 (0.26)
Phonological	-0.69 (0.32)	-0.71 (0.22)	-0.29 (0.18)	-0.58 (0.22)

Table 4. Mean and standard deviation of the slope of the time-course retrieval curve the semantic and phonological condition for each group.

L1 Italian

Considering the behavioral variables (i.e. mean number of words and slope of the time-course retrieval curve) and the tract-specific variables (HMOA and Volume) in the three tracts, there were two correlations with an r-value > .30. The mean number of words produced in the semantic task was negatively correlated with the Volume of the right ILF and the slope in the phonological condition was positively correlated with Volume of the right IFOF. In order to test for the causality relation, we entered these variables in regression analyses with the tract-specific measures as dependent variables and behavioral measures as predictors. The mean number of words produced in the semantic task significantly predicted the Volume of the right ILF, $\beta = -46.86$, SE = 23.19; t = - 2.02, p = .04. This effect did not interact with the predictor Group, p = .52, indicating that it this trend was present in both groups of bilinguals. As can be seen in Figure A2, the mean of the number of words that were retrieved in the semantic fluency task in Italian increased as the Volume of the right ILF decreased.

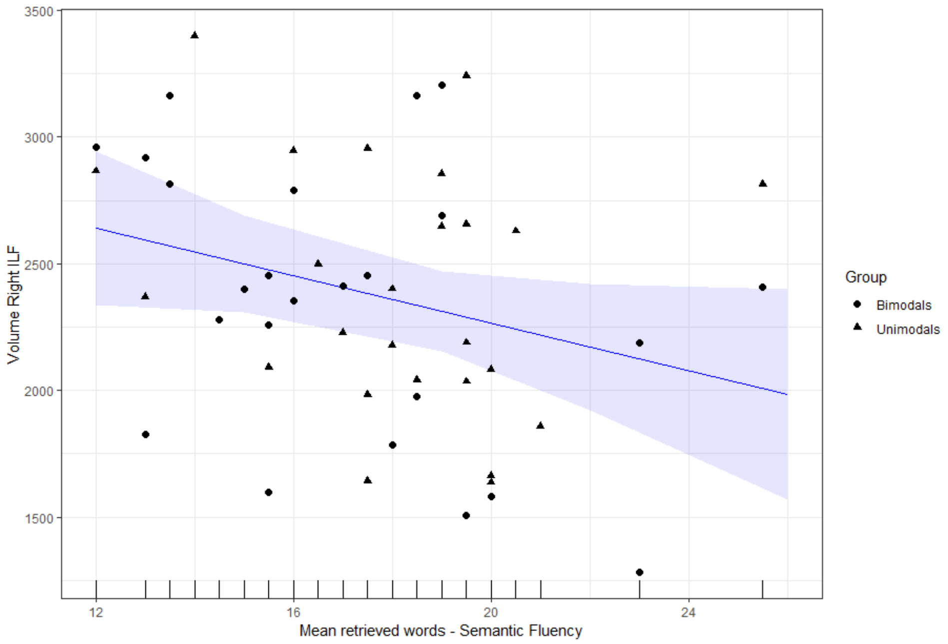

Fig. A2. The volume of the right ILF as a function of the mean number of retrieved words, in the semantic condition in L1.

The effect of the slope of the retrieval curve on the Volume of the right IFOF was also significant, $\beta = 596.4$, SE = 247.1; $t = 2.41$, $p = .01$. There was no interaction with the predictor Group, $p = .13$, indicating that this trend was present in both groups. As can be seen in Figure A3, the closer was the value of the slope to zero, the larger was the Volume in the right IFOF.

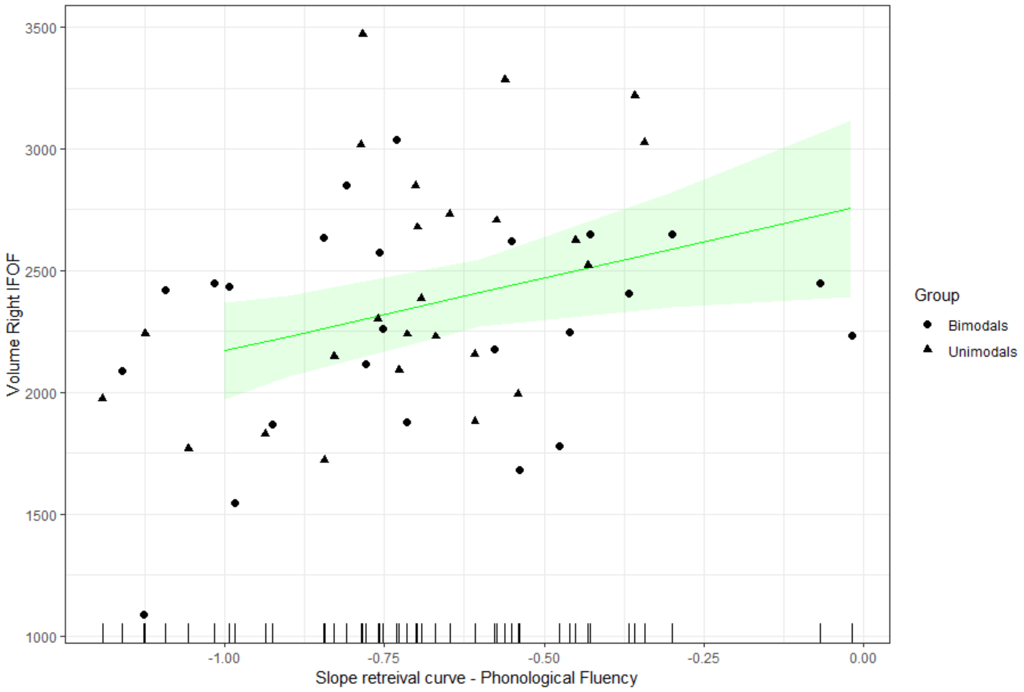

Fig. A3. The volume in the right IFOF as function of the slope in the Phonological fluency task.

L2 - English and LIS

Unimodal bilinguals - English

Four correlations resulted to have a value above r = .30, and all referred to the semantic fluency task: the slope of the retrieval curve in was correlated with (a) the Volume of the right ILF, (b) the HMOA of the right ILF and (c) the Volume of the left UF, the mean number of retrieved words was correlated with the HMOA of the left ILF. The regression analyses performed with the behavioral variables as predictors showed that the slope of the retrieval curve significantly predicted (a) the Volume of the right ILF, β = - 810.5; SE = 365.5; t = - 2.218; p = 0.0367, (b) the HMOA of the right ILF, β = 0.008899; SE = 0.003431; t = 2.593; p = 0.0162, and (c) the volume of the left UF, β = 594.7; SE = 285.7; t = 2.081; p = 0.0487. Moreover the mean number of words produced, predicted the HMOA value of the left ILF, β = - 0.0009184; SE = 0.0004229; t = - 2.172; p = 0.0404. In particular, the closer was the slope to 0 (indicating higher proficiency in L2) in the semantic condition, the smaller was the volume of the right and left ILF and the larger was the volume in the left UF. As for the HMOA, it was smaller as the slope was closer to zero in the right IFL. This pattern was reversed in the left ILF where higher values of HMOA were associated to slope values near to zero.

Bimodal bilinguals - LIS

The correlations resulting stronger than r = .30 involved the following variables: in the semantic fluency task the slope of the retrieval curve was correlated with (a) the Volume of the left ILF; (b) the Volume of the right ILF; (c) the HMOA of the left UF; in the phonological fluency task the mean number of words produced correlated with the Volume and the HMOA the left UF

Regression analyses revealed that the slope of the retrieval curve in the semantic condition significantly predicted the Volume of the left and the right ILF ($\beta = 861.9$; SE = 391.4; $t = 2.202$; $p = 0.0384$ and $\beta = 1043.2$; SE = 483.1; $t = 2.159$; $p = 0.042$, respectively) but not the HMOA of the left UF ($p = 0.10$). The mean number of words produced in the phonological condition significantly predicted the Volume and the HMOA of the left UF ($\beta = - 53.71$; SE = 24.73; $t = - 2.172$; $p = 0.040918$ and $\beta = - 0.002320$; SE = 0.001052; $t = - 2.205$; $p = 0.0382$, respectively).

Contrary to what found for unimodal bilinguals in the semantic condition, in bimodal bilinguals the better was the performance (i.e. slope of the time-course retrieval curve closer to 0) the larger was the Volume of both the right and the left ILF. As for the phonological condition, the mean number of words produced was inversely correlated with the Volume and the HMOA of the left UF.

Interactions with Group

In order to detect modality specific effects, we tested each of the effects found in the two groups in a regression model with "Group" as additional predictor. A modality specific effect was identified when the effect significantly interacted with group.

The interaction with group was significant for the following effects in the semantic fluency task:

(a) Slope of the retrieval curve and Volume of the right ILF (β = - 1853.7, SE = 599.4, t = - 3.093; p = 0.00340). Figure A4 illustrates the interaction. For unimodal bilinguals, the closer was the slope to zero, the smaller was the volume in the right ILF. The effect reversed in the bimodal bilinguals group, with larger volume in the right ILF associated to slope values closer to zero.

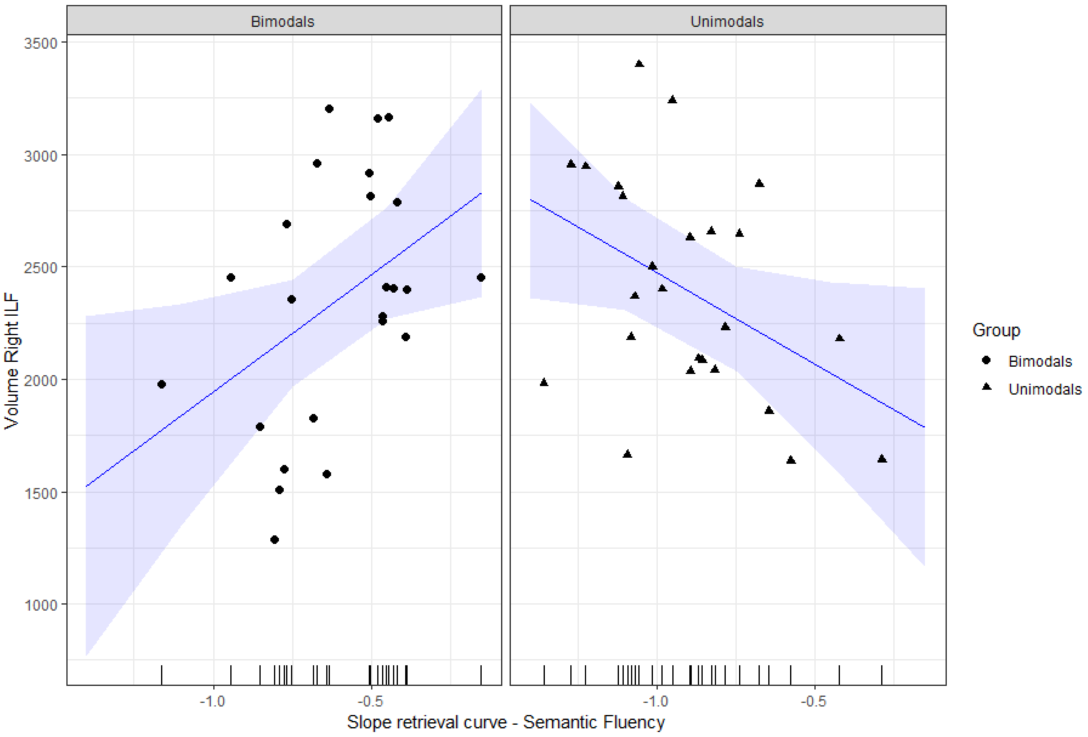

Fig. A4. The panel on the left reports the effect of the slope of the retrieval curve in the semantic condition on volume of the **right ILF** in the bimodal bilingual group. The panel on the right reports the same effect in the unimodal bilingual group.

(b) Slope of the retrieval curve and Volume of the left ILF (β = - 1468.3; SE = 575.5; t = - 2.551; p = 0.0142). As illustrated in Figure A5, for bimodal bilinguals, the closer was the slope to zero, the larger was the volume in the left ILF, whereas for unimodal bilinguals the effect reversed, even if not significantly.

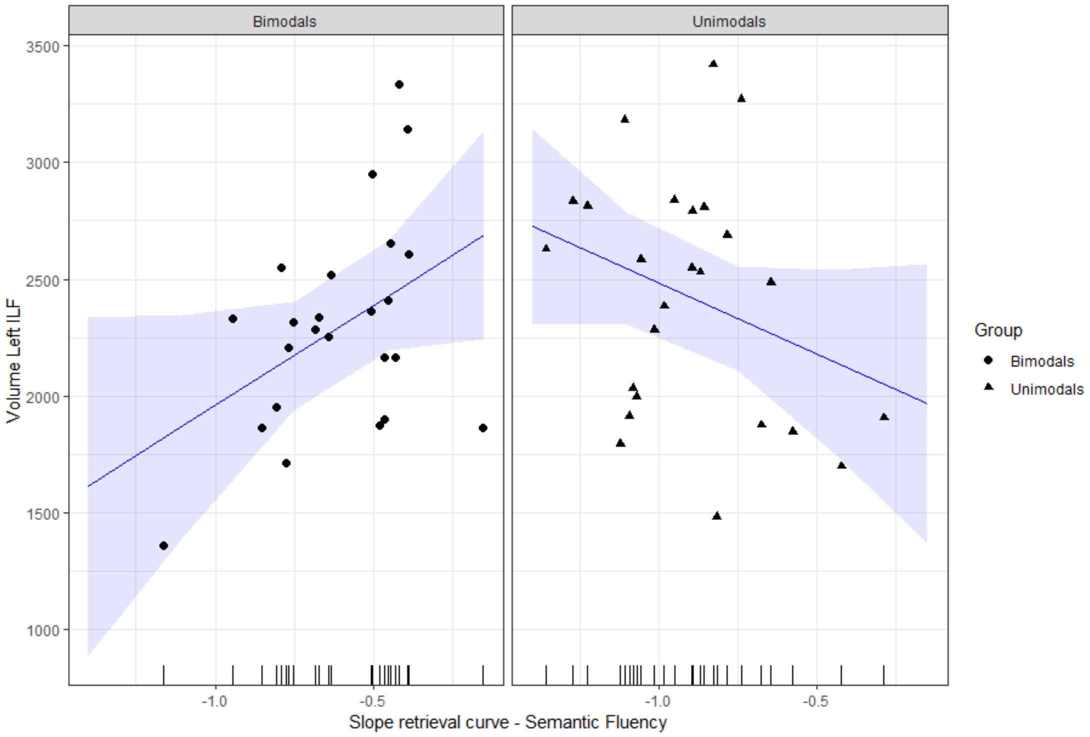

Fig. A5. The panel on the left reports the effect of the slope of the retrieval curve in the semantic condition on volume of the **left ILF** in the bimodal bilingual group. The panel on the right reports the effect of the slope of the retrieval curve in the semantic condition on volume of the left ILF in the unimodal bilingual group.

(c) Slope of the retrieval curve and the Volume of the left UF (β = 805.9; SE = 381.0; t = 2.115; p = 0.0400). For unimodal bilinguals (speaking English), the closer is the slope to zero, the higher is the volume in the left UF. For bimodal bilinguals (signing LIS), the effect is reversed, while not significant. This pattern is illustrated in Figure A6.

