Exploring the ventral white matter language network in bimodal and unimodal bilinguals

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ABSTRACT

We used diffusion magnetic resonance imaging tractography to investigate the effect of language modality on the anatomy of the ventral white matter language network by comparing unimodal (Italian/English) and bimodal bilinguals (Italian/Italian Sign Language). We extracted the diffusion tractography measures of the Inferior Longitudinal fasciculus (ILF), Uncinate fasciculus (UF) and Inferior Fronto-Occipital fasciculus (IFOF) and we correlated them with the degree of bilingualism and the individual performance in fluency tasks. For both groups of bilinguals, the microstructural properties of the right ILF were correlated with individual level of proficiency in L2, confirming the involvement of this tract in bilingualism. In addition, we found that the degree of left lateralization of the ILF predicted the performance in semantic fluency in L1. The microstructural properties of the right UF correlated with performance in phonological fluency in L1, only for bimodal bilinguals. Overall, the pattern shows both similarities and differences between the two groups of bilinguals.

1. Introduction

Bilingualism offers a unique opportunity to investigate the effect of experience on the function and structure of the brain. Learning and using a second language is an impressive example of neuroplasticity, involving changes in the gray and white matter (WM), as well as in subcortical regions. Structural changes may occur rapidly and at all ages (see Hayakawa & Marian, 2019; Li, Legault, & Litcofsky, 2014 for reviews). The composite pattern of brain structures that are modulated by bilingualism has been interpreted as the consequence of the specific linguistic experience of bilingual individuals. Recent approaches to the issue converge on the idea that structural changes follow a dynamic trajectory that reflects the processing needs that bilingual individuals have to face in order to be proficient in two (or more) languages (DeLuca, Rothman, & Pliatsikas, 2019; Green & Abutalebi, 2013; Grundy, Anderson, & Bialystok, 2017; Li et al., 2014; Pliatsikas, 2020).

Bilingual experience might differ in several respects. A relevant one is the modality of the languages used. Bilinguals might know/use two spoken languages (unimodal bilinguals, UB) or a signed and a spoken language (bimodal bilinguals, BBs). Given the non-overlapping input and output modality of the two languages, BBs represent an interesting testing case that allows distinguishing structural changes associated to the activation of abstract/amodal linguistic representations from those associated to the activation of sensory-motor representations during language processing. In addition, the comparison between UBs and BBs might inform regarding the role of inhibitory control in language processing. Thanks to the separated input-output systems, BBs - differently from UBs - can produce both languages simultaneously. This phenomenon, called code-blending, occurs quite frequently in the BB experience, where the production of a spoken word and the corresponding sign may be often combined (Emmorey, Luk, Pyers, & Bialystok, 2008). Code-blends suggest that the production system might access two lexical representations without costs, supporting the idea that control demands might be weakened for BBs in comparison to UBs (Emmorey, Borinstein, Thompson, & Gollan, 2008). In the present study we compared a group of UBs and a group of BBs by focusing on the structural modification of three ventral tracts of the brain, namely the Inferior Longitudinal fasciculus (ILF), the Uncinate fasciculus (UF), and the Inferior Fronto-Occipital fasciculus (IFOF) (see Fig. 1).

These ventral tracts are part of a pathway connecting the prefrontal cortex with the association cortices in the temporal and occipital lobes and might be involved in the integration of information across different domains and modalities. The connection might be bidirectional, allowing the prefrontal cortex to bias posterior brain structures and to adapt

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to task demands (Weiller et al., 2021). Of relevance for the present study, structural modulations of these tracts have been associated with bilingualism. A variety of studies using different imaging techniques report increased integrity of IFOF and UF in old life-long UBs (Luk, Bialystok, Craik, & Grady, 2011), in early UB children (Mohades et al., 2012; 2015), in young highly immersed sequential UBs (Pliatsikas et al., 2015), in early adult UBs (Hämäläinen, Sairanen, Leminen, & Lehtonen, 2017), and in late adult UBs (Rossi, Cheng, Kroll, Diaz, & Newman, 2017). Enhancement of WM integrity of the ILF has been found associated with the degree of L2 experience and learning in UBs (Nichols & Joanisse, 2016; Hosoda, Tanaka, Nariai, Honda, & Hanakawa, 2013; Rossi et al., 2017). Other studies report the opposite pattern, with monolinguals showing higher diffusivity values than UBs (Cummine & Boliek, 2013; Gold, Johnson, & Powell, 2013; Kuhl et al., 2016; Vaughn, Nguyen, Ronderos, & Hernandez, 2021; see Hayakawa & Marian, 2019; Li et al., 2014; Pliatsikas, 2020 for extensive reviews).

With this in mind here we investigate for the first time the microstructural properties of these tracts in UB and BB by means of diffusion magnetic resonance imaging tractography (DTI). We adopted the Spherical Deconvolution approach (Tournier, Calamante, Gadian, & Connelly, 2004; Dell'Acqua et al., 2010, 2013) that has two advantages: (i) to characterize the orientation of more than one fiber per voxel, and (ii) to overcome the crossing fibers problem thus reducing the presence of false negatives (Dell'Acqua & Catani, 2012). To characterize the structure of WM fibers, we utilized the following set of diffusivity measures: (a) the Volume of the fiber; (b) the Hindrance Modulated Orientational Anisotropy (HMOA), a true tract-specific index better reflecting the microstructural organization of tracts in comparison to the more classical Fractional Anisotropy (FA) measure (Dell'Acqua, Simmons, Williams, & Catani, 2013); (c) the Axial diffusivity (AD), that represents the mean diffusion coefficient of water molecules diffusing parallel to the tract; (d) Radial Diffusivity (RD), that represents the mean diffusion coefficient of water molecules diffusing perpendicular to the tract. For HMOA and Volume, we calculate the laterality indexes that

represent a measure of the left-right asymmetry in the microstructure of the tract. This index could reveal whether the anatomical lateralization of the ventral tracts is associated to the functional lateralization of language (Catani et al., 2007; for a review see Ocklenburg, Friedrich, Güntürkün, & Genç, 2016). There is substantial evidence for such association concerning the dorsal white matter tracts, especially the AF (Catani et al., 2007; 2010; Powell et al., 2006; Barrick, Lawes, Mackay, & Clark, 2007), but whether this association extends to the ventral tracts and to what extent is related to bilingualism and language modality have still to be disclosed.

In order to investigate the effect of L2 modality on the brain structure we compared the correlations between the DTI measures and the degree of bilingualism obtained for BBs and UBs. In addition, to evaluate whether signed and spoken languages were supported by different processing neural networks, we compared the correlations between the DTI measures with the performance in a fluency task, a classic test for language and executive function assessment.

The effects of the use of a signed language on the brain have been estimated by comparing bimodal bilinguals with monolinguals (and/or deaf), potentially confounding the effect of deafness, bilingualism, and sign language use. These studies used Voxel-Based morphometry and showed anatomical differences between hearing bimodal bilinguals and monolinguals (or deaf) in areas not typically involved in language processing, which have been interpreted as the increased need of cross-modal integration or higher demands of visual-spatial processing related to signed languages (e.g., Allen, Emmorey, Bruss, & Damasio, 2008; McCullough & Emmorey, 2020). To the best of our knowledge, no previous studies directly compared unimodal and bimodal bilinguals on structural measures. This was the main aim of the present study.