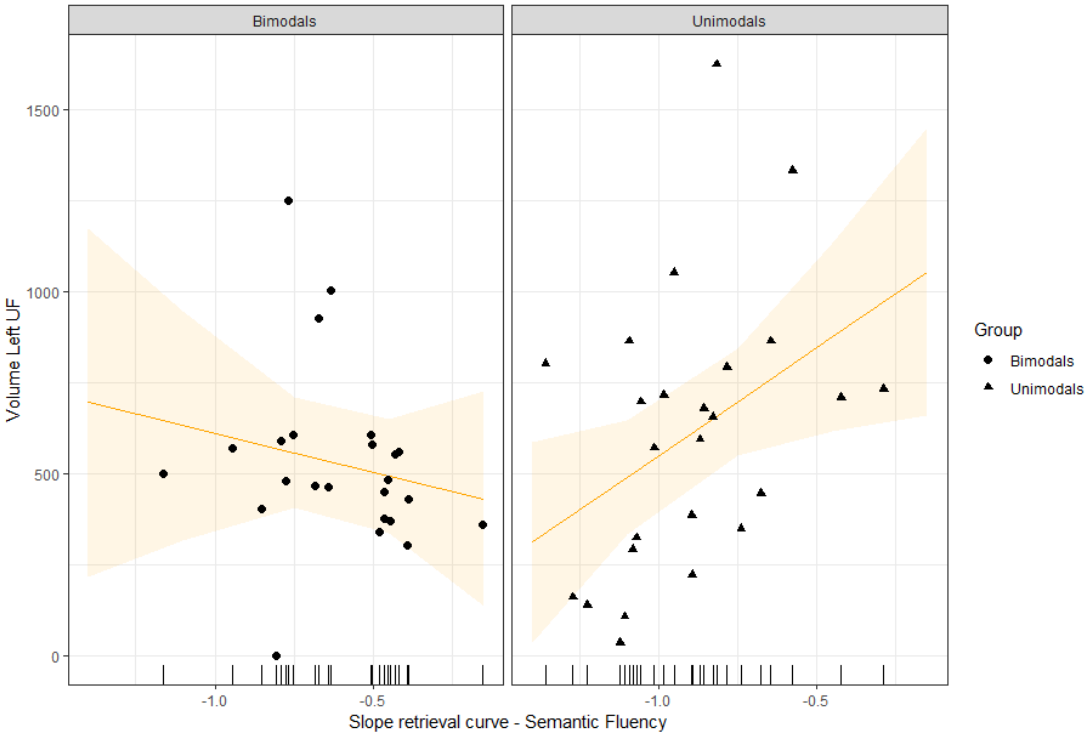

Fig. A6. The panel on the left reports the effect of the slope of the retrieval curve in the semantic condition on volume of the **left UF** in the bimodal bilingual group. The panel on the right reports the effect of the slope of the retrieval curve in the semantic condition on volume of the left UF in the unimodal bilingual group.

The effect of the slope of the retrieval curve on the HMOA of the right and left ILF, that was found in the unimodal bilingual group did not interacted significantly with Group (p = .36 and p= .12, respectively). This suggests that even if the effect of the slope on HMOA was significant only for unimodal bilinguals (i.e. in English), we could not conclude that the effect was absent in the case of bimodal bilinguals (i.e. in LIS).

In the phonological fluency task, two interactions with the predictor Group were tested. The effect of mean number of retrieved words in LIS for the bimodal bilingual group predicted both HMOA and Volume of the left UF. Only for HMOA the interaction with Group was significant (β = 0.0027035; SE = 0.0011203; t = 2.413; p

= 0.0200). Figure A7 shows the pattern obtained. For bimodal bilinguals, the larger the number of words retrieved (in LIS), the lower was the HMOA of the left UF. For unimodal bilinguals, instead, the number of words (in English) did not predict HMOA. As said, the effect of mean number of word retrieved on the Volume of the left UF that was found for bimodal bilinguals did not interact with group (p = 0.20).

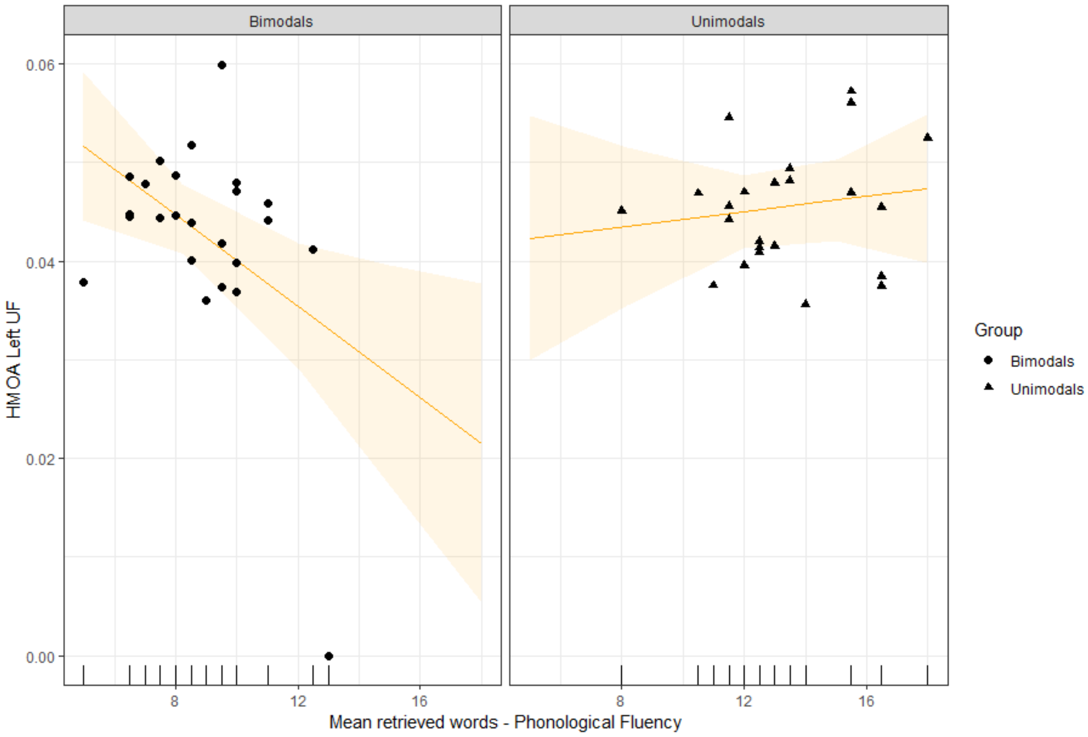

Figure A7. The panel on the left reports the effect of the number of words retrieved in the phonological condition on HMOA of the **left UF** in the bimodal bilingual group. The panel on the right reports the same effect in the unimodal bilingual group.

5.2.2.2. Picture-naming task

In this task participants were required to name a series of pictures varying as a function of the frequency of their names. All pictures were presented two times in two separate blocks. Both mean error rates and latencies were extracted from this task. Errors have been excluded from the analysis applying the criteria reported in the "scoring session".

On average, when responding in Italian, bimodal bilinguals made a percentage of errors equal to 5.58 (SD = 1.65), and unimodal bilinguals equal to 4.72% (SD = 1.24). The percentage of errors split by group and by word frequency, is shown in Table 5.

	Group	
Frequency Type	Bimodal	Unimodal
High Frequency	1.4 %	1.6 %
Low Frequency	9.3 %	7.9 %

Table 5. Mean error rates in the Picture-naming task in L1- Italian reported separately for each group and each word frequency condition.

When responding in L2, bimodal bilinguals made a percentage of errors equal to 8.63% (SD = 6.04) and unimodal bilinguals equal to 26% (SD = 20.8). See table 6.

	Group	
Frequency Type	Bimodal	Unimodal
High Frequency	3 %	8.1 %
Low Frequency	22.8 %	42.9 %

Table 6. Percentage of errors for L2 (LIS and English) in the picture-naming task.

Mean RTs are reported in Table 7. Figure A8 reports the means in the high and low frequency condition.

	L1		L2	
Fluency Type	Bimodal	Unimodal	Bimodal	Unimodal
High Frequency	731 (75)	736 (96)	1103 (376)	922 (178)
Low Frequency	857 (102)	838 (100)	1331 (422)	1028 (260)

Table 7. Mean response times (and Standard Deviations) obtained in L1 and L2 in the picture-naming task from the two groups of bilinguals.

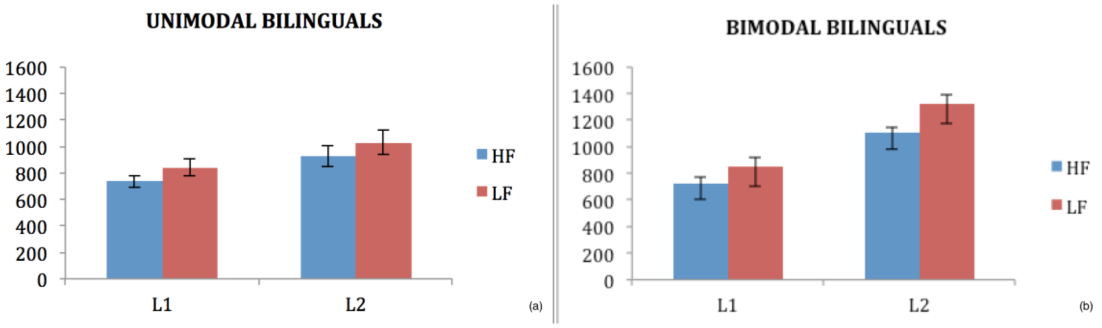

Fig. A8 Mean RTs for unimodal (left panel - a) and bimodal (right panel - b) bilinguals in the picture-naming task in L1 and L2, for high frequency (HF) and low frequency (LF) picture names.

L1- Italian

Mean RTs correlated ($r > .30$) with the Volume of the right ILF and the Volume of the left UF. The regression analyses showed that mean latency significantly predicted the Volume of the right ILF ($\beta = -1.805$, $SE = 0.8537$; $t = -2.115$, $p = .039$). This effect did not interact with the predictor Group, $p = .67$, indicating that the pattern was the same for both groups of bilinguals. As can be seen in Figure A9, the shorter were the RTs in the picture-naming, the larger was the volume of the right ILF.

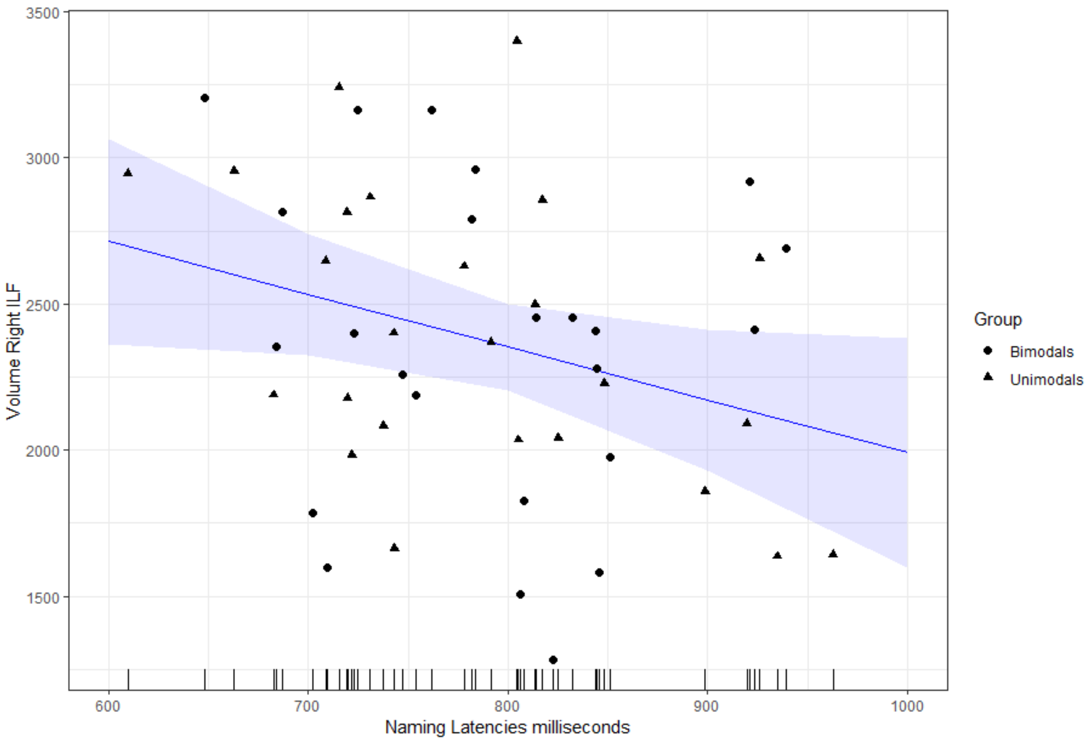

Fig. A9. Volume of the **right ILF** as a function of the mean RTs in the picture-naming task in L1.

The effect of the mean RTs on the Volume of the left UF was also significant, β = 1.148; SE = 0.52; t = 2.17, p = .03. This effect did not interact with the predictor Group (p = .18), indicating that the pattern was the same for the two groups of bilinguals. As shown in Figure A10, faster RTs in the picture-naming task were associated to smaller Volume of the left UF.

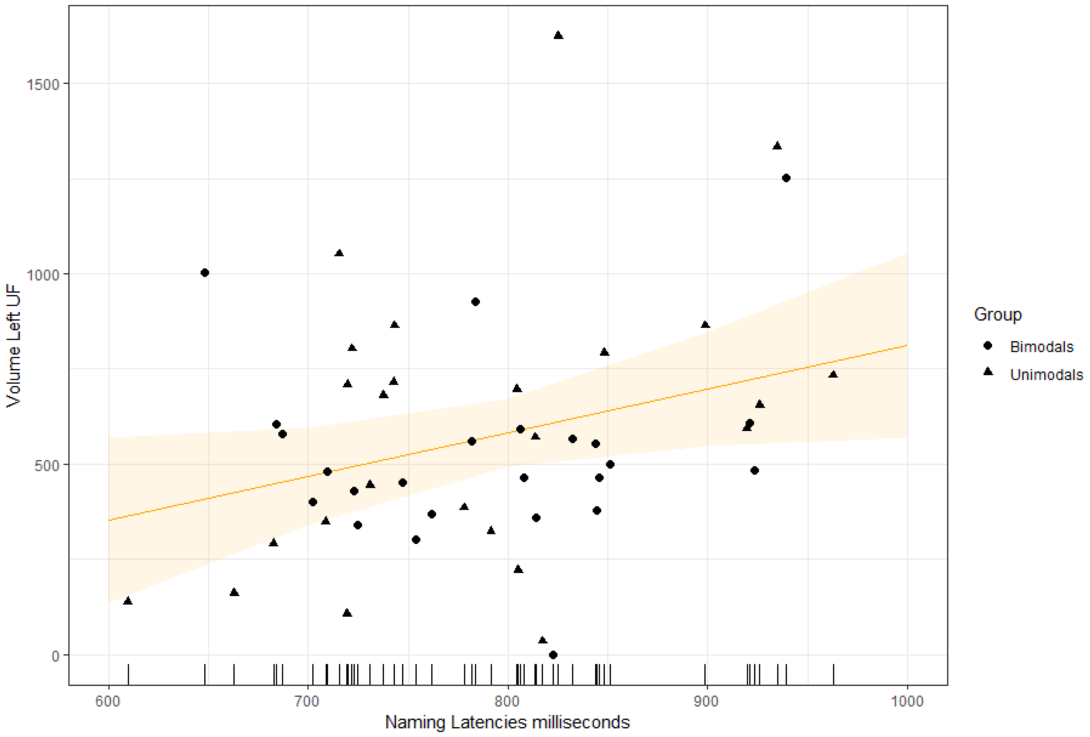

Fig. A10. Volume of the **left UF** as a function of the mean RTs in the picture-naming task in L1.

L2 – English and LIS

Unimodal bilinguals.

Only one negative correlation was larger than .30. This was between mean RTs and the volume of the right ILF. The regression analysis showed that the effect was significant, β = -1.3534; SE = 0.5065; t = -2.672; p = 0.0136.

Bimodal bilinguals.

None of the correlations between behavioral variables and all the tract-specific variables was larger than .30.

Interactions with Group

We tested whether the effect found for unimodal bilinguals interacted with the predictor Group by adding this predictor to the regression analysis. The interaction was significant, β = -1.43407; SE = 0.63916; t = -2.244; p = 0.0298. Figure A11 illustrates the pattern obtained. The Volume of the right ILF was negatively correlated with mean RTs for unimodal bilinguals naming pictures in English, so that the shorter was the response time the larger vas the volume. This pattern was not present for bimodal bilinguals naming pictures in LIS.

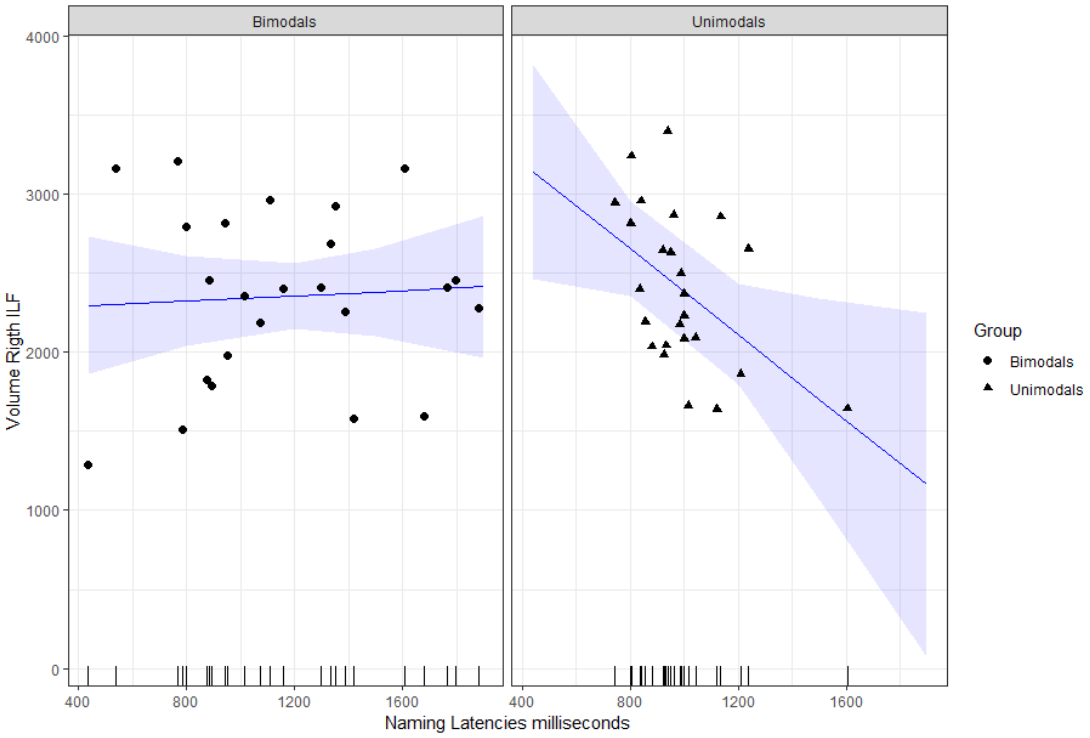

Fig. A11. The panel on the left reports the effect of the mean RTs in the naming task on the Volume of the **right ILF** in the bimodal bilingual group. The panel on the right reports the same effect in the unimodal bilingual group.

5.2.2.3. Sentence verification task

In the sentence verification task, participants were presented with correct sentences and sentences containing a violation at the semantic, syntactic and lexical level. RTs and accuracy for detecting the violation were extracted from this task. Given that sentences have different durations, RTs have been weighted with respect to sentence durations (total RT from sentence onset/sentence duration).

Weighted mean RTs and accuracy obtained when the task was performed in Italian are reported in Table 8 and 9.

	Group	
Condition	Bimodal	Unimodal
Lexical	1.13 (0.07)	1.13 (0.06)
Semantic	1.22 (0.1)	1.19 (0.08)
Syntactic	1.13 (0.05)	1.1 (0.04)

Table 8. Weighted mean RTs (RT/Sentence duration) and standard deviant in brackets obtained in each condition and for each group in the sentence verification task in Italian.

	Group	
Condition	Bimodal	Unimodal
Lexical	98.8 %	98.4 %
Semantic	95.8 %	95.3 %
Syntactic	95.3 %	96.1 %

Table 9. Accuracy obtained in each condition and for each group in the sentence verification task performed in Italian.

Weighted mean RTs and accuracy obtained when the task was performed in L2 (i.e LIS for bimodal and English for unimodal bilinguals) are reported in Table 10 and 11.

Condition	Group Bimodal	 Unimodal
Lexical	0.97 (0.08)	1.39 (0.23)
Semantic	1 (0.07)	1.33 (0.17)
Syntactic	1.03 (0.09)	1.52 (0.27)

Table 10. Weighted mean RTs (RT/Sentence duration) and standard deviant in brackets obtained in each condition and for each group in the sentence verification task performed in English and in LIS.

Condition	Group Bimodal	 Unimodal
Lexical	89.7 %	89.5 %
Semantic	84 %	94.4 %
Syntactic	70.1 %	66.5 %

Table 11. Accuracy obtained in each condition and for each group in the sentence verification task performed in English and in LIS.

L1 – Italian

Weighted RTs and accuracy in the syntactic violation condition correlated ($r > .3$) with the HMOA of the left and right ILF respectively. Accuracy in the lexical violation condition correlated ($r > .3$) with the Volume of the right IFOF and accuracy in the semantic violation condition correlated ($r > .3$) with the HMOA of the right UF. The regression analyses showed that in the syntactic violation condition, weighted RTs significantly predicted HMOA of the left ILF ($\beta = - 0.04593$; SE = 0.02239; $t = - 2.052$; $p = 0.0458$) and accuracy predicted HMOA of the right ILF ($\beta = 0.04482$; SE =

0.01639; t = 2.735; p = 0.00876). As can be seen in Figure A12 and A13, higher HMOA values were associated to shorter RTs and higher accuracy rates. For both the effects, the interaction with the predictor Group was not significant (p > .12), suggesting that the same trend was present for unimodal and bimodal bilinguals.

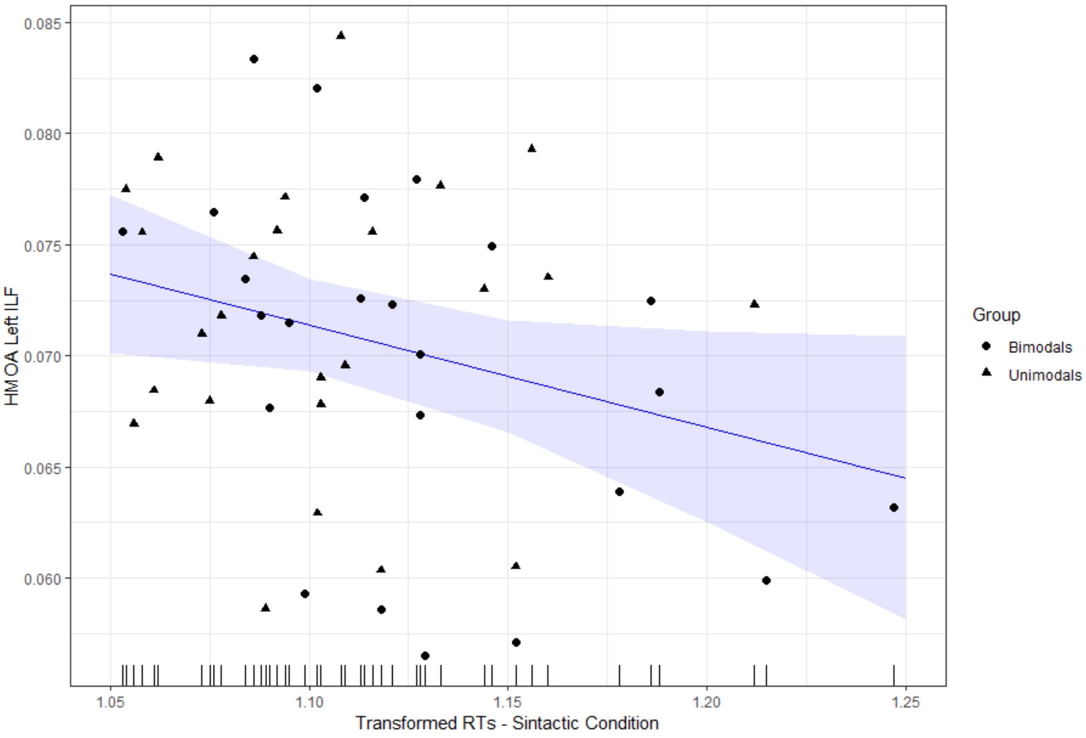

Fig. A12. HMOA of the **left ILF** as a function of weighted RTs (Total RT/Sentence duration) in the detection of syntactic violations in Italian.

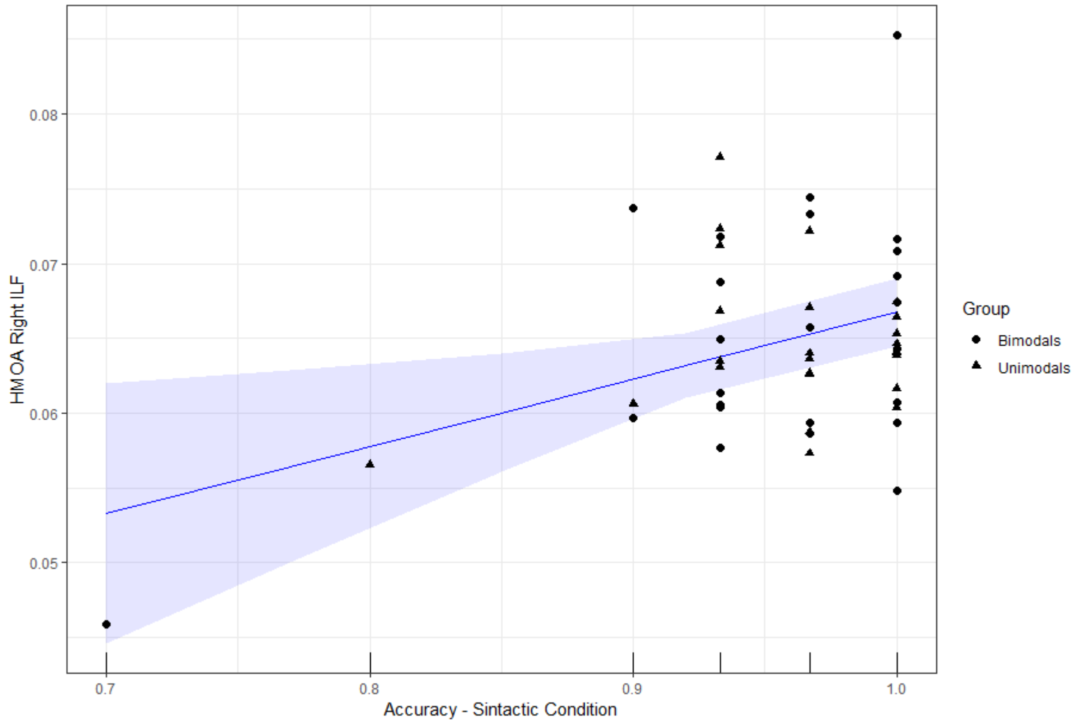

Fig. A13. HMOA of the **right ILF** as a function the accuracy rate in the detection of syntactic violations in Italian.

Accuracy in the lexical violation condition significant predicted the Volume of the right IFOF (β = - 5645; SE = 2203; t = - 2.563; p = 0.013644). In this case the correlation was negative, so that higher levels of accuracy were associated to smaller Volume, as illustrated in Figure A14. No interaction with the predictor Group was found (p = 0.14).

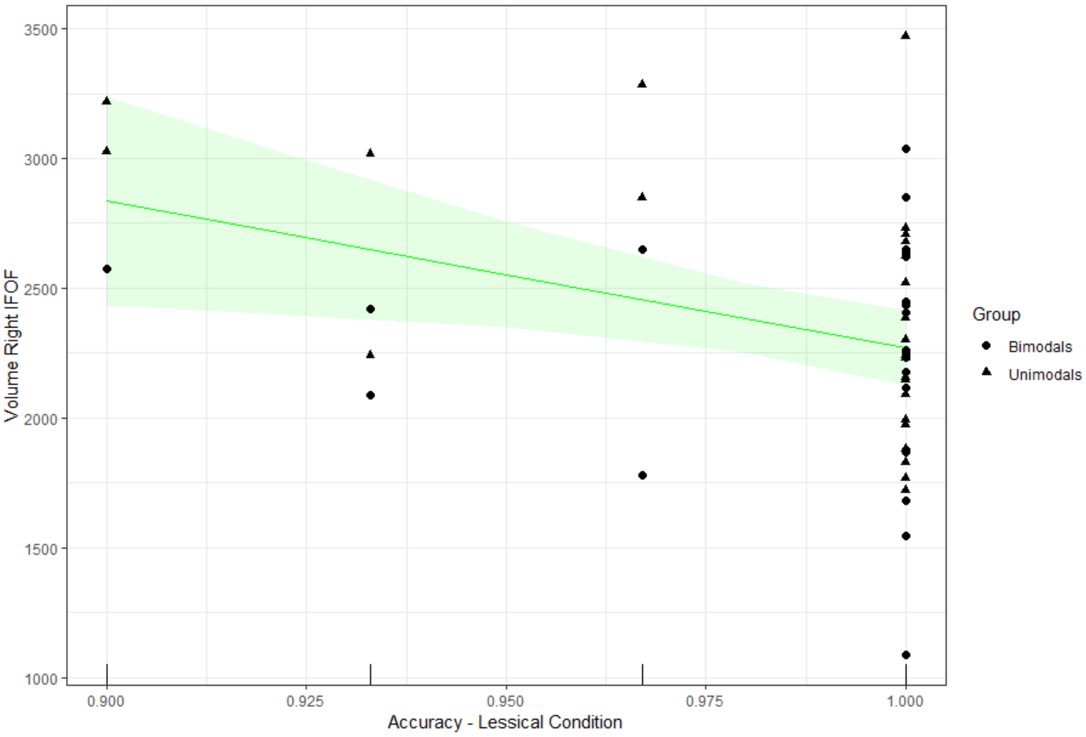

Fig. A14. Volume of the **right IFOF** as a function of the accuracy in the lexical violation condition in Italian.

Accuracy in the semantic violation condition significantly predicted HMOA of the right UF (β = - 0.04200; SE = 0.02067; t = - 2.032; p = 0.0478). Even in this case the correlation was negative, so that higher levels of accuracy were associated to lower HMOA values, as illustrated in Figure A15. Again, the interaction with the predictor Group was not significant (p = .62).

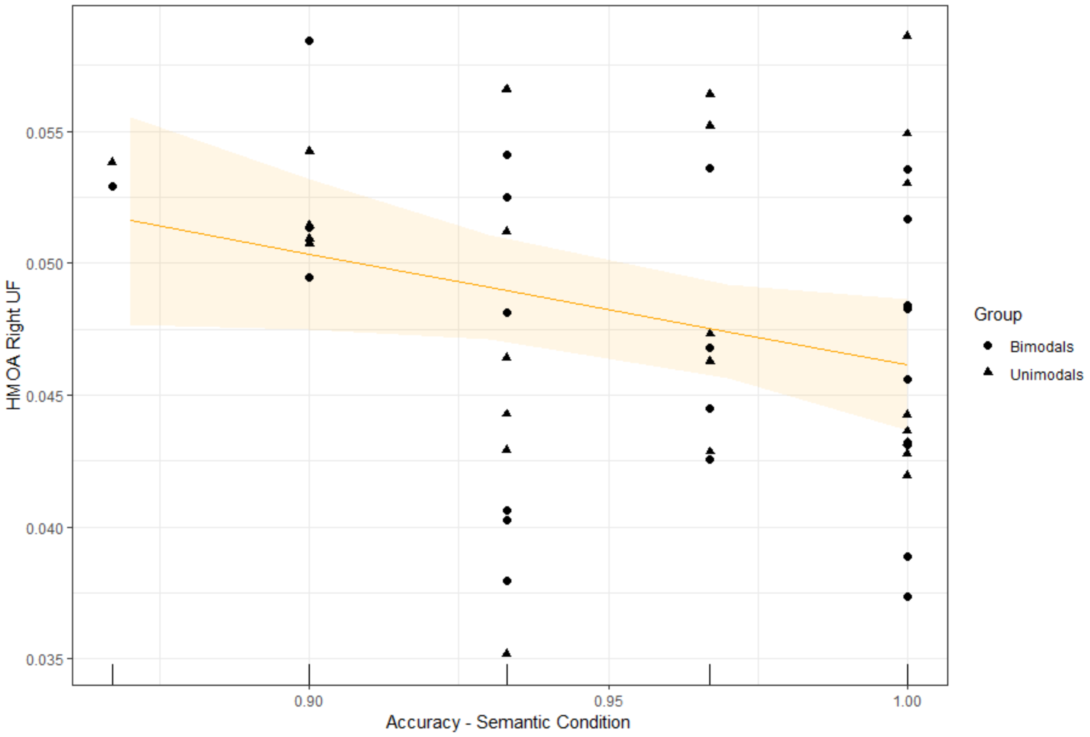

Fig. A15. HMOA of the **right UF** as a function of the accuracy in the semantic violation condition in Italian

L2 – English and LIS

Unimodal bilinguals.

Accuracy rates in all three-violation conditions correlated (r > .3) with HMOA of the right UF. Weighted RTs in the syntactic violation condition also correlated (r > .3) with HMOA in the right UF. When test with regression analyses, only accuracy rates in the syntactic violation condition significantly predicted HMOA values of the right UF (β = 0.016101; SE = 0.005495; t = 2.93; p = 0.00752). Higher accuracy was associated with higher HMOA values of the right UF. No significant effects were obtained for accuracy rates in the semantic (p = 0.10) or lexical (p = 0.09) violations condition, nor for weighted RTs in the syntactic violation condition (p = 0.06).

Bimodal bilinguals.