In addition, and differently from prior research, in which the effects of bilingualism have been investigated by comparing the structural differences between groups, the present study compared how structural measures correlated with individual variables in the two groups of bilinguals. Such correlational approach has the advantage to highlight
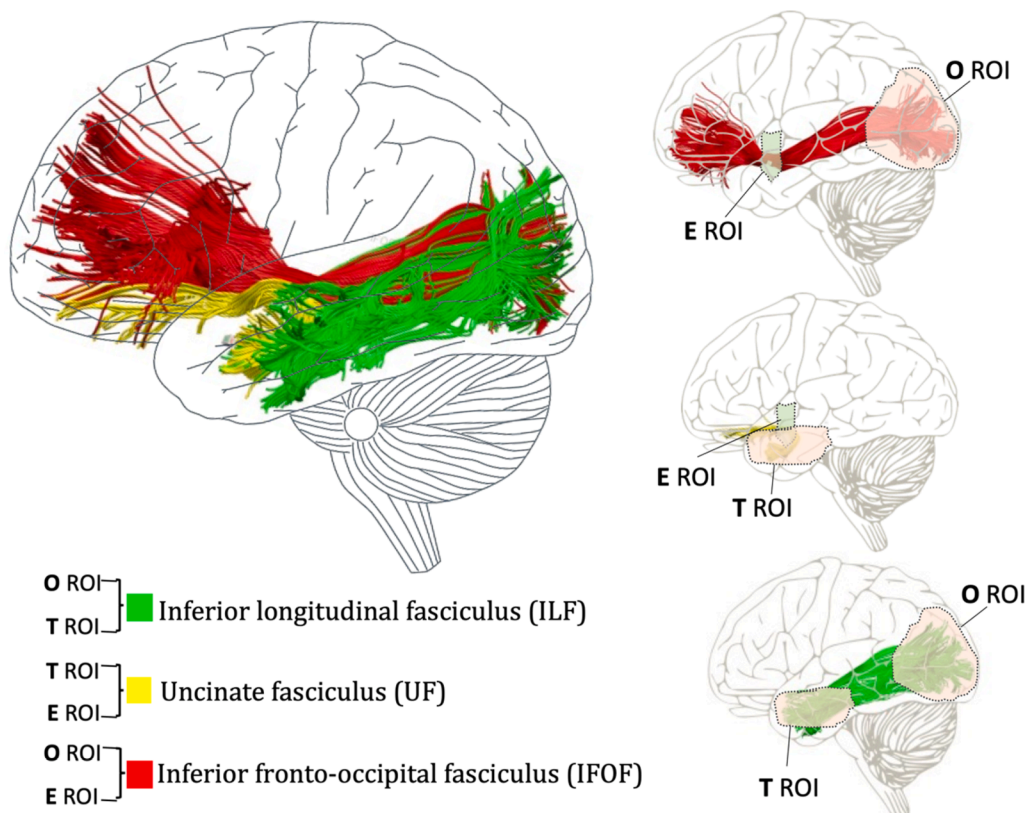
Fig. 1. An example (Subj. 110) of the virtual dissection of the ventral language network tracts in the left hemisphere. The Inferior Longitudinal Fasciculus (ILF; green), the Uncinate Fasciculus (UF; yellow), the Inferior Fronto-Occipital Fasciculus (IFOF; red). The ROIs in the temporal (T), occipital (O) and external-extreme capsule (E) region were delineated according to Catani et al., (2008) and used for the dissections. See the *Dissections* paragraph within the Method section for details. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

O ROI
T ROI — Inferior longitudinal fasciculus (ILF)

T ROI
E ROI — Uncinate fasciculus (UF)

O ROI
E ROI — Inferior fronto-occipital fasciculus (IFOF)

what are the WM changes associated to L2 experience and processing according to modality, disclosing both similarities and differences between the spoken and signed L2.

1.1. Structural changes and individual variables of L2 acquisition, proficiency, and use

As recently suggested by DeLuca et al. (2019) bilingualism can be hardly defined as a categorical variable i.e. being or not being bilingual, but it is better envisaged as a complex dynamic experience modulated by several variables with a partially independent impact on brain structure. Several studies correlated age of L2 acquisition, and amount/quality of L2 immersion with structural changes, not always revealing a linear pattern of adaptation (see Hayakawa & Marian, 2019; Pliatsikas, 2020 for reviews). In UBs age of L2 acquisition has been shown to be correlated with structural modifications of several brain areas, such as the inferior frontal gyrus (Klein, Mok, Chen, & Watkins, 2014) the angular gyrus (Wei et al., 2015), the left insula, the right dorsolateral prefrontal cortex, and the occipital areas, bilaterally (Berken, Gracco, Chen, & Klein, 2016). L2 proficiency was correlated with GM density in the left IFG, inferior parietal lobule, and Hersch's gyrus. The level of L2 immersion was shown to modulate the volume of subcortical regions mainly involved in the control of more than one language (Berken et al., 2016; Pliatsikas, DeLuca, Moschopoulou, & Saddy, 2017).

As for the WM modulations related to experiential variables, Nichols and Joanisse (2016) combining fMRI and DTI data, reported that WM tracts in UBs seem to be independently modulated by age of acquisition and/or proficiency. FA values of the left ILF, Arcuate Fasciculus (AF), and Corpus Callosum (CC) were correlated with L2 age of acquisition (AoA) whereas FA values of the right ILF, right AF, and the forceps of the CC were correlated with L2 proficiency. Rossi et al. (2017), using tract-based spatial statistics (TBSS), showed that FA values in a number of tracts of the left hemisphere including the ILF, IFOF and UF were correlated to L2 AoA, but not to the level of L2 proficiency or L2 immersion. In a more recent TBSS study, Del Maschio et al. (2020) found that in sequential UBs the amount of usage of L2, and not the AoA or standardized levels of proficiency, correlated with FA of several WM tracts. Investigating resting-state functional connectivity, Sulpizio, Del Maschio, Del Mauro, Fedeli, and Abutalebi (2020), showed the role of both individual and joint effects of experiential variables in modulating brain connectivity. Furthermore, a modulation of the lateralization of the AF as a function of the age at which L2 was acquired has been reported, suggesting that early bilingualism is associated with a more balanced structural organization of the perysilvian language tracts (Hämäläinen et al., 2017). Xiang (2015), in line with other results in the literature showing a stronger involvement of the right hemisphere for less proficient bilinguals, showed a shift towards the right lateralization of temporal areas mainly along the AF at the beginning of an intensive L2 training, which disappeared at the end of the course. Interestingly, other studies focusing on the effects of L2 language training showed that the modifications observed in several WM tracts as a consequence of L2 learning tended to disappear sometime after the training program ended (Banaszkiewicz et al., 2021; Hosoda et al., 2013; Mamiya, Richards, Coe, Eichler, & Kuhl, 2016).

According to the Dynamic Restructuring Model (DRM; Pliatsikas, DeLuca, & Voits, 2020; see also Pliatsikas, 2020) structural changes evolved according to use and/or proficiency in L2, suggesting that brain adaptations depend on the linguistic experience of the learners, in terms of both quantity and quality. According to this proposal, the initial stage of L2 learning is mainly associated with an increase in grey matter regions related to vocabulary acquisition and language control, i.e. temporal, inferior parietal, and frontal areas. With increased exposure and proficiency, however, this initial growth disappears and in the second consolidation stage, subcortical and cerebellar modifications occur, together with adaptations of WM matter tracts such as the ILF, the IFOF, the UF, together with the Superior Longitudinal fasciculus, the AF and

the CC. These are the consequence of the brain needing to efficiently transmit information from temporal, frontal, and parietal brain areas related to semantic, phonological, and syntactic processing. Finally in the third stage, when the efficiency peak is reached, subcortical and WM changes are expected to slowly disappear and the modulation of the frontal part of the tracts observed at the initial stages is replaced by the modulation of the posterior parts of the same tracts.

In the present study, we collected several variables related to the acquisition, use, and proficiency in L2 to test whether they exert selective effects on the DTI measures and the degree of lateralization of the considered tracts. In line with the DRM predictions (see also Grundy et al., 2017), we expect WM modulations to be primarily driven by the level of usage and immersion rather than by the age of L2 acquisition *per se*, given that the participants of the present study were in large majority sequential bilinguals. In light of previous studies (e.g., Hämäläinen et al., 2017; Xiang et al., 2015), we might also expect to find an inverse correlation between these variables and the degree of right lateralization of the tracts.

Whether these modulations are due to acquisition and use of a second language independently of its modality, or if they are related to the dynamic of activation of competing perceptual and phonological representations, typical of two spoken languages and absent in the case of a spoken and a signed language has yet to be investigated. The comparison between the pattern obtained from UBs and BBs would inform about this issue, revealing to what extent the linguistic function is based on abstract/amodal networks.

1.2. Structural changes and the fluency task

Based on the hypothesis of differential control demands associated with bimodal and unimodal bilingualism, some studies investigated anatomical differences between BBs and UBs in regions and networks associated to control and executive functions (Emmorey, Giezen, & Gollan, 2016). The results partially support the hypothesis that BBs need lower executive functions than UB. Some studies show that the differences observed in control regions between UBs and monolinguals are not present when comparing BBs and monolinguals (Olulade et al., 2016), other, instead, reported large structural similarities between UBs and BBs in the same areas (Zou, Ding, Abutalebi, Shu, & Peng, 2012; Li, Abutalebi, et al., 2017).

To further explore this issue, in the present study we compared the correlational pattern between the DTI measures extracted from UBs and BBs and the individual performance in fluency tasks. Fluency tasks require participants to actively searching the lexicon according to a specific criterion, and, therefore, are particularly suited to explore language control processes. It has been proposed that the two types of fluency task, semantic and phonological, recruit control processes to a different degree (Luo, 2010; Sandoval, 2010; Shao, 2014). While retrieving words from the same semantic category corresponds to accessing words that are connected within a semantic network, retrieving words on the basis of the initial phoneme is not a usual strategy of word retrieval and may require the inhibition of the more automatic semantically based generation strategy. Due to these reasons, the phonological fluency task is considered to require higher control demands than the semantic fluency task.