Accuracy in the syntactic violation condition was positively correlated ($r > .3$) with HMOA of the right IFOF, so that higher levels of accuracy were associated to higher HMOA values of this tract. The regression analysis resulted significant, $\beta = 0.019853$; $SE = 0.009126$; $t = 2.175$; $p = 0.0406$.

Interactions with Group

In order to detect modality specific effects, we tested each of the effects found in the two groups in a regression model with "Group" as additional predictor. A modality specific effect was identified when the effect significantly interacted with group.

The effect of accuracy rates in the syntactic violation condition on HMOA of the right UF found for unimodal bilinguals responding to English sentences significantly interacted with the predictor Group ($\beta = 0.022279$; $SE = 0.009293$; $t = 2.397$; $p = 0.0207$). While unimodal bilinguals were more accurate when HMOA of the right UF was higher, this pattern was absent in the case of bimodal bilinguals. There results are reported in Figure A16.

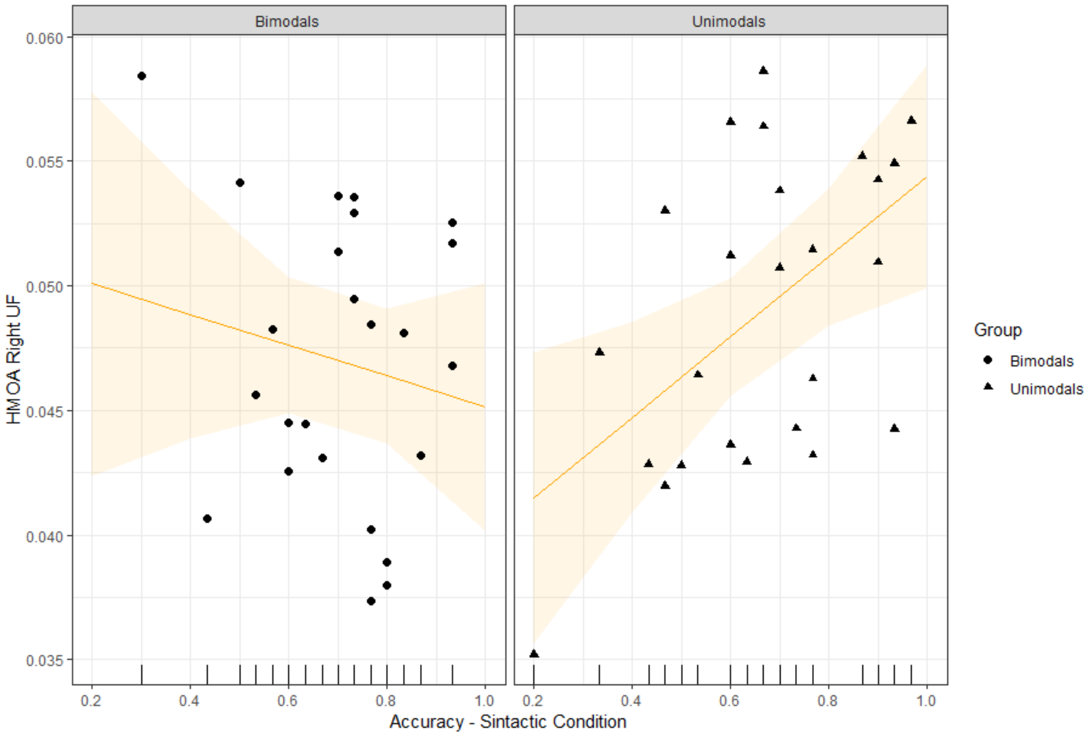

Fig. A16. The panel on the left reports the effect of accuracy in the syntactic violation condition on the HMOA of the **right UF** in the bimodal bilingual group. The panel on the right reports the effect in the unimodal bilingual group.

The effect of accuracy in the syntactic violation condition on the right IFOF found for bimodal bilinguals while detecting the violations in signed sentences did not interacted with Group (β = - 0.013994; SE = 0.010819; t = - 1.294; p = 0.2024). In this case we cannot conclude that the two groups of bilinguals differed with respect to this effect.

5.3. Overview of the principal results

In order to explore whether the type of bilingualism modulates the ventral language pathway, a pool of 49 participants, 24 bimodal bilinguals and 25 unimodal bilinguals have been compared in both tract-specific measures and linguistic (both production and perception of L1 and L2) measures. From the analysis of the HMOA and Volume of three tracts ILF, IFOF and UF in both the hemispheres, no differences between the two groups have been found. Only the age of participants seems to modulate the HMOA of the left ILF. Specifically, the analyses shown that the younger was the participant, the higher were the HMOA values in the left ILF.

Turning to the correlations between the performance in the behavioral task on language production and comprehension and diffusion measures, several results emerged, which reveal some modality specific effects.

In the *Verbal Fluency task*, the performance in the semantic condition was negatively correlated with the volume of the right ILF for unimodal bilinguals (in English) and positively correlated for bimodal bilinguals (in LIS). This latter effect was present also for the measures of the left ILF, only for the bimodal bilingual group. This result showed a strong involvement of the right and left ILF in the semantic fluency task when performed in LIS, but not in English or Italian. The correlational pattern was somehow reversed if we consider the volume of the left UF. In this case the performance in the semantic condition was positively correlated with measures of the left UF for unimodal bilinguals (in English) and not correlated for bimodal bilinguals (in LIS). In the phonological condition, an interaction with group emerged for the effect of mean number of words retrieved on the HMOA of the left UF. A larger number of words retrieved in LIS, was associated to lower HMOA values in the left UF. When the same task is performed in English, no the mean number of words did not predicted the HMOA values of this tract.

In the *Picture-naming* task, a modality specific effect involved the relationship between mean latency and the volume of the right UF. Specifically, in was found that when the pictures were named in English RTs, were negatively related to the volume of the right ILF; when the task was performed in LIS, RTs did not predicted tract-specific measures of this tract.

In the *Sentence verification task*, HMOA values of the right UF were positively correlated with the accuracy in the syntactic violation task. This pattern, however, was present when the task was performed in English but not in LIS.

Considering the effect of the behavioral measures obtained in Italian on the tract-specific measures, we never obtained differences between the two groups. This means that the effects obtained in Italian were the same in the two groups of bilinguals.

CHAPTER 6

General Discussion

The overarching aim of the present PhD thesis was to study the neuroanatomical characteristics (in terms of WM connections) of the language network in two populations of bilinguals. Specifically, the main goal was to emphasize the commonalities and the differences at the level of WM tracts between signed and spoken languages. To this purpose, a group of bimodal bilinguals and a group of unimodal bilinguals, with different levels of proficiency in their L2, have been compared. Since the two groups differ in the input-output systems of the two languages, they provide an unique opportunity to highlight which are the similarities between signed and spoken languages, with respect to the neural substrates that are specific for each linguistic modality. In both groups of bilinguals, three tracts composing the ventral stream of language of both hemispheres have been extracted: the ILF, the UF and the IFOF. Then, tract-specific measures of the three tracts have been analyzed. Precisely, two specific measures have been selected for each tract: (a) HMOA value, which give an index of the microstructural properties of the white matter tract and (b) Volume value, which give an idea of the "magnitude" of the tract. In order to investigate whether a specific language process (task) in spoken and signed language is associated to the same or different brain tract, we collected behavioral data in a set of production and comprehension tasks in English/LIS (L2) and in Italian (L1). Tract measures and behavioral data have been then correlated, revealing the way in which the degree of expertise with signed or spoken language might shape the neural circuitry at the service of specific linguistic functions.

From these correlations, differences have been found mainly involving the ILF and the UF. Previous research indicated that these tracts are involved in lexical retrieval and semantic activation processes (Damasio et al., 1996). We found effects related to the performance according to language and, more interestingly, we also found modality specific effects. We will consider below the main findings, separately for each task.

The verbal fluency task permits to assess the speed of retrieval, the vocabulary knowledge and executive control in word production (Luo et al., 2010). The execution of these tasks has been associated with activation in both temporal and anterior regions, with a predominant involvement of the temporal areas in the semantic fluency condition and of the frontal areas in the phonological fluency condition (Bell et al., 2001; Mummery, Patterson, Hodges, & Wise, 1996). This asymmetry between conditions is likely due to differences at the level of control and in the engagement of semantic memory, given that performance in the phonological condition relies to a larger extent on executive control whereas performance in the semantic condition largely depends on semantic memory activation.

From our results it emerged a main involvement of the right and the left ILF, when the semantic fluency task was performed in LIS. Specifically, the volume the ILF was positively correlated to the ability to retrieve semantically related signs. The fact that this tract results massively involved in sign generation might be due to the visual-spatial modality of this language. There is evidence in the literature about the impact of sign language on other non-linguistic skills, such as on visual spatial abilities or on spatial memory (e.g., Emmorey & McCullough, 2009; Geraci, Gozzi, Papagno, & Cecchetto, 2008), suggesting that the acquisition of a spatial-visual language can have a larger impact on cognitive processing in general. The finding obtained in our study suggests that the interaction between occipital visual areas and the temporal areas (connected by the ILF) is particularly relevant for sign generation and/or production. Another explanation, which may be also connected with this view, rests on the observation that sign languages are far more iconic that spoken languages (see for a review Dingemanse, Blasi, Lupyan, Christiansen, & Monaghan, 2015). In sign languages, the form of many signs is somehow similar to the corresponding referent. Therefore, the activation of concepts/signs belonging to a given semantic category might have been supported by the activation of visual information, which interact with the sign production process. The fact that both the right and the left ILF are related to performance in the semantic fluency task in LIS, seems to suggests that both hemispheres play a relevant role in sign generation when this is based on semantic cues.

It is relevant here to note that a modality specific effect emerged when considering the right ILF. While semantic fluency in LIS was positively related to the tracts' measures of the right ILF, the direction of the relationship reversed when the semantic fluency task was performed in English. This suggests that the right ILF might be involved in the dynamics of retrieval at the semantic and/or lexical level that could differentiate languages according to modality. This issue will be further considered when analyzing the results obtained in picture naming. It is relevant to mention that this modality specific effect is confirmed by the results obtained considering L1. Similar to what observed for English, when semantic fluency was performed in Italian, the mean number of words retrieved along the minute was negatively correlated with the volume of the right ILF.

No relation between tract measures of the ILF and the performance in the phonological condition of the fluency task was found. This result is consistent with studies showing a relationship between phonological processes and the dorsal stream of the linguistic network, specifically the AF (Catani et al., 2005; Forkel et al., 2014; López-Barroso et al., 2013).

Another modality specific effect emerged at the level of the left UF. The volume of this tract is positively related with semantic fluency when the language used is English but not when the language is LIS. It seems therefore that the left UF is highly involved in the activation/generation of semantically related concepts/words in L2, but only when L2 is a spoken language. In literature the UF has been linked with word production and semantic word retrieval (semantic fluency task; Nomura et al., 2010), with the retrieval of proper names (Papagno et al., 2011), and with semantic control processes (Harvey et al., 2013; Agosta et al., 2013). Catani and colleagues (2013) analyzed the performance of a group of patients with primary progressive aphasia and showed a correlation between tract-specific measures of the UF and the performance in the Peabody Picture Vocabulary Test. Evidence contrary to this hypothesis also exists. For example, Kljajevic and collaborators (2016) showed that the deterioration of the UF is not associated to a decline in verbal fluency performance. Our data are partially consistent with the previous evidence, since it emerged that the left UF is implicated in semantically based word generation tasks, but only in L2 and only when L2 is a spoken language. This result might be consistent with the idea that the UF is implicated in control processes related to language production and/or lexical selection and competition. It has been proposed (a) that these processes require stronger control in bilinguals with respect to monolinguals (see Green et al., 1998; Abutalebi et al., 2012) and (b) that this might be true for unimodal bilinguals but not for bimodal bilinguals (Emmorey, Luk, Pyers, & Bialystok, 2008). If the left UF is implicated in control processes related to lexical selection and competition, and if these processes are amplified for unimodal bilinguals, this might explain why the performance in the semantic fluency task -only when performed in L2 English - was associated to the tract-specific measures of the left UF.

Consistent evidence of the involvement of the left UF in control processes related to cross-language interference in the verbal fluency task cames from the results obtained in the phonological condition. The mean number of words retrieved during the phonological task was negatively related to the HMOA values (and volume, even if in this case the interaction with group was not significant) of the left UF when the task was performed in LIS but not when it was performed in English. As previously outlined, the phonological condition of the fluency task requires a stronger involvement of control processes, given that the generation of words on the basis of a phonological cue is considered a far less automated process than the generation of words based on semantic cues (Luo et al., 2010). Given that bimodal bilinguals might not need to inhibit one of the two languages when speaking/signing the other language, the performance in the phonological fluency task might benefit from the activation of both the linguistic codes. As a consequence, in conditions of reduced control, i.e., when the HMOA and Volume values of the left UF are smaller, the performance in this task could be advantaged. At the moment, these explanations remain at a speculative level and further investigation is needed in order to better clarify these issues.

The results found in the fluency task are nicely complemented by the results found in the picture-naming task. The picture-naming task reflects the ability to retrieve the correct name of visually presented pictures. More precisely, it requires the access to the concept represented in the picture and then the retrieval of the corresponding lexical representation among a pool of possible candidates. Our findings showed a modality effect in this task. The speed of the picture name retrieval was positively correlated with the volume of the right ILF when pictures were named in English, but this effect was not present when pictures were named in LIS. The modality effect was confirmed by the fact that when the task was performed in Italian we obtained the same pattern as in English. In both these spoken languages, shorter naming latencies were associated to higher volume values of the right ILF.

As seen in previous chapters, this tract connects the inferior occipital areas with the most anterior temporal areas, with some of its fibers running through the superior, middle and inferior temporal lobe. This trajectory might be suggestive of its role in object recognition and, in particular, in the processes aimed at linking objects with the corresponding lexical concepts. Indeed this tract connects associative visual areas with middle temporal regions, which have been related to semantic retrieval processes in picture naming and word generation (Indefrey & Levelt, 2004).

The fact that the effect was not present when the task was performed in LIS suggests that the processes of semantic retrieval might be partially different in spoken and signed languages. If we consider together the results obtained in the semantic fluency task and in the picture-naming task, it emerged that the right ILF has a prominent role for predicting (a) semantic fluency in LIS but not in English (or Italian), and (b) the picture naming in English (or Italian) but not in LIS. This sort of dissociation suggests that if the ILF is involved in mechanisms related to the dynamic of semantic activation during word production and that such mechanisms are at least partially different in spoken and signed languages. A speculative hypothesis is that such mechanisms correspond to the mechanisms of selection/competition occurring at the semantic level during production. If we consider spoken languages, picture naming and semantic fluency have an inverse correlation with the right ILF's volume: while performance in the semantic fluency task was negatively correlated with the volume's tract, performance in the picture naming task was positively related with it. From this observation it appears that in spoken languages, the right ILF might be involved in processes that have an inverse effect on these two tasks, such as the selection/competition processes at the semantic level. Indeed, when performing the picture-naming task one concept must be selected among other competitors, whereas when performing the semantic fluency task, many concepts need to simultaneously be activated and maintained active as long as possible in order to accomplish the task. The fact that in signed languages these correlations resulted somehow reversed (i.e., the tract volume is positively associated with the performance in the semantic fluency task, while no association emerged for the picture-naming task), might therefore suggest that the dynamics of conceptual activation in signed languages rests on partially different processes, because of the visual/spatial modality of this language.

A further critical result that needs discussion concerns the fact that many of the effects obtained in production tasks emerged in the ILF of the right hemisphere. The common assumption is that the language function is mostly left lateralized and previous evidence mainly showed the involvement of the left ILF in language (e.g., Agosta et al., 2010; Wong et al., 2011). However, two main lines of investigations in literature might help to explain why we found the right hemisphere to be more sensitive to the performance in linguistic tasks. From the one hand, it has been shown that a bilateral organization of the language function is related to higher performance in language and in particular in verbal memory and semantic processing (Catani et al., 2007). Also, even if the more largely investigated dorsal AF seems to show a leftward organization (Nucifora et al., 2005, Powell et al., 2006; Hagmann et al., 2004; Catani et al., 2005), not all white matter tracts of the AF seem to develop asymmetrically. For example the posterior segment of the AF, whose changes seem mostly driven by specific environmental factors, appears not to be left lateralized (Catani & Thiebaut de Schotten, 2012; Catani & Budisavljevic, 2014). Whether the ventral white matter pathways show a preferential lateralization in language, is still matter of debate. The available findings on the lateralization of the ventral route have been concentrated on the connection with Broca's and Wernicke's territories and/or areas related with audition, showing stronger connections on the left hemisphere (e.g., UF and superior MTG; Parker et al., 2005). On the other hand, research comparing brain organization in bilinguals with respect to monolinguals seems to show a reliable bilateral hemispheric involvement in early bilinguals with respect to monolinguals (Hull & Vaid, 2006). Similar results have been obtained analyzing white matter organization. Hämäläinen and collaborators (2017) reported a more bilateral organization of the perisylvian language related tracts in early bilinguals with respect to monolinguals. In conclusion, these data might be consistent with our results showing that (a) behavioral tasks in bilinguals correlated with tracts of the right hemisphere and (b) the differences between the groups of bilinguals concerned the tracts of the right hemisphere.