Given the well-established interaction between L1 and L2 in bilinguals (for reviews see (Kroll, 2015; Costa, 2014), participants in the present study were asked to perform the fluency tasks both in L1 and in L2. In this way, by comparing the correlational pattern obtained for UBs and BBs, we could evaluate the control needs for suppressing L1 (spoken) during the production of L2 (either signed of spoken) and the control needs for suppressing L2 (either signed or spoken) during the production of L1 (spoken).

According to a traditional view, the ventral language network is mainly associated with language comprehension, whereas the classical dorsal language network, (i.e., the AF), is principally involved in

language production (Hickok & Poeppel, 2000; 2004; 2007; Rauschecker & Tian, 2000). Several studies, however, suggest that such strict division of labors is definitely more nuanced than initially thought (Ueno, Saito, Rogers, & Lambon Ralph, 2011). Studies investigating the WM networks showed an involvement of ventral tracts in production tasks. Both the microstructural properties of the IFOF, ILF and the UF have been shown to correlate with the performance in picture naming tasks (Han et al., 2013; Harvey & Schnur, 2015; Grossman et al., 2004; McDonald et al., 2008; Lu et al., 2002; Janssen et al., 2020; Papagno et al., 2011; 2014) and in fluency tasks (Almairac, Herbet, Moritz-Gasser, de Champfleur, & Duffau, 2015; Li, Zhang et al., 2017). The extent to which these tracts are related to production tasks in L2 and whether such relation is confined to speech or it extends to sign languages, is still an unexplored issue.

We might advance some speculative predictions based on different proposals on the role of the ventral pathway in language production. According to Ueno et al. (2011), the left ventral pathway is primarily dominated by the mapping from semantics to the output processes, thus it is involved in conceptually driven production. We might therefore expect to find correlations between the microstructural properties of ventral tracts and the fluency task, in particular for L1 semantic fluency. As for L2, given that the output processes differ in the case of signed and spoken language, we might expect differences between UB and BBs in the pattern of correlations and/or in the tracts involved. In particular, we might expect that those WM tracts connecting occipital areas activated during visual/spatial processing, i.e., the ILF and the IFOF, might be correlated with fluency in L2 more strongly for BBs than for UBs.

A different perspective on the role of the ventral pathway suggests that this pathway, and in particular the left ILF and the left UF, are primarily involved in top-down control during speech production processes, such as word finding and interference control (Roelofs, 2014; Janssen et al., 2020). If this is the case, then we might expect to find correlations between the microstructural properties of ventral tracts and the fluency task, in particular for phonological fluency, which is more demanding in terms of word finding and executive control. In addition, the comparison between BBs and UBs allowed us to evaluate the control requirements associated to language modality. If between-language competition is strengthened by modality overlap, we should expect stronger correlations between performance in fluency task and the DTI measures for UBs than for BBs. In addition, we hypothesized that for UBs control needs should be stronger for L2 than for L1, given that additional resources might be needed to suppress the predominant L1.

2. Method

2.1. Participants

Twenty-four Italian-Italian Sign language (LIS) BBs and twenty-five Italian-English UBs were recruited for the study (see Table 1 for participants' characteristics). All participants lived in Italy and Italian was their dominant language. At the time of testing, all participants declared to use their L2 (LIS for BBs and English for UBs) on daily basis. They took part in two experimental sessions over two days, one for MRI brain scanning and one for collecting demographical and behavioral measures. The behavioral session was administered around a month after scanning. Two participants (one UB and one BB), due to personal inconveniences performed the second session about 5 months later. Participants received a monetary contribution fee of 40 euros.

No participants with a history of neurological illness were included. The basic criteria for the selection were the participant's age (18–45 years) and the right-handedness (verified through the Edinburgh Handedness Inventory Test; Oldfield, 1971). In addition, for the Italian-English bilinguals we adopted the following criteria: i) a certified level of English proficiency corresponding to C1 of the Common European Framework of Reference for Languages (CEFR); ii) they spent at least six months in an English-speaking country and actively used English language in everyday conversations for the last 5 years. For Italian-LIS bilinguals, we selected people having at least the third grade of LIS level, which should give a complete mastery of the language comparable in competence to the English C1. This screening was based on a self-report questionnaire exploring L2 learning and knowledge. It should be noted that none of the two samples had a homogeneous level of L2 knowledge. Both samples had three native bilinguals that have been exposed to the respective L2 before the age of 3 years-old, but the majority of the participants were sequential bilinguals that actively studied L2. As can be seen from Table 1, the two samples were matched for all variables except that for the age of first L2 exposition. This is due to the fact that in Italy English is a compulsory class in the primary school since the last 20 years, so the large majority of the UBs have been exposed to English at the age of 6/7 years. On the contrary, LIS learning for those individuals not belonging to deaf families usually starts in adolescence, as a consequence of personal interests.

2.2. MRI data acquisition

Diffusion imaging data was acquired using a Siemens Avanto 1.5T scanner housed in Padova University Hospital with actively shielded magnetic field gradients (maximum amplitude 45mT/m[1]). The body coil was used for RF transmission, and an 8-channel head coil for signal reception. Protocol consisted of a localizer scan, followed by a single-

Table 1

Means and standard deviations (in parentheses) of the principal characteristics of the two groups of bilinguals. Vocabulary scores have been derived using a modified version of the MINT test (Gollan et al., 2012) as described in the *Behavioral testing* section. Language spoken at home refers to the percentage of people who is using L1 (Italian) or/and L2 (English/LIS) at home. Percentage of switch refers to the percentage of people who reported a given frequency of switching (from both L1 to L2 and L2 to L1).

			Unimodal Bilinguals, M (SD)						Bimodal Bilinguals, M (SD)		
N°			25						24		
Gender			8 M – 17F						1 M – 23 F		
Age in years			25.4 (4.93)						27.79 (6.01)		
Raven SPM			41.61 (2.68)						40.12 (5.39)		
L2 AoA			6.04 (1.54)						16.7 (7.84)		
Years of L2 knowledge			18.56 (5.20)						11.08 (10.14)		
Self-report proficiency			7.2 (1.22)						7.8 (1.88)		
% L2 use			47.92 (20.79)						42.08 (24.88)		
Vocabulary score L1			65.44/68 (1.87)						65.41/68 (1.74)		
Vocabulary score L2			48.92/68 (6.20)						58.70/68 (6.81)		
Language spoken at home			ITA 100% – ENG 0% - Both 0%						ITA 75% – LIS 12.5% - Both 12.25%		
% of language switch	Never	Rarely	Some times	Often	Almost always/always	Never	Rarely	Some times	Often	Almost always/Always
	0	12	20	56	12	0	21	25	42	12

shot, spin-echo, EPI sequence with the following parameters: TR = 8500, TE = 97, FOV = 307.2 × 307.2, matrix size = 128 × 128, 60 slices (no gaps) with isotropic (2.4 × 2.4 × 2.4 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 three times, in order to increase signal to noise ratio. Gains and scaling factors were kept constant between acquisitions. Scanning lasted approximately 30 min.

2.2.1. Correction of motion and eddy current distortion, and estimation of the fiber orientation distribution

Each subject's raw images data were examined before proceeding with further analyses as to detect outliers, including signal drop-outs, poor signal-to-noise ratio, and image artefacts such as ghosts. Any subject whose raw data contained volumes with significant image quality issues was removed from further analyses. DWI datasets were concatenated and corrected for subject motion and geometrical distortions using ExploreDTI (https://www.exploredti.com; Leemans, Jeurissen, Sijbers, & Jones, 2009). Spherical deconvolution (Dell'Acqua et al., 2007) approach was chosen to estimate multiple orientations in voxels containing different populations of crossing fibers (Alexander, 2005). Spherical deconvolution was calculated by 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 Hindrance Modulated Orientational Anisotropy (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 GM 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).

2.2.2. 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).

2.2.3. Tract dissections

We used TrackVis Software (https://www.trackvis.org; Wang, Benner, Sorensen, & Wedeen, 2007) to virtually dissect the WM tracts of interest and quantify tracts specific measures. Each of the tracts was defined using a Regions of Interest (ROIs) approach according to the method provided by Catani and Thiebaut de Schotten (2008) by delineating the ROIs in the temporal (T), occipital (O) and external-extreme capsule (E) region (see Fig. 1, Panel b). The first ROI (temporal, T) is defined around the WM of the anterior temporal lobe, usually on five axial slices (MNI L15 to L19). The temporal ROI is defined on a slice

(MNI L15) located three slices below the slice containing the junction between the frontal and temporal branches of the anterior floor of the external capsule (MNI L9). The second ROI (occipital, O) is defined around the WM of the occipital lobe, usually on 13–15 slices. The lowest region is defined on a slice containing the WM of the lingual and fusiform gyrus (MNI, L9). The most dorsal region is defined on the slice where the fibers of the left and right splenium join at the midsagittal line (MNI 15). A third ROI (external/extreme capsule, E) is defined around the WM of the anterior floor of the external/extreme capsule, usually on five axial slices (MNI 1 to L7). The insula defines the lateral border of the "E" ROI, the lenticular nucleus its medial border. The ILF is dissected using the "T" ROI and the "O" ROI. The UF is dissected using the "E" ROI and the "T" ROI. The IFOF is dissected using the "O" ROI and the "E" ROI.