Finally, in the Sentence verification task participants judged various sentences and detected whether they were grammatically correct or incorrect. The incorrect sentences contained violations at the semantic, at the syntactic, or at the lexical level. The pattern of results obtained in this task was more complicated. The syntactic condition proved to be more sensitive than the lexical or the semantic condition for predicting the specific tract measures. A modality effect emerged in this task with respect to the HMOA values of the right UF. Accuracy in the syntactic condition in

English predicted HMOA values. This effect was not present in LIS. This result, combined with what obtained in the fluency task, suggests that the right UF is involved in L2 processing when this is spoken and not when this signed. Indeed we previously discussed the fact that performance in the semantic fluency task predicted the volume of the right UF when performed in English but not in LIS. We need to highlight here that in our task, lexical, semantic and syntactic violations were presented randomly in a single block of trials. This unfortunate methodological choice leaded us to the impossibility of considering the specific effects of three types of violations, as we planned to do. With respect to the lexical and semantic violations, syntactic violations were much harder to be detected. Indeed, in this condition, the last part of the sentence was anyhow meaningful and semantically consistent/predictable. Moreover, as far as English and Italian are concerned, the violation often consisted in the substitution/deletion of one letter-morpheme. As a result, we think that performance in the syntactic condition did not reflect syntactic competencies but, since this condition was the most difficult, it reflected comprehension skills more in general and it resulted to be more sensitive to the correlation with the specific tract measures.

As for the role of the right UF in sentence comprehension we found for English, this result was quite unexpected given that, to our knowledge, no previous study showed a specific involvement of this tract in sentence comprehension. For example, a study on primary progressive aphasia showed that both microstructural and macro-structural (number of streamlines and FA) abnormalities of the UF were associated to deficits in single words comprehension and in naming (Catani et al., 2013). Other studies associated the damage of this fasciculus to semantic deficits (Agosta et al., 2010; Galantucci et al., 2011).

Accuracy in the syntactic condition in LIS was found to be correlated with HMOA of the right IFOF, suggesting that this tract might play a role in sentence processing in LIS. In this respect many studies in the literature pointed out the importance of facial expressions in sign languages when representing several lexical and syntactic structures (see paragraph 3.3.1). For example, deaf studies show an enhanced ability in the detection of different facial features, thanks to the intensive experience with sign language perception (Bettger, Emmorey, McCullough, & Bellugi, 1997). The right IFOF, which connects occipital visual areas with the anterior areas of the brain, could have a prominent role in the detection of sentence violations in LIS because when perceiving sentences in LIS, bimodal bilinguals engage visual areas for detection of facial expression and other visual elements, which give information about the sentence structure. The fact that comprehension processes mainly involved the right hemisphere is also in line with the data of the literature (Poizner et al., 1987; Corina et al., 2013). For example, Poizner pointed out that signers with damage to the right hemisphere, show syntactic comprehension difficulties, while a left hemisphere damage may lead to problems in syntactic production processes of sign language (Poizner et al., 1987). Finally accuracy in the syntactic condition in Italian was found to be correlated with HMOA values in the left ILF, suggesting that this tract is also involved in sentence comprehension in L1. Even this result was quite unexpected, given that the ILF has not been specifically linked to syntactic processing in previous work.

We also performed a main comparison between groups in relation to the DTI measures extracted. A few recent studies investigated the effect of bilingualism on white matter tracts, as reported in the previous chapters of the present thesis. All were focused on the comparison between bilinguals and monolinguals or among bilinguals with different L2 proficiency levels and they reported differences between monolinguals and bilinguals mainly at at the level of the right IFOF and right UF, left IFOF and the corpus callosum (e.g., Luk et al., 2011; Mohades et al., 2012). To our knowledge, no study has compared bimodal bilinguals with unimodal bilinguals. Our results did not reveal differences in the volume and HMOA values of the ventral tracts, in neither of the two hemispheres. Such null result was not surprising and it might be explained in different ways. From the one side, participants of both groups had variable levels of proficiency (and age of acquisition) in their L2, and this might have not permitted to properly highlight neuroanatomical modifications due a long and deep experience with a second language. From the other side, the absence of significant differences between the groups might suggest that the neural consequences reported in previous studies that involved the ventral tracts are modality independent. In this view, handling a second language produces some neural modifications that are independent from language input and output modality. Finally, one might hypothesize that main differences between the two bilingual populations could be found analyzing other white matter tracts involved in language processing (i.e., the segments of the AF) or in language control (i.e., frontal aslant tract; Catani et al., 2005; 2012). Further investigation is therefore needed in order to show whether group differences between bimodal and unimodal bilinguals do exist. Specifically, the future step in this regard should be the analysis of the other white matter tracts involved in language processing in the groups of bilinguals. If no differences would be found with the mixed proficient groups of the present study, the comparison should be restricted to proficient unimodal and bimodal bilinguals. In this respect, it would also be interesting to assessing the effect of linguistic training (i.e., how long should be the training) in order to produce a modulation of white matter connections.

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Appendix

APPENDIX A

Motor tasks

- **Purdue Pegboard Test** (Tiffin & Asher, 1948)

This task is usually used to assess the fine motor skills of the participant. Specifically, it is considered as a test of manual dexterity and bimanual coordination and it involves two different abilities: gross movements of arms, hands, and fingers, and fine motor extremity ("fingerprint" dexterity). It consists of a plastic board with some holes placed in two vertical lines.

Procedure. Each of the tasks described below were performed for three times consecutively. In the first part of the task, the participant had to insert with the right hand, a series of pin in the appropriate holes, starting from the one at the top of the board. The same task has been performed with the left hand, in a second separate sub-test. Each sub-test had a duration of 30 seconds and has to be completed trying to be as accurate and fast as possible. The second sub test asked to do the same previous task, but with both the hands at the same time. Also this task lasted 30 seconds. The last part consisted in an assembly, where to the participant was asked to place a pin and then, alternating the two hands, a collar and two washers which should scroll inside the pin alternately. This last task lasted for 60 seconds.

Scoring. The total scoring of the test and the scoring of the sub parts have been both collected. One point was given to every correct rod positioned on the right place within the 30 seconds. As for the first three sub-test, the total number of "Right + Left + Both the hands" was calculated. As for the last task, 4 points were given for a completed assembly (one point for each piece: one pin, one washer, one collar and another washer placed correctly) and one point was given for every piece, composing the uncompleted assembly (usually placed at the end and not finished because the time ended up).

- Line Bisection Test (see Cattaneo, Lega, Cecchetto, & Papagno, 2014)

This test is usually performed to assess unilateral spatial neglect in dementia or in patients with neurological impairments. In this case, we adopted it just to have a more measure of motor and spatial skills and to assure the participants were matched for other non-linguistic measure.

Procedure. The participant was sat in front of an empty table but just the line bisection test. The task requires the participant to split in two totally identical parts, a 20cm line placed at the center of a white horizontal A4 sheet (one line per sheet). The test was first performed for 5 times using the right hand and then other 5 times with the left, for a total of 10 line bisections.

Scoring. The scoring was extracted measuring the distance, for every line, between the true center point of the line ("0 mm" point) and the line drawn by the participant (see Figure A1). An average of the performance between the 5 sheets per hand has been recorded.

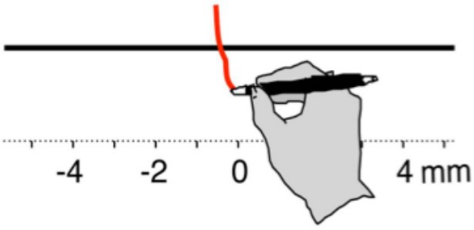

Figure A1. Example of Line Bisection scoring (from Thiebaut de Schotten et al. 2011).

APPENDIX B

- Picture-naming Task

Code	Picture.bmp	Name	COLFISvalue	LunghezzaFONO_Italiano	Lingua	Frequency
101	casa	casa	2954	4	Italiano	HF
102	macchina	macchina	687	7	Italiano	HF
103	cuore	cuore	672	5	Italiano	HF
104	telefono	telefono	433	8	Italiano	HF
105	tavolo	tavolo	390	6	Italiano	HF
106	televisione	televisione	335	11	Italiano	HF
107	gamba	gamba	330	5	Italiano	HF
108	bocca	bocca	322	5	Italiano	HF
109	finestra	finestra	287	8	Italiano	HF
110	scala	scala	217	5	Italiano	HF
111	scarpa	scarpa	195	6	Italiano	HF
112	moto	moto	187	4	Italiano	HF
113	uovo	uovo	169	4	Italiano	HF
114	gatto	gatto	169	5	Italiano	HF
115	bandiera	bandiera	153	8	Italiano	HF
116	camicia	camicia	131	7	Italiano	HF
117	naso	naso	131	4	Italiano	HF
118	sigaretta	sigaretta	127	9	Italiano	HF
119	bottiglia	bottiglia	122	8	Italiano	HF
120	patata	patata	99	6	Italiano	HF
121	autobus	autobus	92	7	Italiano	HF
122	penna	penna	80	5	Italiano	HF
123	cipolla	cipolla	76	7	Italiano	HF
124	pianoforte	piano	70	10	Italiano	HF

125	tazza	tazza	57	5	Italiano	HF
201	faro	faro	39	4	Italiano	LF
202	aquila	aquila	21	4	Italiano	LF
203	asparago	asparago	13	8	Italiano	LF
204	campana	campana	36	7	Italiano	LF
205	catapulta	catapulta	2	9	Italiano	LF
206	cerotto	cerotto	5	7	Italiano	LF
207	delfino	delfino	28	7	Italiano	LF
208	gruccia	gruccia	2	6	Italiano	LF
209	brocca	brocca	11	5	Italiano	LF
210	lavatrice	lavatrice	11	9	Italiano	LF
211	molletta	molletta	1	8	Italiano	LF
212	pettine	pettine	20	7	Italiano	LF
213	pipa	pipa	18	4	Italiano	LF
214	rubinetto	rubinetto	21	9	Italiano	LF
215	scivolo	scivolo	5	5	Italiano	LF
216	scolapasta	scolapasta	1	10	Italiano	LF
217	secchio	secchio	11	5	Italiano	LF
218	ventaglio	ventaglio	13	9	Italiano	LF
219	vulcano	vulcano	30	7	Italiano	LF
220	mestolo	mestolo	8	7	Italiano	LF
221	grattugia	grattugia	2	9	Italiano	LF
222	ancora	ancora	10	6	Italiano	LF
223	cavatappi	cavatappi	1	9	Italiano	LF
224	amaca	amaca	6	5	Italiano	LF
225	trattore	trattore	5	8	Italiano	LF

Table B1. Corpus of the Italian picture used to perform the picture-naming task.

Code	Picture.bmp	English	LIS	COLFIS-LIS	CELEX-ENG	LunghezzaFONO-ENG	Lingua	Frequency
301	occhio	eye	occhio	1297	55997	3	L2(Inglese-LIS)	HF
302	fiore	flower	fiore	815	10639	6	L2(Inglese-LIS)	HF
303	fuoco	fire	fuoco	609	76494	4	L2(Inglese-LIS)	HF
304	chiesa	church	chiesa	515	100328	6	L2(Inglese-LIS)	HF
305	braccio	arm	braccio	480	48146	3	L2(Inglese-LIS)	HF
306	montagna	mountain	montagna	322	41090	8	L2(Inglese-LIS)	HF
307	pistola	gun	pistola	250	43619	3	L2(Inglese-LIS)	HF
308	pantalone	trousers	pantalone	127	3470	6	L2(Inglese-LIS)	HF
309	orecchio	ear	orecchio	203	20464	3	L2(Inglese-LIS)	HF
310	cucchiaio	spoon	cucchiaio	197	8072	5	L2(Inglese-LIS)	HF
311	pane	bread	pane	187	21102	5	L2(Inglese-LIS)	HF
312	nave	ship	nave	182	32210	4	L2(Inglese-LIS)	HF
313	bicchiere	glass	bicchiere	162	52447	5	L2(Inglese-LIS)	HF
314	tetto	roof	tetto	154	18623	4	L2(Inglese-LIS)	HF
315	uccello	bird	uccello	146	24037	4	L2(Inglese-LIS)	HF
316	specchio	mirror	specchio	138	21669	6	L2(Inglese-LIS)	HF
317	coltello	knife	coltello	117	17321	5	L2(Inglese-LIS)	HF
318	scatola	box	scatola	109	53250	3	L2(Inglese-LIS)	HF
319	bicicletta	bicycle	bicicletta	104	6156	7	L2(Inglese-LIS)	HF
320	limone	lemon	limone	103	13306	5	L2(Inglese-LIS)	HF
321	divano	couch	divano	95	11573	5	L2(Inglese-LIS)	HF
322	pomodoro	tomato	pomodoro	88	8528	6	L2(Inglese-LIS)	HF
323	armadio	wardrobe	armadio	87	2889	8	L2(Inglese-LIS)	HF
324	gonna	skirt	gonna	83	8420	5	L2(Inglese-LIS)	HF
325	formaggio	cheese	formaggio	79	23722	6	L2(Inglese-LIS)	HF
401	ananas	pineapple	ananas	15	2192	6	L2(Inglese-LIS)	LF
402	siringa	syringe	siringa	33	1305	7	L2(Inglese-LIS)	LF

403	vassoio	tray	vassoio	28	5950	4	L2(Inglese-LIS)	LF
404	ascia	axe	ascia	21	1715	3	L2(Inglese-LIS)	LF
405	slitta	sledge	slitta	19	402	6	L2(Inglese-LIS)	LF
406	mulino	windmill	mulino	18	635	8	L2(Inglese-LIS)	LF
407	pala	shovel	pala	15	2718	6	L2(Inglese-LIS)	LF
408	ciliegia	cherry	ciliegia	14	7643	6	L2(Inglese-LIS)	LF
409	melanzana	eggplant	melanzana	13	2155	8	L2(Inglese-LIS)	LF
410	canguro	kangaroo	canguro	12	724	8	L2(Inglese-LIS)	LF
411	calzino	sock	calzino	12	1943	4	L2(Inglese-LIS)	LF
412	fiammifero	match	fiammifero	11	24921	5	L2(Inglese-LIS)	LF
413	palloncino	ballon	palloncino	11	54	6	L2(Inglese-LIS)	LF
414	calamita	magnet	calamita	10	3198	6	L2(Inglese-LIS)	LF
415	cannuccia	straw	cannuccia	2	6643	5	L2(Inglese-LIS)	LF
416	rasoio	razor	rasoio	21	2852	5	L2(Inglese-LIS)	LF
417	gufo	owl	gufo	9	3255	3	L2(Inglese-LIS)	LF
418	righello	ruler	righello	1	2645	5	L2(Inglese-LIS)	LF
419	zaino	backpack	zaino	9	3805	8	L2(Inglese-LIS)	LF
420	fungo	mushroom	fungo	38	2802	8	L2(Inglese-LIS)	LF
421	scopa	broom	scopa	12	2152	5	L2(Inglese-LIS)	LF
422	zucca	pumpkin	zucca	6	4169	1	L2(Inglese-LIS)	LF
423	zebra	zebra	zebra	5	1066	1	L2(Inglese-LIS)	LF
424	sgabello	stool	sgabello	8	3719	7	L2(Inglese-LIS)	LF
425	lavagna	blackboard	lavagna	15	1023	5	L2(Inglese-LIS)	LF

Table B2. Corpus of the picture used to perform the picture-naming task in L2, English and in LIS.

APPENDIX C

- Sentence Verification task

<u>List of Italian sentences:</u>

Item	**Sentence**
ITA_V_SINT_item1	L'olio extra vergine condisce in modo molto saporite
ITA_V_SINT_item2	Un mantello pesante scalda nelle notti più freddo
ITA_V_SINT_item3	Il tartufo nero profuma in modo molto intense
ITA_V_SINT_item4	La terra si spacca sotto il solleone estive
ITA_V_SINT_item5	I criceti agitati corrono tra le siepe
ITA_V_SINT_item6	Le lumache lente rientrano nel loro gusci
ITA_V_SINT_item7	Le lucciole luminose volano sui fiori giallo
ITA_V_SINT_item8	I passeri tranquilli dormono nel piccolo nidi
ITA_V_SINT_item9	Il treno espresso parte in perfetto orari
ITA_V_SINT_item10	Il ceppo odoroso crepita nel nuovo caminetti
ITA_V_SINT_item11	Il faro lontano appare nella fitta nebbie
ITA_V_SINT_item12	Lo scaffale polveroso crolla per il pesi
ITA_V_SINT_item13	Le nuvole nere aumentano prima della tempeste
ITA_V_SINT_item14	I ciclamini bianchi profumano in modo delicate
ITA_V_SINT_item15	Le zebre paurose fuggono davanti al leopardi
ITA_V_SINT_item16	Il libro di favole si bagna sotto la piogge
ITA_V_SINT_item17	Il vecchio cervo gira tranquillo nel fitto boschi
ITA_V_SINT_item18	La donna spaventata fugge veloce davanti al cacciatori
ITA_V_SINT_item19	Il bambino educato mangia seduto alla nostra tavole
ITA_V_SINT_item20	L'imputato del delitto confessa di fronte al testimoni
ITA_V_SINT_item21	Lo spettatore straniero applaude mostrando un grande entusiasmi
ITA_V_SINT_item22	Il nuovo capotreno fischia alla partenza della locomotive
ITA_V_SINT_item23	I letti antichi cigolano in modo fastidiosi
ITA_V_SINT_item24	Gli arrosti saporiti cuociono nella vecchia cucine
ITA_V_SINT_item25	Il pasticcere abile guarnisce con la frutta candite
ITA_V_SINT_item26	Il barbone disperato piange in una via cittadine
ITA_V_SINT_item27	Il maggiordomo indiano spolvera nella bella villa moderne
ITA_V_SINT_item28	La campionessa olimpionica sguazza nella grande piscina comunali
ITA_V_SINT_item29	Il topolino grigio entra nella sua tana segrete
ITA_V_SINT_item30	La mucca pezzata rumina nel grande campo coltivati
ITA_V_SEM_item1	Il cameriere anziano serve con espressione piovosa
ITA_V_SEM_item2	La segretaria bionda chiama per un rispetto
ITA_V_SEM_item3	La cuoca esperta frigge nella vecchia scopa
ITA_V_SEM_item4	La bambina malata gioca con la cantina
ITA_V_SEM_item5	Il gruppo musicale suona con grande lunghezza
ITA_V_SEM_item6	Il pescatore stanco riposa vicino al timore
ITA_V_SEM_item7	Il ragazzo straniero legge sul treno amaro
ITA_V_SEM_item8	Il giovane falegname sega senza alcuna valigia
ITA_V_SEM_item9	Il vecchio calzolaio lavora con grande confessione

ITA_V_SEM_item10	Il medico chirurgo arriva appena in momento
ITA_V_SEM_item11	Le maestre felici parlano a voce scalza
ITA_V_SEM_item12	I macellai esperti tagliano con grande entrata
ITA_V_SEM_item13	I cassieri nervosi contano con estrema bellezza
ITA_V_SEM_item14	I postini veloci lavorano girando in candela
ITA_V_SEM_item15	I nostri vicini potano con le grandi sedie
ITA_V_SEM_item16	I commessi attenti puliscono preparando i misteri
ITA_V_SEM_item17	Le mamme econome comprano solo al sentimento
ITA_V_SEM_item18	I nuovi imbianchini stuccano in modo petulante
ITA_V_SEM_item19	I ragionieri stressati discutono controllando le nebbie
ITA_V_SEM_item20	I pensionati vigorosi leggono senza gli armadi
ITA_V_SEM_item21	Il lupo solitario mangia i resti rumorosi
ITA_V_SEM_item22	La rondine instancabile vola per tutto il sacchetto
ITA_V_SEM_item23	Il gatto persiano corre sotto il sale
ITA_V_SEM_item24	La leonessa solitaria vaga nella notte condita
ITA_V_SEM_item25	La lucertola pigra riposa al sole arrabbiato
ITA_V_SEM_item26	La gallina bianca cova nella mia motivazione
ITA_V_SEM_item27	Il cavallo affaticato dorme nella sua tasca
ITA_V_SEM_item28	Lo squalo grigio nuota intorno al letargo
ITA_V_SEM_item29	Il coccodrillo affamato sonnecchia vicino al corridoio
ITA_V_SEM_item30	La capra magra rumina sul prato assordante
ITA_V_LESS_item1	I canarini gialli beccano senza alcuna fosto
ITA_V_LESS_item2	I ghepardi assetati corrono nella calda gnoba
ITA_V_LESS_item3	Le piccole api ronzano nella calura prisi
ITA_V_LESS_item4	Le rane rumorose gracidano nello stagno docaro
ITA_V_LESS_item5	Le brune cicale cantano tutta la tapaci
ITA_V_LESS_item6	Il gelsomino fiorito profuma nella notte cogia
ITA_V_LESS_item7	La macchina sportiva viaggia sulla strada tonca
ITA_V_LESS_item8	La palla rossa rotola tra la cinama
ITA_V_LESS_item9	Il vetro blindato protegge dal rumore pusto
ITA_V_LESS_item10	I violenti temporali scoppiano senza alcun gnufo
ITA_V_LESS_item11	Le stelle lontane brillano nel cielo sceto
ITA_V_LESS_item12	I venti estivi soffiano con grande stoso
ITA_V_LESS_item13	Gli orecchini argentati restano nel vorca
ITA_V_LESS_item14	I muri sbrecciati crollano poco per eglia
ITA_V_LESS_item15	Gli alunni svogliati ascoltano sempre con aria tranoma
ITA_V_LESS_item16	La sarta distratta stira senza prestare alcuna rodazza
ITA_V_LESS_item17	L'esperta infermiera cura in modo troppo binamba
ITA_V_LESS_item18	I soldati coraggiosi partono al galoppo senza diminio
ITA_V_LESS_item19	Il vecchio pagliaccio inciampa nelle grosse scarpe dorta
ITA_V_LESS_item20	Il contadino stanco semina senza avere alcuna arezzama
ITA_V_LESS_item21	Il ladro esperto penetra nella splendida chida
ITA_V_LESS_item22	Le cinque galline covano nel calore del tagnidro
ITA_V_LESS_item23	La pesante foca sguazza nel mare in bepre
ITA_V_LESS_item24	Il possente ippopotamo sbadiglia nello zoo quasi forconto
ITA_V_LESS_item25	Il corvo nero saltella sotto gli alberi bachimio
ITA_V_LESS_item26	La gazza ladra svolazza intorno alla canimedo
ITA_V_LESS_item27	Il giovane elefante avanza in modo troppo vugherzo

ITA_V_LESS_item28	Il giovane gallo canta nel pollaio al buolo
ITA_V_LESS_item29	La lampada fluorescente illumina senza dare alcun locostato
ITA_V_LESS_item30	La penna stilografica cade dal vecchio regnosto
ITA_FILL_item1	Il gomitolo di lana è nella scatola di cartone
ITA_FILL_item2	La ragazza mora va al lavoro nel ristorante
ITA_FILL_item3	L'autista preciso guida con prudenza
ITA_FILL_item4	La formica instancabile lavora la notte
ITA_FILL_item5	Il merlo impaurito si rifugia nella grande cesta
ITA_FILL_item6	La nave carica attracca al porto nebbioso
ITA_FILL_item7	La nonna premurosa abbraccia il nipote stanco
ITA_FILL_item8	L'acqua fresca disseta i turisti tedeschi
ITA_FILL_item9	La rana agile salta tra le foglie secche
ITA_FILL_item10	Il barista instancabile serve tra i tavoli affollati
ITA_FILL_item11	La ballerina elegante danza con molta professionalità
ITA_FILL_item12	L'attore impegnato recita la prima scena del film
ITA_FILL_item13	Il commissario scrupoloso ispeziona la casa abbandonata
ITA_FILL_item14	Il pulcino si lava le piume gialle con cura
ITA_FILL_item15	La cantina polverosa è pulita dalla zia Maria
ITA_FILL_item16	I rami dell'albero si muovono per il forte vento
ITA_FILL_item17	L'aereo pieno di turisti atterra puntuale a destinazione
ITA_FILL_item18	Le amiche allegre indossano vestiti colorati
ITA_FILL_item19	Lo scoiattolo avido corre verso le ghiande
ITA_FILL_item20	Il serpente velenoso è allontanato dal parco giochi
ITA_FILL_item21	Il pane appena sfornato è sul tavolo della cucina
ITA_FILL_item22	Il preside arrabbiato punisce gli studenti ritardatari
ITA_FILL_item23	Il calzolaio assonnato ripara le scarpe senza attenzione
ITA_FILL_item24	Il pizzaiolo pratico impasta la pizza con manualità
ITA_FILL_item25	Il tunnel vasto collega velocemente le due città
ITA_FILL_item26	Il ruscello veloce scorre lungo la pianura verdeggiante
ITA_FILL_item27	Il giornalaio mattutino consegna le riviste ai passanti
ITA_FILL_item28	L'edera folta cresce per tutto il muro
ITA_FILL_item29	Il cartolaio scocciato chiude il negozio in anticipo
ITA_FILL_item30	L'arcobaleno colorato si estende ad arco nel cielo
ITA_FILL_item31	Il camaleonte appena nato segue la sua mamma
ITA_FILL_item32	Il cammello assetato si dirige verso il pozzo
ITA_FILL_item33	I conigli affamati rosicchiano le carote appena comprate
ITA_FILL_item34	La bibliotecaria ripone i libri negli scaffali numerati
ITA_FILL_item35	L'attrice di film romantici consegna autografi agli ammiratori
ITA_FILL_item36	Il vaso di ceramica poggia in entrata
ITA_FILL_item37	Il marinaio solitario pulisce la vela
ITA_FILL_item38	Il calciatore famoso segna il goal della vittoria
ITA_FILL_item39	Lo chef del ristorante di lusso viene intervistato
ITA_FILL_item40	La maestra permissiva lascia giocare i bambini in giardino
ITA_FILL_item41	Il cantante promettente intona l'inno nazionale
ITA_FILL_item42	La babysitter giovane prepara la minestra ai bambini
ITA_FILL_item43	La cocorita canterina imita il suo padrone

ITA_FILL_item44	Il salotto appena imbiancato asciuga per molte ore
ITA_FILL_item45	Il comodino abbandonato contiene delle lettere antiche
ITA_FILL_item46	Il papà severo rimprovera i figli vivaci
ITA_FILL_item47	La lavandaia spazientita strofina le lenzuola con vigore
ITA_FILL_item48	Il cancello automatico permette l’entrata ai condomini
ITA_FILL_item49	La vicina timida scappa verso il portone del palazzo
ITA_FILL_item50	Gli scolari incostanti saltano la lezione di matematica
ITA_FILL_item51	I granchi appena nati prendono il sole sugli scogli
ITA_FILL_item52	Il collega pigro esce dall’ufficio prima del previsto
ITA_FILL_item53	La coccinella maculata cammina sopra le foglie verdi
ITA_FILL_item54	La zia generosa paga la pizza ai nipotini
ITA_FILL_item55	La torta prelibata è venduta alla famiglia festosa
ITA_FILL_item56	Il negoziante gentile serve i clienti con serietà
ITA_FILL_item57	Il colonnello baffuto addestra i soldati inesperti
ITA_FILL_item58	Le pecore affamate brucano l’erba della campagna
ITA_FILL_item59	Il lettore interessato compra un manuale storico
ITA_FILL_item60	Il bagnino preparato sorveglia la spiaggia affollata
ITA_FILL_item61	L’albergo frequentato offre camere a prezzi scontati
ITA_FILL_item62	Il salumiere disponibile imbottisce tutti i panini
ITA_FILL_item63	La finestra aperta lascia entrare un vento gelido
ITA_FILL_item64	La scimmia ammaestrata esegue il numero al circo
ITA_FILL_item65	Il giocatore incerto esita davanti ai suoi avversari
ITA_FILL_item66	La cesta di frutta cade dal tavolo instabile
ITA_FILL_item67	Il pesce palla nuota nelle acque più profonde
ITA_FILL_item68	La cartellina rossa contiene dei documenti importanti
ITA_FILL_item69	L’altoparlante acceso trasmette i cori del corteo
ITA_FILL_item70	Le tazze di cristallo poggiano salde sulla credenza
ITA_FILL_item71	I panni umidi sono stesi fuori dal balcone
ITA_FILL_item72	La mamma castoro protegge i piccoli dai serpenti
ITA_FILL_item73	Le vespe affannate cercano di costruire l’alveare
ITA_FILL_item74	Le stanze ampie ospitano gli invitati al ballo
ITA_FILL_item75	I calciatori dilettanti vincono l’ultima partita
ITA_FILL_item76	Il sacchetto rigido contiene l’occorrente per il pranzo
ITA_FILL_item77	La pecora di peluche è dimenticata sul pavimento
ITA_FILL_item78	la scopa usurata giace nel ripostiglio buio
ITA_FILL_item79	La rivista famosa vende milioni di copie l’anno
ITA_FILL_item80	La lontra prudente nuota vicino alla riva
ITA_FILL_item81	Il cantiere sicuro costruisce centinaia di navi
ITA_FILL_item82	L’inserviente smemorato arriva a lavoro in ritardo
ITA_FILL_item83	Il parroco caritatevole prepara pasti per i poveri
ITA_FILL_item84	La mamma chioccia nutre tutti i pulcini
ITA_FILL_item85	L’anello di diamanti brilla sotto la luce calda
ITA_FILL_item86	Le lucertole assonnate riposano tra le siepi
ITA_FILL_item87	I grilli canterini tengono svegli gli agricoltori
ITA_FILL_item88	La vedova tenace cuce a mano i vestiti
ITA_FILL_item89	Il ciclista snello pedala nelle salite meno ripide
ITA_FILL_item90	Gli animatori allegri ballano senza sosta

List of English sentences:

Item	**Sentence**
ENG_LEX_V_item1	The old grandparent decides to merlik
ENG_LEX_V_item2	The new white bag comes from my fludresh
ENG_LEX_V_item3	The little baby cries aloud all the mesby
ENG_LEX_V_item4	The black piano is played by the gloost
ENG_LEX_V_item5	The hot sun is shining above the linsing
ENG_LEX_V_item6	A strange person stands in front of my delms
ENG_LEX_V_item7	The lazy donkey waits for food without coosish
ENG_LEX_V_item8	A beautiful lady runs fast towards the bertish
ENG_LEX_V_item9	The sweet child gives a red rose to his pasish
ENG_LEX_V_item10	The bitter cherries fall from the high clyest
ENG_LEX_V_item11	The deserted house is overrun by corvest
ENG_LEX_V_item12	The hand painted handles cost more than pillish
ENG_LEX_V_item13	The orangutan sleeps peacefully close to the repowl
ENG_LEX_V_item14	The thirsty dromedary seeks the nearest rowlest
ENG_LEX_V_item15	The competitive bakers make cakes with great warnel
ENG_LEX_V_item16	The burned pancakes smell in the ellist
ENG_LEX_V_item17	The abandoned penguin moves to the sellones
ENG_LEX_V_item18	A violent storm terrifies the big kellind
ENG_LEX_V_item19	The freshwater fish swim in the wingle
ENG_LEX_V_item20	The tall runner wins the competition against the rispow
ENG_LEX_V_item21	The colored rainbow appears in the yospel
ENG_LEX_V_item22	The little eggs grow up under the poosty
ENG_LEX_V_item23	Fresh carrots give you lots of jessish
ENG_LEX_V_item24	The dehydrated pine drys under the powls
ENG_LEX_V_item25	The rich heiress squanders all her tennil
ENG_LEX_V_item26	The long hair cover the girl’s horrint
ENG_LEX_V_item27	The kind hostess welcomes travelers in the ronnes
ENG_LEX_V_item28	The thick forest scares the young nerpy
ENG_LEX_V_item29	The stamp collector buys a rare tullin
ENG_LEX_V_item30	The Ingenious spider spins slowly his deelis
ENG_SEM_V_item1	The big dog lies in his colored air
ENG_SEM_V_item2	The green bottle contains some strange numb
ENG_SEM_V_item3	The little panda sleeps near the fear
ENG_SEM_V_item4	The unused papers are put on the nervous trashcan
ENG_SEM_V_item5	The smelly garbage is made up of strange love
ENG_SEM_V_item6	The dirty blackboard needs to be apple
ENG_SEM_V_item7	On the white desk is some glasses of jealousy
ENG_SEM_V_item8	The orange projector has pieces of weather
ENG_SEM_V_item9	The fire alarm flashes very bright cows
ENG_SEM_V_item10	The renovated boat floats on the metal door
ENG_SEM_V_item11	The factual books lies on the happiness
ENG_SEM_V_item12	The cordless phone rings ten times per joy
ENG_SEM_V_item13	The access card lets you have a snow
ENG_SEM_V_item14	The broken motorcycle has long pretty milk