2.2.4. Diffusion tractography measures

We extracted the following indexes: Hindrance Modulated Orientational Anisotropy (HMOA) Radial Diffusivity (RD), Axial Diffusivity (AD) and Volume. HMOA is defined as the absolute amplitude of each lobe of the FOD, and represents an index of the degree of tract anisotropy. AD describes the mean diffusion coefficient of water molecules parallel to the tract and it is presumed to reflect integrity of microtubules along the axon (Alexander, Lee, Lazar, & Field, 2007; Song et al., 2002). RD indexes diffusion of water molecules perpendicular to the tract have been consistently associated to axon myelination which is related to increased conduction of action potentials along WM pathways (Song et al., 2002; 2005; Fields, 2008). Lateralization indexes for Volume and HMOA were calculated using the following formula: (Left (i) - Right (i)) / (Left (i) + Right (i)), where (i) denotes the chosen index. Lateralization index is used to investigate the degree of structural lateralization of language pathways (Catani et al., 2007). To allow comparison with previous studies we also extracted Mean Diffusivity (MD) and FA values. The results concerning MD and FA are reported in the Supplementary materials (Table 5 and 6).

2.3. Behavioral testing

The behavioral session was conducted in a quiet testing room located within the Department of Development Psychology and Socialization at the University of Padua, equipped with a PC Acer Intel Core i7, display 17″. During this session participants performed the following tasks: (i) a semantic fluency task, with the semantic categories "Animals" and "Transports" used for Italian and the categories "Food" and "Clothes" for English and LIS; (ii) a phonological fluency task with the phonemes "F" and "L" in Italian and the phonemes "S" and "P" in English and the hand configurations "1" and "B" in LIS. Participants completed the tasks first in L1 and then, in L2. The order of the tasks was fixed for all participants, given that we were not interested in comparing the performance between tasks or groups but we aimed at comparing diffusion tractography measures and behavioral measures collected in the same conditions. The participants seated in front of the PC and were instructed to produce, as quickly and accurately as possible, all the words that come to their mind in a minute of time while trying to avoid repetitions, derivatives, personal and geographical names, all of which were considered errors. For the registration of the vocal response participants wore a pair of Microsoft LifeChat LX-3000 earplugs with a built-in microphone. Responses were recorded using Audacity software. For the registration of the signed responses a camera was placed in front of the participant framing the participant's peri-personal space and participants started the task with the hands on the table and then they were asked to return to the starting position after each sign was made. Every audio (or video) was listened to/viewed and every word was manually recorded. One point was given for every correct word/sign retrieved within the minute; for each error (e.g., proper names, repetitions, etc.), a score of zero was assigned. The number of words/signs produced in each semantic category were averaged to obtain a mean semantic score and the number of

words/signs produced for each phoneme/handshape were averaged to obtain a mean phonological score.

To evaluate the level of L2 proficiency we used both objective and subjective measures. As objective vocabulary measure, following the idea adopted in the Multilingual Naming test (Gollan, Weissberger, Runnqvist, Montoya, & Cera, 2012), we developed a vocabulary test composed by 68 pictures presented with a fixed order of estimated increasing difficulty (i.e., lexical frequency of the items decreased with each presented item). Participants were asked to name each picture. The scoring corresponds to the number of the trials followed by three omissions or wrong responses in a row. None of the pictures' names were cognates across Italian and English. Picture names' frequencies were checked using "*Corpus e Lessico di Frequenza dell'Italiano Scritto*" - COLFIS (Bertinetto, Burani, Laudanna, Marconi, Ratti, Rolando, & Thornton, 2005) and "*Corpus of Contemporary American English*" - COCA (Davies, 2015). No frequency count is available for LIS and sign frequency was estimated on the basis of the frequency of the corresponding Italian word (for a similar procedure, see Navarrete, Caccaro, Pavani, Mahon, & Peressotti, 2015; Navarrete, Peressotti, Lerose, & Miozzo, 2017). The test was administered first in L1 and then in L2. Mean vocabulary scores are reported in Table 1. We considered the difference between L1 and L2 scores as indicative of the level of vocabulary proficiency reached in L2 (i.e., L2 vocabulary proficiency). Subjective measures were collected through a questionnaire in which we asked participants to self-evaluate their proficiency level through a 10-point Likert scale, where 1 corresponded to "None" and 10 corresponded to "Like a native speaker". We also asked participants to evaluate the percentage of daily L2 use, and report age of L2 acquisition and years of L2 knowledge. Participants performed other verbal and non-verbal tasks, which will be described elsewhere. At the end of the session, non-verbal intelligence was tested using the Raven Standard Progressive Matrices. The research protocol was approved by the Ethical Committee for Psychological Research of the University of Padova (Protocol n. 2015).

2.4. Statistical analyses

All analyses were performed with the software R (R Core Team, 2020). We explored the impact of individual variables of L2 acquisition, proficiency and use on the structural properties of the WM ventral tracts by calculating Pearson's correlations between these experiential variables and the tractography measures extracted. In order to evaluate the involvement of the ventral pathway in language production and control, we calculated Pearson's correlations between the tractography measures and the mean number of words (or signs) produced in the semantic and phonological fluency tasks in L1 and in L2. Partial correlation was used in order to control for Gender and Age (see below). We calculate the p value both uncorrected and fdr-corrected, according to Benjamini and Hochberg (1995), separately for each tract and either the experiential or the behavioral measures. In addition to the frequentist approach, we also applied Bayesian statistics for data analyses. This has the advantage to quantify the evidence in favor of the alternative hypothesis and to overcome the problem of multiple testing (Dienes, 2011). For each correlation we estimated the Bayes Factor estimation using the function correlationBF from "BayesFactor" package (Morey et al., 2015). As reported in literature, Bayes factor (BF10) of 1, 1–3, 3–10, 10–30, 30–100, or >100 point respectively towards no, anecdotal, substantial, strong, very strong, or decisive evidence for the alternative hypothesis (Jeffreys, 1961). To capture modality independent effects we performed the correlations on the whole group of participants. To capture modality specific effects we performed the correlations on BBs and UBs bilinguals separately. If a given correlation was significant only for one group of bilinguals, we compared the correlation coefficients of the two groups using Fisher's Z transformations (Sheskin, 2003) to assess significant group differences.

In order to control for whole group differences and to assess the impact of age and gender on the DTI measures we compared the tractography measures extracted from the UB and BB groups through linear mixed models with participants as random factor and Group and Hemisphere or Gender and Age as fixed factors. If either Gender or Age resulted significantly correlated with a tract measure, that variable will be always controlled for in the analyses involving that tract. Models were computed using the *lmer* function from lme4 package. The results of these analyses are reported in the Supplementary materials.

3. Results

Tract dissection in a representative participant (Subj. 110) is shown in Fig. 1. Gaussian distribution for the tractography measures was assessed from the visual observation of the data distribution. One participant (Subj. 116) was excluded from the analyses concerning the left UF, since the dissection procedures could not successfully reconstruct its fibers.

3.1. Structural changes and experiential variables of L2 acquisition, proficiency and use

We collected 5 variables related to age of acquisition, proficiency and use of L2. Given that some of these variables were highly related among each other we run a Principal Component Analysis (PCA) using the function *prcomp* from "stats" package (R Core Team, 2020) in order to understand whether it was possible to extract few independent measures. The 5 variables entered in the PCA were (1) the age of first L2 exposition, (2) years of L2 use, (3) percentage of L2 daily use, (4) self-report proficiency in L2 production, and (5) L2 vocabulary proficiency. Variables were centered and scaled prior to the application of the PCA. The PCA was run applying rotation of the loadings. The PCA with factor selection criterion eigenvalue > 1 yielded a two-component solution, which accounted for 73.66% of the variance in the data. Component 1 was strongly correlated with the age of first L2 exposition ($r = -0.898$) and the years of L2 use ($r = 0.886$), and was labeled *L2ACQ* (L2 acquisition). Component 2 was strongly correlated with the percentage of L2 daily use ($r = 0.624$), the self-reported proficiency level in L2 production ($r = 0.690$), and the vocabulary proficiency in L2 ($r = 0.821$), and it was labeled *L2PROF* (L2 proficiency).