ENG_SEM_V_item15	The black socks uses nice sound
ENG_SEM_V_item16	The new umbrella provides good chair
ENG_SEM_V_item17	The cheerful carpenter builds a innovative sarcasm
ENG_SEM_V_item18	The mountain climber writes a new wine
ENG_SEM_V_item19	The strong nurse cleans the pink comprehension
ENG_SEM_V_item20	The wrinkled shirt is worn by the loneliness
ENG_SEM_V_item21	The striped zebra walks on the apprehension
ENG_SEM_V_item22	The lion cub sleeps under the grammar
ENG_SEM_V_item23	The dog sitter reads a good freedom
ENG_SEM_V_item24	The video gamer bakes a tasteful bag
ENG_SEM_V_item25	The short grandmother hugs the nephew's music
ENG_SEM_V_item26	The gypsy girl eats the mother's collaboration
ENG_SEM_V_item27	The old magician walks on a green kindness
ENG_SEM_V_item28	The naïve duck flies through the completion
ENG_SEM_V_item29	The blue case protects the important excitement
ENG_SEM_V_item30	The spiky porcupine sharpens his many celebrations
ENG_SYN_V_item1	My cousin's restaurant is furnished by many table
ENG_SYN_V_item2	The sporty car is parked close to lots of house
ENG_SYN_V_item3	The elementary school has a lot of building
ENG_SYN_V_item4	The fat statue has one large mouths
ENG_SYN_V_item5	The brown glasses are made up of two lense
ENG_SYN_V_item6	The new sofa has a broken legs
ENG_SYN_V_item7	Some small mosquitos have six black eye
ENG_SYN_V_item8	The white snails slither through a big rocks
ENG_SYN_V_item9	The aggressive polar bear fights a seals
ENG_SYN_V_item10	The rich taxi driver has a fast cars
ENG_SYN_V_item11	The old hobo does not have a pillows
ENG_SYN_V_item12	The skinny seagull does not have a wings
ENG_SYN_V_item13	The spotted giraffe sleeps next to a trees
ENG_SYN_V_item14	The grey rhinoceros walks next to a rivers
ENG_SYN_V_item15	The wise owl grabs a small foxes
ENG_SYN_V_item16	The big wall has a lot of watch
ENG_SYN_V_item17	The poor farmer buys a small chickens
ENG_SYN_V_item18	The financial executive buys his first boats
ENG_SYN_V_item19	The experienced mason buys a large piece of woods
ENG_SYN_V_item20	The spacemen fly in a big spaceships
ENG_SYN_V_item21	The unemployed fireman saves a small cats
ENG_SYN_V_item22	The old baker cooks a delicous meals
ENG_SYN_V_item23	The young policeman hosts a good friends
ENG_SYN_V_item24	The trained doctor uses an expert techniques
ENG_SYN_V_item25	The pretty hairdresser gives a great discounts
ENG_SYN_V_item26	The bilingual translator goes to many conference
ENG_SYN_V_item27	Some tourist centers sell a lot of snack
ENG_SYN_V_item28	The funny janitor makes a lot of joke
ENG_SYN_V_item29	The electronic engineers buy a big pizzas
ENG_SYN_V_item30	The slow turtle has many small toe
ENG_FILLER_item1	The blond aunt walks very close to the river
ENG_FILLER_item2	The blue baby carriage transports the sleeping child

ENG_FILLER_item3	The delicious cake is cooking in the oven
ENG_FILLER_item4	The little pony eats from the round bowl
ENG_FILLER_item5	The angry bull shoots toward the young matador
ENG_FILLER_item6	The annoying flies buzz around the plate
ENG_FILLER_item7	A gold swimsuit stands in the shop window
ENG_FILLER_item8	Black cats are discriminated against because of their colour
ENG_FILLER_item9	Protective kangaroos keep puppies in their pouches
ENG_FILLER_item10	The girl hears bad comments about her looks
ENG_FILLER_item11	The lady sells a portrait of her father
ENG_FILLER_item12	The active crowd shouts slogans about peace
ENG_FILLER_item13	The interested boys hear stories about Africa
ENG_FILLER_item14	Wendy sees pictures of her best friends
ENG_FILLER_item15	The man admires a sketch of the landscape
ENG_FILLER_item16	The woman ignores complaints about the noise
ENG_FILLER_item17	The curious children enjoy stories about the farm
ENG_FILLER_item18	The newspaper prints a picture of the accident
ENG_FILLER_item19	The daughter enjoys cartoons about animals
ENG_FILLER_item20	The bored boys see films about America
ENG_FILLER_item21	The suspicious agent reads a report of the case
ENG_FILLER_item22	The informed scientist criticizes a proof of the theorem
ENG_FILLER_item23	The intoned students sing songs about freedom
ENG_FILLER_item24	The famous firm needs ideas about marketing
ENG_FILLER_item25	The editor publishes a report about drugs
ENG_FILLER_item26	The mayor discusses a speech about migrants
ENG_FILLER_item27	The serious judge reads an article about crime
ENG_FILLER_item28	The inexpert visitors accept advice about the money
ENG_FILLER_item29	Most nostalgic people enjoy stories about the past
ENG_FILLER_item30	The poet praises a poem about the moon
ENG_FILLER_item31	The new company asks for advice about taxes
ENG_FILLER_item32	The repaired elevator goes to the sixth floor
ENG_FILLER_item33	The cheerful dolphin jumps through the circle
ENG_FILLER_item34	The pink flamingo stands on one leg
ENG_FILLER_item35	The hungry pig seeks food in the manger
ENG_FILLER_item36	The transparent jellyfish scares the vacationers
ENG_FILLER_item37	The fresh salmon is cooking on the hot griddle
ENG_FILLER_item38	The disoriented mole digs under the ground
ENG_FILLER_item39	The busy architect proposes several houses
ENG_FILLER_item40	The rich dentist extracted the wisdom teeth
ENG_FILLER_item41	The occupational psychologist interviews the candidates
ENG_FILLER_item42	The pediatrician visits the children with fever
ENG_FILLER_item43	The careful volunteer distributes the meal to everyone
ENG_FILLER_item44	The ice cream man serves several families
ENG_FILLER_item45	The bright Christmas trees liven up the city
ENG_FILLER_item46	The pharmacies of the city work at night
ENG_FILLER_item47	The bamboo grows tall close to the river
ENG_FILLER_item48	The doghouse hosts many abandoned animals
ENG_FILLER_item49	The fountain pen writes smoothly on the parchment
ENG_FILLER_item50	The children's snack is full of vitamins

ENG_FILLER_item51	The international conference starts on time
ENG_FILLER_item52	The picnic basket contains many sandwiches
ENG_FILLER_item53	The famous DJ arrives with two bodyguards
ENG_FILLER_item54	The smart girl graduates with full marks
ENG_FILLER_item55	The beaches of the south coast are the best
ENG_FILLER_item56	The traffic wardens show the alternative route
ENG_FILLER_item57	The airport is closed because of bad weather
ENG_FILLER_item58	The poor man wins a lot of money
ENG_FILLER_item59	All the canadaian citizens watch the hockey game
ENG_FILLER_item60	The beach umbrella moves because of the wind
ENG_FILLER_item61	The dishes full of meat arrive on the table
ENG_FILLER_item62	The loud radio transmits the best hits
ENG_FILLER_item63	The large roundabout makes the traffic run smoothly
ENG_FILLER_item64	The blue suitcase contains summer clothes
ENG_FILLER_item65	The cold winter season continues to persist
ENG_FILLER_item66	A big whale swims not far from the beach
ENG_FILLER_item67	The speech therapist helps the children of the school
ENG_FILLER_item68	The egyptian museum is open late everyday
ENG_FILLER_item69	The small child scribbles in the notebook
ENG_FILLER_item70	The newly stocked supermarket offers fresh fruit
ENG_FILLER_item71	The birthday party begins in the afternoon
ENG_FILLER_item72	The square-shaped pack contains a beautiful dress
ENG_FILLER_item73	The frozen cocktail refreshes the thirsty guests
ENG_FILLER_item74	A wooden torch marks the dark way
ENG_FILLER_item75	The leather purse costs more than the fabric one
ENG_FILLER_item76	The gas fireplace heats up the cold room
ENG_FILLER_item77	The pointy knife opens the packed boxes
ENG_FILLER_item78	The vintage car carries the bride to the church
ENG_FILLER_item79	The playing cards are set on the green table
ENG_FILLER_item80	The color printer requires new cartridges
ENG_FILLER_item81	The famous library requires tickets for entry
ENG_FILLER_item82	An unfinished manuscript reveals a great secret
ENG_FILLER_item83	The pregnant woman buys blue clothes
ENG_FILLER_item84	An elegant butler welcomes the hosts
ENG_FILLER_item85	The colored pens leave their ipermenant mark
ENG_FILLER_item86	The pendulum clock strikes at midnight
ENG_FILLER_item87	The tall basketball player pulls toward the basket
ENG_FILLER_item88	The rushed cashier forgets to give the receipt
ENG_FILLER_item89	The computer mouse falls from the desk
ENG_FILLER_item90	Disney cartoons keep children entertained

List of LIS sentences:

Item	**Sentence**
LIS_SEM_V_item1	L’uomo biondo la macchina mangia
LIS_SEM_V_item2	Lo zio pensionato un cavallo pesca
LIS_SEM_V_item3	Il ferramenta distratto, una pietra abita

LIS_SEM_V_item4	La mamma dal pescivendolo, una finestra compra
LIS_SEM_V_item5	Il pesciolino rosso sotto il mare stampa
LIS_SEM_V_item6	La terra bagnata, dal grattacielo è venduta
LIS_SEM_V_item7	La torre disabitata, dagli animali è dipinta
LIS_SEM_V_item8	Nell'albero rigoglioso, una bottiglia nasce
LIS_SEM_V_item9	Le piante grandi il vulcano preoccupano
LIS_SEM_V_item10	La fitta grandine, le case regala
LIS_SEM_V_item11	La bicicletta nuova, la mamma nuota
LIS_SEM_V_item12	L'agenda piena di impegni sul tavolo si vergogna
LIS_SEM_V_item13	La coperta sottile l'armadio rompe
LIS_SEM_V_item14	La bambola di pezza l'ascensore ferma
LIS_SEM_V_item15	La porta vecchia dalle chiavi è dipinta
LIS_SEM_V_item16	Nel giardino grande la neve impara
LIS_SEM_V_item17	Il negozio il panettiere mattutino impasta
LIS_SEM_V_item18	La colomba premurosa i figli scrive
LIS_SEM_V_item19	Il grande autobus compra il bambino
LIS_SEM_V_item20	Il giocoliere sicuro le palline colorate incuriosisce
LIS_SEM_V_item21	Lo studente intelligente le ripetizioni annaffia
LIS_SEM_V_item22	I parcheggi sono separati dalla simpatia
LIS_SEM_V_item23	I cespugli spinosi il portafoglio cantano
LIS_SEM_V_item24	Gli stivali nuovi la ragazza ricordano
LIS_SEM_V_item25	I ragazzi urlanti la pizza ballano
LIS_SEM_V_item26	La maglia di lana una lucertola paga
LIS_SEM_V_item27	Il quaderno di appunti un animale licenzia
LIS_SEM_V_item28	La moto in corsa dal vento è pitturata
LIS_SEM_V_item29	I pesci nel laghetto un'alga sfogliano
LIS_SEM_V_item30	Il falò acceso un indiano arrampica
LIS_SIN_V_item1	Gli studenti la lavagna copiano
LIS_SIN_V_item2	La maestra lo studente i compiti insiste su di se
LIS_SIN_V_item3	Il treno arriva in stazione, treno segnato in orizzontale
LIS_SIN_V_item4	Al mare la sabbia una ragazza abbronzata cammina
LIS_SIN_V_item5	C'è un fiore il bambino lo prende da un altra parte
LIS_SIN_V_item6	Gianni festa di compleanno io regalo comprato e lo do a me
LIS_SIN_V_item7	Io arrivo in aeroporto motivo vacanza, aereo decolla, decollare verso il basso
LIS_SIN_V_item8	Francesco casa sua idraulico aggiusta il lavandino, finito, da i soldi a se stesso
LIS_SIN_V_item9	Oggi Giulia laurea fatto, messaggio inviare voglio a me
LIS_SIN_V_item10	L'esame di biologia passato fatto non
LIS_SIN_V_item11	Cugina mia Islanda toccato fatto non
LIS_SIN_V_item12	Anna lavoro contratto non firmare
LIS_SIN_V_item13	Alberto oggi studiare deve. Libro lì. Prende libro in un'altra direzione.
LIS_SIN_V_item14	Il bandito mascherato la donna uccide, uccide da un'altra parta
LIS_SIN_V_item15	La ragazza entra nel negozio, vestito verde vuole. Prende da un'altra parte.
LIS_SIN_V_item16	L'elettricista l'allarme della casa non sistema

LIS_SIN_V_item17	Il pompiere il gattino piccolo dall'incendio non salva
LIS_SIN_V_item18	La mamma porta il bambino a scuola, porta un pacco anzichè il bambino
LIS_SIN_V_item19	Al convegno Mario relatore domanda vuole. Segno di domanda in altra direzione.
LIS_SIN_V_item20	Stadio lì. Stasera concerto. Alice va (in altra direzione)
LIS_SIN_V_item21	Lisa montagna, a nord, andare deve motivo matrimonio. Va verso sud.
LIS_SIN_V_item22	Persona fiori vende aprire negozio vuole. Apre da un'altra parte.
LIS_SIN_V_item23	Al supermercato una bottiglia di acqua comprato fatto non
LIS_SIN_V_item24	Torta al cioccolato preparato fatto non
LIS_SIN_V_item25	L'albero ciliegie fatto non
LIS_SIN_V_item26	Sara libro non legge
LIS_SIN_V_item27	Casa delle vacanze non costruita
LIS_SIN_V_item28	Oggi fa caldissimo, io voglio andare in piscina e mi tuffo da un altra parte.
LIS_SIN_V_item29	Pesce rosso dentro la boccia. Gatto lo vede, lo vuole. Zampata in un'altra direzione.
LIS_SIN_V_item30	Forbice nuova fogli non taglia
LIS_LESS_V_item1	L'aria condizionata rinfresca l'ambiente caldo
LIS_LESS_V_item2	La bambina bionda vede il disegno di un cane
LIS_LESS_V_item3	La mendicante allegra beve del vino rosso
LIS_LESS_V_item4	La casa editrice rifiuta di pubblicare il libro horror
LIS_LESS_V_item5	Il negozio di estetica regala campioncini di shampoo
LIS_LESS_V_item6	La bambina dispettosa ruba il giocattolo al fratello
LIS_LESS_V_item7	La disegnatrice di mobili crea un nuovo modello di cucina
LIS_LESS_V_item8	Il ferro da stiro rimane acceso tutta la notte
LIS_LESS_V_item9	Il magazziniere trasporta carichi molto pesanti
LIS_LESS_V_item10	I passanti guardano le vetrine di vestiti costosi
LIS_LESS_V_item11	Le ceste di vimini contengono l'uva raccolta
LIS_LESS_V_item12	La classe di bambini parte per la gita scolastica
LIS_LESS_V_item13	Il musicista jazz è applaudito dalla grande folla
LIS_LESS_V_item14	La grande campana della chiesa suona ogni ora
LIS_LESS_V_item15	Il copridivano in stoffa protegge dalle macchie
LIS_LESS_V_item16	Il pastore tedesco è considerato un cane socievole
LIS_LESS_V_item17	Gli anziani accuditi chiacchierano nella sala ricreativa
LIS_LESS_V_item18	I festeggiamenti del matrimonio continuano fino a tardi
LIS_LESS_V_item19	I fumatori accaniti danneggiano gravemente i polmoni
LIS_LESS_V_item20	La mamma di Antonio compra una crostata per pranzo
LIS_LESS_V_item21	Le stelle cadenti si ammirano nelle notti estive
LIS_LESS_V_item22	Il figlio della maestra corre nelle aule di informatica
LIS_LESS_V_item23	Mangiare verdura è fondamentale per una dieta sana
LIS_LESS_V_item24	Lo studente ansioso riceve bei voti nella pagella
LIS_LESS_V_item25	Le fragole rosse abbelliscono la torta di compleanno
LIS_LESS_V_item26	La poliziotta discreta entra a controllare nel negozio
LIS_LESS_V_item27	Il gelato fresco è servito con la panna
LIS_LESS_V_item28	La papera bianca siede vicino al canale