L2ACQ and *L2PROF* were used to evaluate the impact of degree of bilingualism on the tractography measures extracted. We correlated Volume, HMOA, AD, RD and the lateralization indexes for Volume and HMOA of left and right ILF, UF and IFOF with the factors *L2ACQ* and *L2PROF*. Table 2 reports the results of these analyses. We observed an inverse correlation between RD of the right ILF and the component *L2PROF* ($r = -0.416$; $p = 0.003$; p(fdr) = 0.024). Lower RD values are associated with higher proficiency in L2 (see Fig. 2A). The Bayesian analysis indicated that the evidence for this correlation was strong (BF10 = 17.119). Partial correlation analysis revealed that the correlation remained significant after controlling for the variable Age ($p = 0.011$).

We then performed the same analyses on the two groups of bilinguals, separately (see Table 2 of the Supplementary materials). After fdr-corrections, significant correlations were observed in neither group.

Overall, these results indicate that the level of proficiency and the amount of usage of a spoken or signed language, but not age of acquisition, are associated with the microstructural properties of the right ILF. Analyses performed on the two groups of bilinguals separately did not reveal significant between-group differences in the correlational pattern.

3.2. Tractography measures and fluency task

Table 3 reports the descriptive statistics for the fluency task in the two groups of bilinguals.

We correlated Volume, HMOA, AD, RD and the Lateralization

Table 2

Correlations between *L2PROF* and *L2ACQ* with the tractography measures extracted from the left (L) and right (R) ILF, UF and IFOF and Lateralization Index (LI) on the whole group of participants: Pearson r, p-fdr corrected, p-uncorrected and BF10. Correlations with p < 0.05 and BF10 > 3 are marked in bold. The asterisk on the p value indicates that the correlation remained significant after controlling for Age and Gender. BF10 with an asterisk indicates substantial evidence and BF10 with two asterisks indicates strong evidence in favor of the alternative hypothesis.

	L2ACQ				L2PROF			
	Pearson's r	p-fdr	p-uncorr	BF10	Pearson's r	p-fdr	p-uncorr	BF10
ILF left								
Volume	−0.006	0.966	0.966	0.321	−0.049	0.889	0.738	0.337
HMOA	0.119	0.889	0.415	0.433	−0.044	0.889	0.762	0.334
AD	−0.062	0.889	0.671	0.348	−0.134	0.889	0.358	0.469
RD	−0.084	0.889	0.564	0.373	−0.041	0.889	0.778	0.332
ILF right								
Volume	0.177	0.629	0.224	0.625	0.034	0.814	0.814	0.329
HMOA	−0.042	0.814	0.775	0.333	0.172	0.629	0.236	0.604
AD	−0.086	0.814	0.556	0.375	−0.071	0.814	0.629	0.356
RD	−0.055	0.814	0.707	0.342	−0.416	**0.024***	**0.003***	**17.119****
LI VOLUME	−0.189	0.907	0.194	0.686	−0.038	0.956	0.797	0.331
LI HMOA	0.132	0.907	0.365	0.464	−0.192	0.907	0.186	0.706
IFOF left								
Volume	0.228	0.542	0.116	0.979	0.016	0.981	0.911	0.323
HMOA	0.114	0.583	0.437	0.421	−0.004	0.981	0.981	0.321
AD	0.167	0.542	0.251	0.581	−0.160	0.542	0.271	0.554
RD	−0.208	0.542	0.152	0.808	−0.115	0.583	0.430	0.425
IFOF right								
Volume	0.136	0.867	0.351	0.475	−0.075	0.867	0.609	0.361
HMOA	0.062	0.867	0.671	0.348	0.107	0.867	0.463	0.409
AD	−0.032	0.867	0.826	0.328	−0.057	0.867	0.695	0.344
RD	−0.025	0.867	0.867	0.325	−0.153	0.867	0.295	0.525
LI VOLUME	0.076	0.907	0.602	0.363	0.060	0.907	0.680	0.346
LI HMOA	0.074	0.907	0.612	0.360	−0.108	0.907	0.460	0.411
UF left								
Volume	0.137	0.712	0.353	0.477	0.081	0.751	0.584	0.371
HMOA	0.196	0.712	0.182	0.721	0.047	0.751	0.751	0.339
AD	−0.111	0.726	0.454	0.417	0.062	0.751	0.677	0.350
RD	−0.248	0.712	0.089	1.193	−0.136	0.712	0.356	0.475
UF right								
Volume	0.052	0.827	0.724	0.339	−0.053	0.827	0.719	0.340
HMOA	0.184	0.547	0.205	0.663	0.107	0.814	0.463	0.409
AD	−0.097	0.814	0.509	0.390	−0.003	0.982	0.982	0.321
RD	−0.310	0.240	**0.030**	2.652	−0.200	0.547	0.167	0.757
LI VOLUME	0.007	0.964	0.964	0.324	0.107	0.907	0.471	0.409
LI HMOA	0.019	0.964	0.897	0.326	−0.143	0.907	0.331	0.495

Indexes for the Volume and the HMOA of left and right ILF, UF and IFOF with the number of words produced during the semantic and phonological fluency tasks first in L1 and then in L2 for both the whole group of participants and separately for each group. Tables 4 and 5 show the results of the analyses of the whole group of participants (see Table 3 and 4 of the Supplementary material for the separate correlations for BBs and UBs).

3.2.1. L1

A positive correlation was found between the Lateralization Index of the ILF's Volume and the mean number of words retrieved in the semantic fluency task (see Fig. 3, Panel a). A stronger left lateralization of the ILF's Volume was associated with higher performance in the task (r = 0.404; p = 0.004; p(fdr) = 0.48). The Bayesian analysis indicated that the evidence for this correlation was strong (BF10 = 13.482). As can be seen in Panel b of Fig. 3 the same positive trend is present for both groups of bilinguals.

3.2.2. L2

No significant correlations were observed after fdr-corrections.

The same correlational analyses were performed considering separately the two groups of bilinguals. The whole pattern of results is reported in Tables 3 and 4 of the Supplementary material.

3.2.3. Bimodal bilinguals

An inverse correlation emerged between the number of words produced in the phonological fluency task in L1 and the AD of the right UF (r = −0.559; p = 0.005; p(fdr) = 0.040, see Fig. 3, panel c). The Bayesian analysis indicated that the evidence for this correlation was strong (BF10 = 11.610). Lower AD of the right UF was associated with a better performance in phonological fluency. In order to investigate to what extent this pattern was typical of BBs we compared the correlation coefficient obtained in the two groups of bilinguals and we observed a statistically significant difference (Fisher's Z = −1.98, p = 0.023; see Fig. 3c). As for L2, no significant correlations were observed between the fluency tasks and the DTI measures extracted.

3.2.4. Unimodal bilinguals

After fdr corrections, no significant correlations between the DTI measures and the performance in the fluency tasks in L1 or L2 emerged.

Overall the fluency task seems to depend on the processing occurring along the ventral WM tracts, only for L1. The left ILF resulted involved in the semantic fluency task for both groups of bilinguals; the right UF in the phonological fluency task, only for BBs.
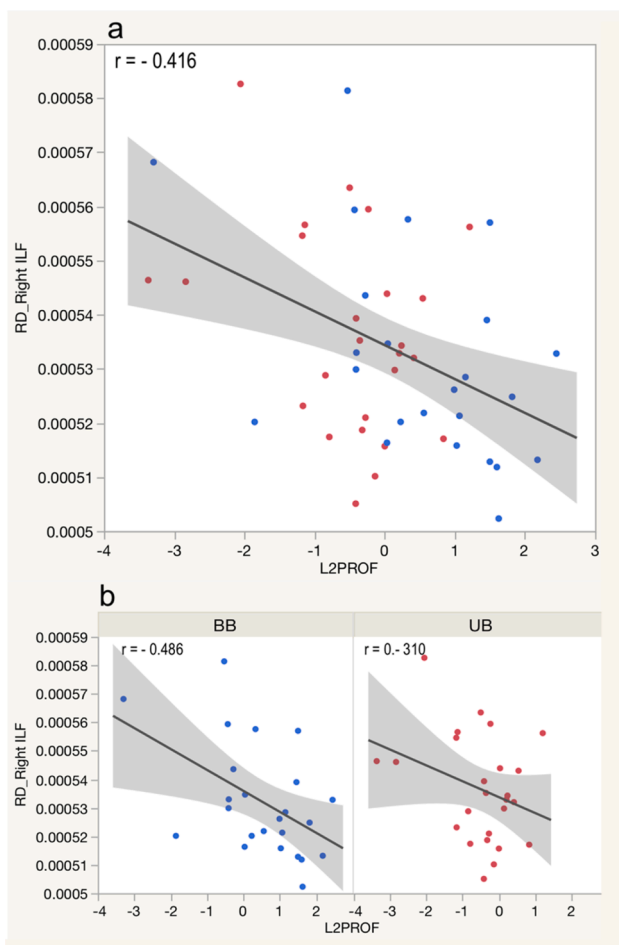
Fig. 2. Correlation between RD of the right ILF and *L2PROF* for all participants (a) and for BBs and UBs separately (b). Red dots represent UBs and blue dots BBs. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3
Mean number of words reported in the semantic and phonological fluency task in L1 and in L2 for both groups of bilinguals.

	Sem Fluency		Phon Fluency	
	L1	L2	L1	L2
BBs	17.15 (3.45)	14.40 (3.45)	14.23 (2.78)	8.88 (1.94)
UBs	18.16 (2.78)	15.10 (2.90)	14.12 (3.15)	13.28 (2.29)
Mean N	17.66	14.76	14.17	11.12

4. Discussion

The present study compares the microstructural properties of ventral WM tracts extracted from two bilingual populations, namely bimodal bilinguals (BBs) and unimodal bilinguals (UBs). DTI measures were correlated with the degree of bilingualism in order to reveal the impact of the acquisition and use of L2 -either spoken or signed- on the brain. The same DTI measures were also correlated with performance in behavioral tasks in order to reveal whether language modality modulates the brain networks implicated in language processing in bilinguals. We reported both commonalities and differences between the two groups of bilinguals. The impact of experiential variables related to bilingualism on the WM tracts seems independent of language modality. For both BBs and UBs, higher proficiency in L2 was associated with lower RD within the right ILF. The correlation pattern obtained with the fluency task revealed that both groups of bilinguals seem to rely on a

left-lateralized neural network involving the ILF when performing the semantic fluency task in the L1. However, differences between BBs and UBs emerged considering the involvement of the right UF in the phonological fluency task in L1. While for the BB group, lower AD values of the right UF were associated to better performance in this task, the two variables were not associated for the UB group.

These results will be discussed with reference to (i) the impact of the degree of bilingualism on the WM tracts of the ventral pathway; and (ii) the involvement of the ventral WM tracts in language production and control.

4.1. Structural changes and degree of bilingualism

Most of the studies assessing brain microstructural differences due to bilingualism, compared bilingual versus monolingual individuals (Cummine & Boliek, 2013; Gold et al., 2013; Luk et al., 2011; Mohades et al., 2012; Pliatsikas, Moschopoulou, & Saddy, 2015; Schlegel, Rudelson, & Tse, 2012; Singh et al., 2018), and showed conflicting results likely due to differences in the characteristics of bilingual participants such as the age of L2 acquisition, the years on L2 exposure, the percentage of daily use and the competence/proficiency in L2. As revealed by the PCA analysis, in our sample those variables could be summarized into two largely independent factors, one related to the age of L2 acquisition and the other to the degree of proficiency and daily use. This suggests that L2 age of acquisition and proficiency did not "a priori" correlate in bilingual populations. Although both UBs and BBs of the present study learn L2 at different ages, their proficiency level appears unrelated to when acquisition begun. Rather, to the learning opportunities they encountered afterwards. The independence between these two factors is consistent with the idea that they might selectively affect brain structure and functioning (Del Maschio et al., 2020; Sulpizio et al., 2020). The results obtained in the present study suggest that only proficiency and/or daily use and not age of acquisition might affect the WM structures of the ventral pathway and in particular of the RD of the right ILF. We found that lower RD was associated to a higher level of proficiency. In the present study we observed the same correlational pattern between RD of the right ILF and *L2PROF* in the two groups of bilinguals. This similarity suggests that the role of the right ILF in bilingualism is neither related to language input and output modality, nor to processes specifically related to oral or signed languages. However, since the group-separated analyses showed no significant correlations, such conclusion should be taken with caution.

As already pointed out by Nichols and Joanisse (2016), the existence of a correlation does not allow establishing a causal relation between proficiency and the microstructural properties of WM tracts. In this respect, we can speculate that both extended use and practice with the second language reinforces WM brain structures, or vice versa that people with higher myelination of WM tracts could more successfully learn a second language. Support to this contention comes from the study by Qi, Han, Garel, San Chen, and Gabrieli (2015) who scanned a group of native English speakers before they learned Mandarin Chinese through an intensive 14-day course. Results show that higher performance in the final exam after the end of course was associated with higher FA and lower RD of the right ILF and the parietal bundle of the right superior longitudinal fasciculus. This result may suggest that individual variability in the microstructural properties of these tracts might predict the ability of L2 learning. Contrary to this conclusion, Schlegel et al. (2012) showed FA and RD changes in a longitudinal study in which L2 learners took part to a 9-month intensive course. Changes occurred in the language related areas of the left hemisphere and the homologous areas of the right hemisphere, and also in the genu of the corpus callosum. Overall, these studies might suggest that the structural modifications of WM structure following L2 learning might be the results of the interaction between individual predisposition and linguistic experience (Mamiya et al., 2016). Disclosing this interaction at the group level would be very hard, if not impossible, and such confound

Table 4

Correlations between the number of words in the semantic and in the phonological fluency tasks in L1 with the tractography measures of the left (L) and right (R) ILF, UF and IFOF and Lateralization Index (LI) on the whole group of participants: Pearson r, p-fdr corrected, p-uncorrected and BF10. Correlations with p < 0.05 and BF10 > 3 are marked in bold. The asterisk on the p value indicates that the correlation remained significant after controlling for Age and Gender. BF10 with an asterisk indicates substantial evidence and BF10 with two asterisks indicates strong evidence in favor of the alternative hypothesis.

L1	Semantic Fluency				Phonological fluency			
	Pearson's r	p-fdr	p-uncorr	BF10	Pearson's r	p-fdr	p-uncorr	BF10
ILF left								
Volume	0.178	0.644	0.221	0.630	−0.049	0.845	0.739	0.337
HMOA	−0.049	0.845	0.739	0.337	0.097	0.811	0.507	0.391
AD	−0.216	0.644	0.135	0.877	−0.023	0.874	0.874	0.324
RD	0.156	0.644	0.284	0.538	−0.144	0.644	0.322	0.499
ILF right								
Volume	−0.283	0.392	0.049	1,838	−0.139	0.546	0.341	0.483
HMOA	−0.209	0.501	0.149	0.822	−0.077	,0.686	0.600	0.363
AD	−0.191	0.501	0.188	0.699	−0.162	0.534	0.267	0.559
RD	−0.079	0.686	0.589	0.366	−0.006	0.965	0.965	0.321
LI VOLUME	0.404	**0.048***	**0.004***	**13.482****	0.046	0.944	0.752	0.336
LI HMOA	0.109	0.886	0.457	0.412	0.157	0.855	0.280	0.542
IFOF left								
Volume	0.072	0.915	0.625	0.357	0.016	0.915	0.915	0.322
HMOA	−0.017	0.915	0.906	0.323	0.222	0.500	0.125	0.926
AD	−0.184	0.549	0.206	0.659	−0.041	0.915	0.778	0.332
RD	0.055	0.915	0.710	0.341	−0.237	0.500	0.100	1,082
IFOF right								
Volume	0.209	0.523	0.149	0.821	−0.078	0.645	0.592	0.365
HMOA	−0.068	0.645	0.642	0.354	0.188	0.523	0.196	0.681
AD	−0.108	0.645	0.462	0.410	−0.067	0.645	0.645	0.353
RD	−0.077	0.645	0.601	0.363	−0.251	0.523	0.082	1,249
LI VOLUME	−0.156	0.855	0.285	0.537	0.100	0.886	0.494	0.396
LI HMOA	0.022	0.944	0.882	0.324	0.095	0.886	0.517	0.388
UF left								
Volume	0.043	0.880	0.770	0.337	−0.167	0.524	0.256	0.578
HMOA	−0.091	0.811	0.536	0.385	−0.165	0.524	0.262	0.570
AD	−0.204	0.524	0.163	0.776	−0.206	0.524	0.161	0.784
RD	−0.076	0.811	0.608	0.365	−0.013	0.932	0.932	0.325
UF right								
Volume	−0.079	0.784	0.588	0.366	−0.005	0.970	0.970	0.321
HMOA	−0.163	0.558	0.262	0.565	−0.137	0.558	0.349	0.476
AD	−0.251	0.558	0.082	1,255	−0.212	0.558	0.143	0.842
RD	−0.047	0.853	0.746	0.336	−0.148	0.558	0.310	0.510
LI VOLUME	−0.070	0.944	0.636	0.358	−0.182	0.857	0.855	0.647
LI HMOA	0.010	0.944	0.944	0.325	−0.020	0.975	0.944	0.327

might have contributed to the contrasting pattern of results concerning the structural modifications induced by bilingualism. Our study helps to this endeavor by showing the relevance of variables related to both proficiency and usage in the structural modulatory effects of bilingualism.