LIS_LESS_V_item29	L’aragosta appena pescata scappa verso il mare
LIS_LESS_V_item30	Il piccolo cerbiatto cammina dietro la sua mamma
LIS_FILLER_item1	La figlia del salumiere mangia un panino
LIS_FILLER_item2	L’aquila reale vola libera sopra la città
LIS_FILLER_item3	Il coiote selvatico scappa dai bracconieri
LIS_FILLER_item4	La candela di cera non consuma energia elettrica
LIS_FILLER_item5	Lo stagno vasto ospita una famiglia di rane
LIS_FILLER_item6	L’interprete professionale lavora alla conferenza
LIS_FILLER_item7	I porcellini d’india appena nati dormono nella cesta
LIS_FILLER_item8	La giovane badante accompagna la signora al parco
LIS_FILLER_item9	I coinquilini festosi organizzano una cena etnica
LIS_FILLER_item10	Il critico d’arte interviene alla presentazione della mostra
LIS_FILLER_item11	La moglie arrabbiata non prepara la cena
LIS_FILLER_item12	Il battello attracca saldo al porto di Napoli
LIS_FILLER_item13	La regina elegante attraversa la città in carrozza
LIS_FILLER_item14	Il tennista colpisce la palla con maestria
LIS_FILLER_item15	Il cliente maleducato lascia i vestiti in camerino
LIS_FILLER_item16	La guardia giurata controlla i passanti in aeroporto
LIS_FILLER_item17	Il bambino appena nato dorme gran parte della giornata
LIS_FILLER_item18	La lavanderia a gettoni è aperta 24 ore
LIS_FILLER_item19	La scuola di Michele organizza la festa estiva
LIS_FILLER_item20	La zia in bicicletta attraversa la piazza
LIS_FILLER_item21	La ragazza dai capelli rossi compra una pianta
LIS_FILLER_item22	Il pesce rosso nuota annoiato nell’acquario
LIS_FILLER_item23	La casalinga impegnata rammenda dei pantaloni
LIS_FILLER_item24	La zia vuole tagliare i capelli e va dal parrucchiere
LIS_FILLER_item25	Il maialino addomesticato gioca con una palla
LIS_FILLER_item26	L’apprendista inesperta prende appunti attentamente
LIS_FILLER_item27	Il gregge ammaestrato entra nel recinto
LIS_FILLER_item28	La centralinista risponde gentilmente alle chiamate
LIS_FILLER_item29	La star della serata posa per le fotografie
LIS_FILLER_item30	Il bambino irrequieto chiede la favola della buonanotte
LIS_FILLER_item31	La fata delle fiabe aiuta sempre i protagonisti
LIS_FILLER_item32	Il fidanzato distratto dimentica il giorno dell’anniversario
LIS_FILLER_item33	Lo spremiagrumi inutilizzato è riposto nella scatola
LIS_FILLER_item34	Il parcheggiatore attento riporta la macchina al cliente
LIS_FILLER_item35	La damigiana di vino poggia al centro del banchetto
LIS_FILLER_item36	Il pollo arrosto sfama la comitiva al mare
LIS_FILLER_item37	La cartolina da Malta arriva dopo molti mesi
LIS_FILLER_item38	La truccatrice capace prepara il trucco della sposa
LIS_FILLER_item39	I capi della fabbrica assumono nuovo personale
LIS_FILLER_item40	Il politico battagliero vince la campagna elettorale
LIS_FILLER_item41	Il coro melodico si esibisce nell’arena di Verona
LIS_FILLER_item42	Il trapezista compie il suo numero migliore al circo
LIS_FILLER_item43	La giovane coppia entra nell’agenzia immobiliare
LIS_FILLER_item44	Il cartello stradale indica un divieto d’accesso
LIS_FILLER_item45	La cagnolina incinta partorisce dal veterinario
LIS_FILLER_item46	L’ubriaco al bar spende tutti i suoi soldi

LIS_FILLER_item47	Il commercialista programma i suoi appuntamenti
LIS_FILLER_item48	Il coordinatore dell’evento distribuisce i dépliant
LIS_FILLER_item49	Il nonno ripara la vecchia macchina da scrivere
LIS_FILLER_item50	Il bravo surfista americano si allena tra le onde
LIS_FILLER_item51	La tigre accaldata dorme sotto un albero
LIS_FILLER_item52	Il tirocinante bravo entra nella stanza
LIS_FILLER_item53	L’archeologo famoso è invitato a scuola
LIS_FILLER_item54	Gli scommettitori puntano sul cavallo vincente
LIS_FILLER_item55	I viaggiatori organizzano una cassa comune
LIS_FILLER_item56	Il giostraio mette in funzione le astronavi volanti
LIS_FILLER_item57	La frutta secca è consigliata per chi fa sport
LIS_FILLER_item58	La pianta grassa ha bisogno di poca acqua
LIS_FILLER_item59	La collega raffreddata beve una spremuta d’arancia
LIS_FILLER_item60	I burattinai provano lo spettacolo
LIS_FILLER_item61	La segreteria studenti apre solo la mattina
LIS_FILLER_item62	Il corallo rosso è utilizzato per fare gioielli
LIS_FILLER_item63	Gli attestati di partecipazione sono consegnati all’ingresso
LIS_FILLER_item64	Il borsone pesante contiene molti libri
LIS_FILLER_item65	Le lenti a contatto possono essere fastidiose
LIS_FILLER_item66	Venezia è famosa per i suoi canali
LIS_FILLER_item67	Il grafico apre uno studio in centro città
LIS_FILLER_item68	Il cortile della scuola è addobbato per natale
LIS_FILLER_item69	I balli in maschera riscuotono tanto successo
LIS_FILLER_item70	Le sirene dell’acqua alta suonano in anticipo
LIS_FILLER_item71	Il casello autostradale è fuori servizio
LIS_FILLER_item72	La suocera compra un regalo per la nuora
LIS_FILLER_item73	Lo scivolo del parco rallegra i bambini
LIS_FILLER_item74	La riunione annuale si tiene in aula magna
LIS_FILLER_item75	I partecipanti alla competizione ricevono una medaglia
LIS_FILLER_item76	La banca attenta si prende cura dei suoi clienti
LIS_FILLER_item77	Il pilota dell’aereo esegue dolcemente l’atterraggio
LIS_FILLER_item78	Gli abbonamenti semestrali sono i più convenienti
LIS_FILLER_item79	I saldi nell’abbigliamento iniziano tra due settimane
LIS_FILLER_item80	Gli artisti di strada suonano dalla mattina
LIS_FILLER_item81	Il trombettista entra nel negozio di musica
LIS_FILLER_item82	Gli abitanti dell’isola mangiano spesso pesce
LIS_FILLER_item83	Le cantine vinicole offrono aperitivi nei weekend
LIS_FILLER_item84	La donna preoccupata chiama la scuola del figlio
LIS_FILLER_item85	Il garage vuoto si affitta per i mesi estivi
LIS_FILLER_item86	La forchetta di plastica si rompe con facilità
LIS_FILLER_item87	Il grosso rospo salta di foglia in foglia
LIS_FILLER_item88	Le medicine alleviano momentaneamente il mal di testa
LIS_FILLER_item89	Lo scorpione può essere molto pericoloso
LIS_FILLER_item90	Il cane bassotto cammina in modo goffo

APPENDIX D

- Language proficiency and demographic data questionnaires. English version. A similar version has been presented for LIS participants.

QUESTIONARIO SULLA TUA STORIA LINGUISTICA

COD.___________

Ti ringraziamo per la tua partecipazione. Attraverso questo questionario intendiamo raccogliere informazioni relative la sua storia linguistica passata e presente. Ti preghiamo di rispondere nel modo più accurato possibile. Ogni dato che ci fornirà sarà trattato in forma confidenziale solamente dai collaboratori alla presente ricerca, così come specificato nel Foglio Informativo.

DATI ANAGRAFICI

DATA DI NASCITA ________________________

GENERE ☐M☐☐☐☐☐F

NAZIONALITA'____________________________

EDUCAZIONE PERSONALE *(indicare l'ultimo titolo educativo di cui è in possesso. Es. "diploma", "laurea triennale"...)*

____

OCCUPAZIONE ATTUALE

____

NAZIONALITA' MATERNA

____

NAZIONALITA' PATERNA

____

EDUCAZIONE MATERNA *(indicare l'ultimo titolo educativo del genitore)*

____

EDUCAZIONE PATERNA *(indicare l'ultimo titolo educativo del genitore)*

____

<u>INFORMAZIONI LINGUISTICHE</u>

Vorremmo farti delle domande sulla tua conoscenza passata e presente della lingua inglese.

1. Hai imparato l'inglese prima dei 6 anni?
☐ Sì ☐ No
Se si, come?__________________________

2. Qualcuno della tua famiglia è di madrelingua inglese? ☐ Sì ☐ No
Se si
- mio padre, con lui parlo ___________% del tempo in inglese
- mia madre con lei parlo ___________% del tempo in inglese
- un altro componente della famiglia___________ . Con lei/lui parlo ___________% del tempo in inglese

3. Hai studiato l'inglese a <u>scuola/università?</u>
☐ Sì ☐ No
Se si, da che età e per quanto tempo? Età:___________
tempo:______________

4. Hai studiato l'inglese presso una scuola privata (es. Oxford University, etc.)?
☐ Sì ☐ No
Se si, da che età e per quanto tempo? Età:___________
tempo:______________

5. Hai frequentato scuole bilingui italiano-inglese?
☐ Sì ☐ No
Se sì, indica anche a che età hai iniziato e per quanto tempo hai studiato in quella scuola:

A che età hai iniziato	Per quanto tempo
_____________________	_______________________________
_____________________	_______________________________
_____________________	_______________________________

6. In percentuale, quanto ritieni di aver usato (parlato, ascoltato, letto, scritto) la lingua inglese <u>durante la tua adolescenza</u>?

____

7. Quanto spesso ti è capitato di passare da una lingua all’altra (italiano-inglese / inglese-italiano) durante la tua adolescenza?

☐☐☐☐☐☐☐ ☐☐☐☐☐☐☐☐ ☐☐☐☐☐☐☐☐
☐☐☐☐☐☐☐ ☐☐☐☐☐☐☐☐

Mai☐☐☐☐☐☐ Raramente☐☐☐ Qualche volta Spesso Quasi sempre

8. In percentuale, quanto ritieni di usare (parlare, ascoltare, leggere, scrivere) attualmente la lingua inglese nella tua vita quotidiana?

____

9. Prendendo in considerazione la tua vita attuale, quanto spesso ti capita di passare da una lingua all’altra (italiano-inglese / inglese-italiano) nel tuo quotidiano?

☐☐☐☐☐☐☐ ☐☐☐☐☐☐☐☐ ☐☐☐☐☐☐☐☐
☐☐☐☐☐☐☐ ☐☐☐☐☐☐☐☐

Mai☐☐☐☐☐☐ Raramente☐☐☐ Qualche volta Spesso Quasi sempre

Vorremmo infine farti alcune domande relative alla tua percezione di competenza nella tua seconda lingua. Ti chiediamo di rispondere alle seguenti domande, utilizzando una scala da 1 a 10, dove:

1= Novizio Basso. Non è presente una reale abilità. Impossibilità a partecipare ad uno scambio conversazionale.
2= Novizio Medio. Può comunicare in modo minimale e con difficoltà, usando un numero isolato di parole o segni e frasi memorizzate.
3= Novizio Alto. Può comunicare con successo riguardo argomenti semplici. Uso di frasi brevi o incomplete, frequenti incomprensioni comunicative.
4= Medio Basso. Può padroneggiare con successo un numero limitato di compiti comunicativi, combinandoli e ricombinandoli in affermazioni brevi.
5= Medio Intermedio. Può padroneggiare con successo una varietà poco complicata di compiti comunicativi riguardo argomenti semplici (cibo, viaggi, famiglia, attività giornaliere…). Comunicazione con frasi complete e, spesso, con più frasi collegate tra loro.
6= Medio Alto. Può padroneggiare con successo una varietà poco complicata di compiti comunicativi e situazioni sociali che necessitano uno scambio di informazioni base. Alcune esitazioni ed errori possono comunque essere presenti.
7= Avanzato Basso. Partecipazione attiva a conversazioni informali e ad un numero più limitato di conversazioni formali e, a grado minore, a conversazioni connesse a eventi di lavoro, argomenti attuali, interessi personali etc. Uso in contesti professionali e formali per periodi brevi.
8= Avanzato Medio. Padroneggia con confidenza un grande numero di situazioni comunicative, sia formali che informali, riguardo una varietà di argomenti concreti. Riesce a destreggiarsi in un ambiente formale e professionale, ma non in modo continuato e con una vasta gamma di argomenti.
9= Avanzato Alto. Può partecipare a pieno ad una grande varietà di argomenti e situazioni, sia formali che informali, sia concrete che astratte. Anche se alcuni errori possono ancora essere presenti, questi non interferiscono con la comunicazione.
10= Superiore. Produzione al pari di un comunicatore nativo della lingua. Possono esserci ancora errori occasionali che non interferiscono nella comunicazione.

PRODUZIONE

1. Prendendo in considerazione tutti i contesti della tua vita quotidiana in cui usi la lingua inglese per comunicare, come valuti la tua capacità di PRODUZIONE in inglese, in base alla scala fornita?

☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
1	2	3	4	5	6	7	8	9	10

COMPRENSIONE

2. Prendendo in considerazione tutti i contesti della tua vita quotidiana in cui usi la lingua inglese per comunicare, come valuti la tua capacità di COMPRENSIONE in inglese, in base alla scala fornita?

☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
1	2	3	4	5	6	7	8	9	10

SCRITTURA

3. Prendendo in considerazione le situazioni in cui ti capita di SCRIVERE in inglese, come valuti la tua capacità di scrittura, in base alla scala fornita?

☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
1	2	3	4	5	6	7	8	9	10

LETTURA

4. Prendendo in considerazione le situazioni quotidiane in cui ti capita di LEGGERE in inglese, come valuti la tua capacità di lettura, in base alla scala fornita?

☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
1	2	3	4	5	6	7	8	9	10

__________________ **Grazie per la collaborazione** ______________________

APPENDIX E

- **Multilingual Naming Test** (Gollan Weissberger, Runnqvist, Montoya & Cera, 2012) Italian and LIS adaptation.

Stimuli. 68 line drawings images were used as stimuli. The pictures are presented in order of increasing difficulty, from the most frequent/common object to the less frequent/common one. The frequency based on the order of every picture was controlled through the same databases used for the other two production tasks (COLFIS for Italian and LIS and CELEX for English). To avoid the influence of one language to the other one, the respective translation of every image was also checked in order to verify the presence of cognates among the two languages (Italian and English). No one of the figures had similar names across the languages. The material presented (the 68 line drawings images), was the same for L1 and L2. This means that participants performed the task, naming the same pictures in the two languages.

Procedure. Participants were positioned in front of a computer screen and their task was to name as accurately as possible the picture presented in the center of the screen, through a PowerPoint presentation. For Italian and English, the responses were manually registered by the experimenter through a scoring grid. When assessing LIS performance, the responses have been filmed using a camera for post-test scoring. After giving the response participants were instructed to press the space bar to see the next picture. The experimenter could not give any indication or suggestion, but in the case in which the participants did not recognized the image, she gave a semantic prompts related to the object. This was decided because the figures have been drawing in a way similar to handmade and sometimes the participants were not able to recognize the image. For example, the image of the “hinge” (“cardine” in Italian), was described by the experimenter as the object usually placed in doors or windows. A similar procedure has been used for LIS. In this condition participants’ responses were video recorded.

Scoring. The word produced in response of every picture has been collected by the experimenter. Errors could be omissions or wrong words/signs. Wrong responses in Italian have been evaluated by the experimenter. Wrong responses in English have been evaluated by the experimenter and checked in the list of items for English by Gollan et al. (2012). Wrong responses in LIS have been evaluated by a LIS signer. In the case of ambiguous responses in LIS, this was double checked by a second signer. Synonyms, of the target words/signs were considered correct. One point was assigned for each correct answer and “zero” for the wrong responses or omissions. Given that there were 68 target pictures, the final score obtained for each participant could reach a maximum of 68.

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> "*If you talk to a man in a language he understands, that goes to his head. If you talk to him in his language, that goes to his heart*."
>
> Nelson Mandela

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