The effects of bilingualism on the brain structure have been recently conceived according to a dynamic perspective. According to the DRM (Pliatsikas et al., 2020; see also Pliatsikas, 2020). adaptations of WM tracts may occur only after a certain amount of learning, during consolidation of lexical, phonological and grammatical knowledge, when the brain become more efficient in the transmission of signals between temporal, frontal and parietal areas. *L2PROF* in the present study represents an interesting variable summarizing vocabulary knowledge, self-evaluated proficiency and percentage of daily use of L2 that could likely index the time-course of the structural adaptation. Our results suggest that the right ILF might be one of the WM tracts that first, and more strongly adapts to the use of L2. This conclusion seems coherent with previous studies showing the plasticity of this tract in relation to bilingualism. Luk et al. (2011) comparing life-long old bilinguals versus age matched monolinguals reported increased WM integrity for bilinguals in both the left and right ILF. Hosoda et al. (2013), showed with TBSS a modulation of WM integrity of the right ILF associated with L2 vocabulary learning, with higher FA values

associated to a richer vocabulary.

Finally, we did not observe any significant correlations between the degree of bilingualism and the lateralization pattern of the DTI measures. At least for the proficient bilinguals who took part to the present study, the acquisition, learning and use of L2 is not associated to variations in the degree of left–right asymmetry of the ventral tracts.

4.2. Structural changes and the fluency task

Semantic fluency in L1 was correlated with a left-ward lateralization of the volume of the ILF. These results speak in favor of the hypothesis that the asymmetry of WM intra-hemispheric connections could explain the left-hemispheric dominance observed in language processing (Ocklenburg et al., 2016; Vallesi & Babcock, 2020). While the relation between WM left-right asymmetry and performance in verbal tasks have been mainly documented for the AF (e.g., Catani et al., 2007; see Ocklenburg et al., 2016 for a review), to our knowledge this is the first study that extends this result to the ILF.

The left ILF has been previously suggested to play a major role in the semantic language function (e.g., Almairac et al., 2015; Duffau, Herbet, & Moritz-Gasser, 2013). This hypothesis has been primarily based on the impaired lexico-semantic abilities of patients with semantic dementia (Agosta et al., 2010) or primary progressive aphasia (Mandelli et al.,

Table 5
Correlations between the number of words in the semantic and in the phonological fluency tasks in L2 with the tractography measures of the left (L) and right (R) ILF, UF and IFOF and Lateralization Index (LI) on the whole group of participants: Pearson r, p-fdr corrected, p-uncorrected and BF10. Correlations with p < 0.05 and BF10 > 3 are marked in bold. The asterisk on the p value indicates that the correlation remained significant after controlling for Age and Gender. BF10 with an asterisk indicates substantial evidence and BF10 with two asterisks indicates strong evidence in favor of the alternative hypothesis.

L2	Semantic Fluency				Phonological fluency			
	Pearson's r	p-fdr	p-uncorr	BF10	Pearson's r	p-fdr	p-uncorr	BF10
ILF left								
Volume	0.210	0.554	0.148	0.823	0.234	0.554	0.105	1,047
HMOA	−0.137	0.554	0.346	0.478	0.110	0.604	0.453	0.414
AD	−0.145	0.554	0.319	0.502	−0.183	0.554	0.208	0.656
RD	−0.017	0.908	0.908	0.323	−0.046	0.862	0.754	0.335
ILF right								
Volume	0.015	0.972	0.921	0.322	0.055	0.972	0.709	0.342
HMOA	−0.005	0.972	0.972	0.321	0.036	0.972	0.808	0.329
AD	−0.150	0.972	0.303	0.518	−0.021	0.972	0.884	0.324
RD	−0.310	0.240	0.030	2,650	−0.055	0.972	0.705	0.342
LI VOLUME	0.152	0.629	0.296	0.524	0.132	0.629	0.367	0.463
LI HMOA	−0.144	0.629	0.325	0.496	0.043	0.784	0.768	0.334
IFOF left								
Volume	0.195	0.620	0.178	0.725	0.116	0.620	0.425	0.427
HMOA	0.035	0.814	0.814	0.329	0.127	0.620	0.384	0.452
AD	−0.184	0.620	0.205	0.662	−0.107	0.620	0.465	0.408
RD	−0.058	0.793	0.694	0.344	−0.160	0.620	0.271	0.554
IFOF right								
Volume	0.138	0.797	0.343	0.481	−0.035	0.814	0.814	0.329
HMOA	0.100	0.797	0.493	0.397	−0.059	0.797	0.687	0.345
AD	0.094	0.797	0.521	0.386	−0.130	0.797	0.374	0.458
RD	−0.206	0.797	0.156	0.793	−0.057	0.797	0.697	0.344
LI VOLUME	0.040	0.784	0.784	0.332	0.146	0.629	0.317	0.504
LI HMOA	−0.054	0.784	0.712	0.341	0.192	0.629	0.186	0.705
UF left								
Volume	0.010	0.946	0.946	0.324	0.027	0.946	0.856	0.329
HMOA	−0.083	0.769	0.577	0.373	0.102	0.769	0.488	0.402
AD	−0.160	0.666	0.272	0.553	−0.185	0.666	0.204	0.665
RD	−0.143	0.666	0.333	0.494	−0.199	0.666	0.176	0.739
UF right								
Volume	0.140	0.538	0.336	0.487	0.035	0.813	0.813	0.329
HMOA	0.052	0.813	0.725	0.339	0.105	0.630	0.472	0.405
AD	−0.206	0.320	0.160	0.785	−0.329	0.088	**0.022***	**3.380***
RD	−0.291	0.115	**0.043**	2,036	−0.338	0.088	**0.017**	**4.094***
LI VOLUME	−0.106	0.711	0.474	0.408	−0.139	0.629	0.347	0.482
LI HMOA	−0.218	0.629	0.136	0.881	−0.042	0.784	0.779	0.335

2014; D'Anna et al., 2016; Tu, Leyton, Hodges, Piguet, & Hornberger, 2016) who show a degeneration of this tract. Only few recent studies investigated the involvement of the ILF in language processing in healthy participants. Ripollés et al. (2017), in a study with 40 healthy participants, showed that the RD of the left ILF was associated with the performance in a word-meaning learning task, and concluded that this tract plays a role in the capacity of identifying associations between words and meanings. Hodgetts et al. (2017) used a word-cue recall task and scored the number of semantic and episodic details recalled by each participant. Significant correlations were found between the MD and the FA of the left ILF and the number of semantic details recalled. The fact that in the present study left-lateralization of the ILF is associated with the number of words recalled in a semantic fluency task further corroborates the idea that the left ILF may play a crucial role in semantic memory retrieval. This result is also consistent with the hypothesis that the ILF in the left ventral pathway is involved in conceptually driven production (Ueno et al., 2011); the fact that the correlation was present for L1 and not for L2, might depend on the evidence that, with respect to L1, performance in L2 might be less dependent on less dependent on semantic retrieval processes and more reliant on executive control processes.

As for phonological fluency we assumed that the phonological fluency task would require more control resources than the semantic fluency task, since in the former task participants need also to inhibit the more automatic semantic associative links between words. Performance in this task should be therefore supported by a neural network mainly devoted to controlled processes. We found that the AD of the right UF was inversely correlated to phonological fluency in L1 for BBs; in addition, considering uncorrected p values, we also found a similar correlation between the left UF and phonological fluency in L2 when the two groups of bilinguals were considered together. Overall, the pattern points towards a role of the UF in language control. The UF, that connects the anterior part of the temporal lobe with the regions of ventro-lateral prefrontal cortex and the Inferior Frontal Gyrus, can be considered the interface between semantic representations and the control system of lexical production; a decrease in the FA values of the left UF has been reported in patients with semantic memory impairments, such as Alzheimer's disease or fronto-temporal dementia, showing deficits in knowledge retrieval and naming tasks (for a review see Papagno et al., 2011). Consistent with the hypothesis that the UF is
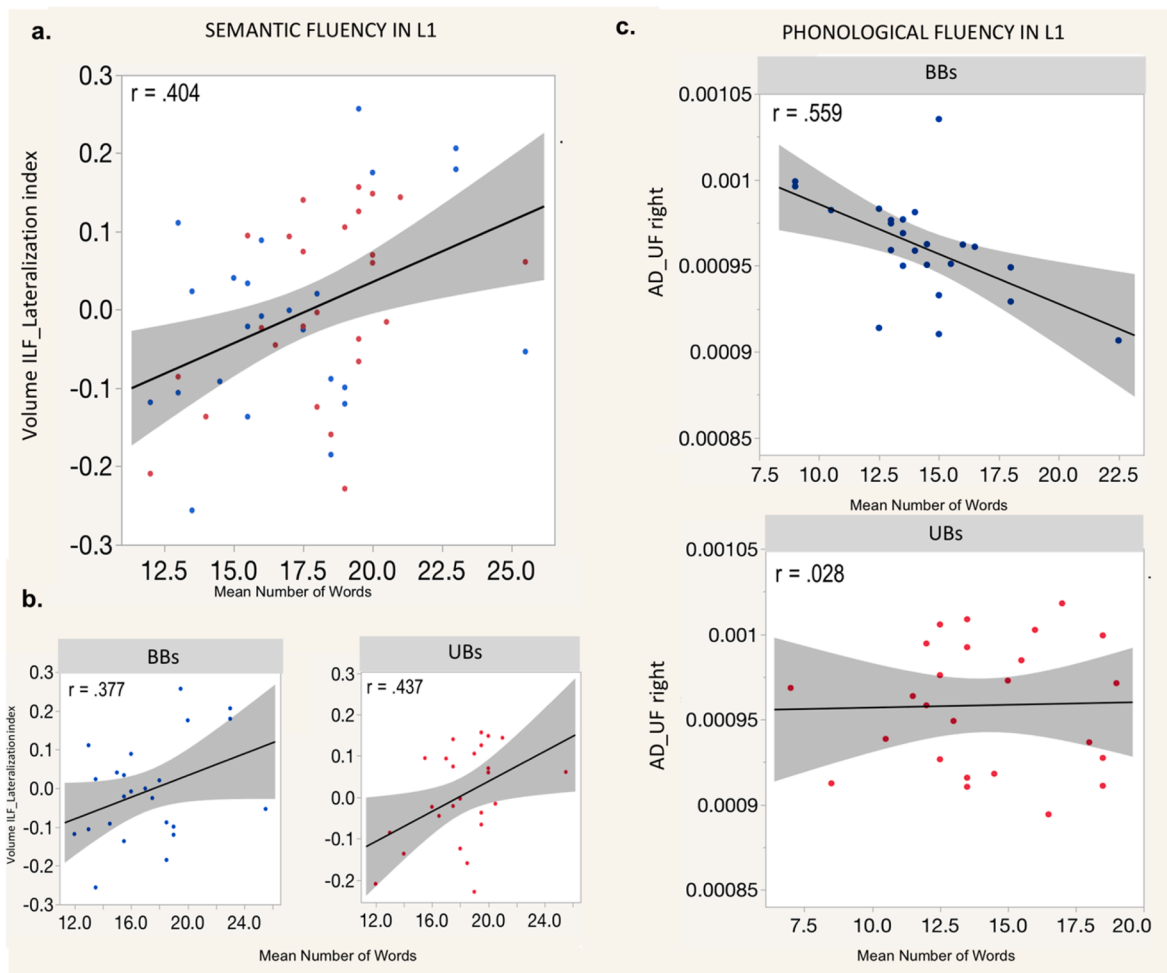
Fig. 3. Panels 'a' and 'b' represent the correlations between the mean number of words reported in the semantic fluency task in L1 and the lateralization index of ILF Volume. Panels 'c' represent the correlation between the mean number of words reported in the phonological fluency task in L1 and the AD of the left UF for bimodal (upper panel) and unimodal (lower panel) bilinguals.

part of the network devoted to control language production, Di Tella et al. (2020) recently showed that a highly demanding word production tasks, requiring selection among competing alternatives, correlated with the microstructural changes of both the right and the left UF in Parkinson's disease patients. Our results further show that the UF might play a role in highly controlled processes of word retrieval, such as those involved in the phonological fluency task. In particular, for those in which the cue for memory retrieval is not semantic but phonological and speeded retrieval is strictly related to the inhibition of irrelevant, more directly associated words. The results speak in favor of an involvement of the left UF in top-down control during production, and in particular in word finding and interference control processes (Roelofs, 2014; Janssen et al., 2020).

With respect to the modality effects, we predicted that if language competition is enhanced by modality overlap, UBs should show more control requirements than BBs, especially when performing the phonological fluency task in L2. The results did not meet these predictions. Rather, they reveal an unexpected pattern of cross-language competition in BBs. The AD of the right UF was correlated to phonological fluency in L1, only for this group of bilinguals, suggesting that the right UF could be selectively involved in the control of sign language during spoken language production in BBs. Producing words on the basis of a phonological cue in L1 could be a demanding task for BBs, who need to control the whole linguistic manual modality. This hypothesis is corroborated by the fact that BBs, even during spoken conversations with non-signers, produced specific American Sign elements (Pyers & Emmorey, 2008;

Casey & Emmorey, 2009). This indicates that complete suppression of sign language during spoken production might be very difficult. Geizen & Emmorey (2016) further showed that BBs presented the same disadvantage reported for UBs with respect to monolinguals in phonological fluency, suggesting that the two languages of the bilinguals compete for production, even if they do not use the same articulators. What our result suggest is that the control of a language with a different modality might be supported by a rightward network involving the UF. It is interesting to note here that, even if not significant when corrected for multiple tests, the AD of the left UF correlated with the phonological task in L2 for both groups of bilinguals. Tentatively, this result may indicate that the left UF might be involved in the control of L1 (spoken for both groups of bilinguals) during L2 production. Altogether, the results point to a modality specific role of the left and right UF in bilinguals: while the right UF would be involved in the control of signed language, the left UF would be involved in the control of spoken language. However, given the not significant correlation involving the left UF and the post hoc explanation given to the correlation involving the right UF, this hypothesis should be taken cautiously, awaiting further research to clarify the role of UF in verbal fluency.

As a final remark, we would like to highlight that the correlation we found between the AD of the right UF and the performance in phonological fluency is inverse, i.e. better performance in phonological fluency was correlated with lower AD values. This inverse relationship is counterintuitive but it is not unusual. This result echoes the results found with highly experts bilinguals who showed reduced WM and GM

in regions supporting linguistic functions and language control (Elmer, Hänggi, Meyer, & Jäncke, 2011; 2014). Within the DRM, Pliatsikas et al. (2020) interpreted such reductions as a signal that the peak of efficiency processing has been reached. According to this model, structural changes of WM and GM observed during L2 learning and consolidation tend to slowly disappear as efficiency and automaticity increase. We might interpret the decreased AD of the right UF as a signal of established efficiency. For the expert BBs involved in the present study, the control processes devoted to the activation/suppression of the manual modality might become less costly and based on more efficient and specialized networks. How this increased efficacy may be related to the decreased AD of WM tracts has still to be fully disclosed and further research is needed to validate this hypothesis.

4.3. Concluding remarks

In the present DTI-tractography study the microstructural properties of three ventral tracts, the ILF, the UF and the IFOF in unimodal and bimodal bilinguals were correlated with level of L2 acquisition/proficiency/use and the performance in a fluency task. As for the effects of individual language variables on WM structure, we have found some associations on the anatomy of the ILF The microstructural properties of the right ILF were associated with L2 proficiency and L2 daily use, and not to age of acquisition, independent of L2 modality, suggesting that this tract is modulated by the degree of second language learning. The degree of leftward asymmetry of the ILF was associated to the processes of semantic memory and word retrieval in L1, congruent with the idea that the left ILF is involved in retrieval from semantic memory during language production. The microstructural properties of the right UF correlated with performance in the phonological fluency task in L1, only for BBs. Given that phonological fluency is more demanding in terms of the load on executive functions, this result may indicate that the right UF has a critical role in language control. In addition, since the correlation was absent for UBs, we interpreted this finding as suggesting that the right UF might be selectively involved in the control of the signed language during spoken word production.

Finally, we would like to acknowledge the limitations of the present study. They are mainly related with the exploratory nature of the research in terms of the selected samples, tasks and WM measures. For this reason, we could set out only tentative hypotheses regarding the relations between WM indexes and the individual variables related to L2 learning and production. This is why we opted for a descriptive approach, based on a wide range of correlations. Another critical aspect concerns the matching of age of L2 acquisition between the two groups of bilinguals. In Italy, English as a foreign language starts to be taught in primary schools, whereas for people belonging to families with no deaf members sign language learning starts later on, during adolescence. For these reasons we could not fully match the two samples on this variable.

To conclude, by tracing the connections between seed regions that were traditionally associated with specific language tasks, our approach allows for an integrative, anatomically informed, and constrained investigation of brain networks of, in principle, any aspect of language processing with specific reference to bilingualisms. It will be of interest to investigate whether the considered or different neural streams are sufficient to accommodate other levels of natural language processing beyond production.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.bandl.2022.105187.

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