THE ROLE OF THE FRONTAL ASLANT TRACT IN BILINGUAL LANGUAGE CONTROL

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ABSTRACT

In the present study the microstructural properties of the right and left Frontal Aslant tract (FAT) have been investigated in relation to bilingualism and to language modality by comparing a group of unimodal bilinguals (i.e., bilinguals of two spoken languages) and a group of bimodal bilinguals (i.e., bilinguals of a spoken and a signed language). The microstructural properties of the left FAT correlated with performance in picture naming and semantic fluency in L2 for both groups of bilinguals. The microstructural properties of the both the right and left FAT correlated with picture naming performance in L1 for bimodal bilinguals. No significant correlations were found with performance in a language comprehension task. Overall, the results suggest that the FAT plays a relevant role in language control in bilinguals. While the left FAT seems to be mainly involved in the suppression of the spoken native language (L1) during the use of the spoken or signed L2, both the right and the left FAT seem to be involved in the suppression of sign language (L2) during speaking in L1.

1.INTRODUCTION

A prominent issue in the recent literature is related to the control needs associated to bilingualism. A bilingual person not only needs to acquire and store lexical phonological and grammatical information of two languages, but they also need to keep the two languages separated to avoid interference. It has been proposed that, in order to optimally adapt to the linguistic context, bilingual people should resort to executive control processes such as inhibition, shifting and updating (Bialystock, 2017; Abutalebi & Green, 2008). Understanding how the brain orchestrates its response to such enhanced control demands has been a major focus of research on bilingualism. Since several years it has been shown that learning a second language induces a structural reorganization of the brain (for reviews see Hayakawa & Marian, 2019; Pliatsikas, 2019). This reorganization is very rapid, it occurs even in adulthood, and it may involve changes in the grey matter of cortical and subcortical regions as well as in the white matter (WM) tracts connecting the different regions of the brain (Li et al., 2014). Changes are likely to occur dynamically, according to the specific needs and the specific experience of the bilingual person (Green & Abutalebi, 2013; Grundy et al., 2017; Pliatsikas et al., 2020). Grundy et al. (2017) proposed that when a second language (L2) is initially learned, the need for managing the competition between the two languages mainly entails the involvement of frontal regions. However, with increasing experience and specialization in L2, brain activity is remodulated, with fewer resources devoted to anterior regions in favor of larger reliance of posterior and subcortical regions. This anterior to posterior and subcortical shift corresponds to a shift from more demanding to more automatic processing of the languages.

Pliatsikas et al. (2020) adopted a similar dynamic perspective of brain changes and proposed a three-stage model of structural modifications. The initial stage of L2 learning is mainly associated with gray matter modifications of regions related to vocabulary acquisition

(temporal and inferior parietal areas) and language control (frontal areas). In the second consolidation stage these modifications would disappear, and WM and subcortical modification will occur; finally in the third stage, when the peak of efficiency is reached, subcortical and WM modulations are expected to slowly disappear, and the modulation of the frontal white matter tracts observed at the initial stages would be replaced by the modulation of more posterior tracts.

In the present study we focused on two bilingual populations, bimodal and unimodal bilinguals and we examined whether their linguistic performance is associated to the microstructural properties of a frontal WM tract, associated to inhibitory control, which has never been investigated in relation to bilingualism, namely, the Frontal Aslant tract.

1.1 Bimodal Vs Unimodal bilingualism

It is now well known that both languages that a bilingual person knows are simultaneously active even when only one of them of is in use (for a review, see Kroll et al., 2015). This implies that languages can influence each other and compete for cognitive resources. Learning a second language, therefore, implies learning how to control and regulate the competition between the second (L2) and the native (L1) language. Control requirements for L1 and L2, however, seem to be asymmetric, as shown by the results obtained in paradigms where bilinguals were required to switch between languages. These suggest that suppressing the L1 is associated to larger processing costs with respect to the suppression of the L2 (Meuter & Allport, 1999; Reynolds et al., 2016).

Control requirements might also depend on language modality. Unimodal bilinguals (UBs) are people who have acquired two spoken languages, whereas bimodal bilinguals (BBs) have acquired a spoken and a signed language. Such difference in the L2 modality might be associated to differences in the way in which the two languages are controlled,

represented, and handled by the brain. For example, BBs can utter a word and make a sign at the same time, a quite frequent experience during everyday conversations (Emmorey et al., 2008). Differently, UBs have always to select one word for production. In addition, it has been observed an overwhelming preference for code blends in BBs, both during signing and speaking. Furthermore, evidence collected analyzing the processing costs to switch form a code blend to a single language in BBs suggests that, similarly to what found with UBs, inhibiting a language, either spoken or signed, is associated with a processing cost; however the analysis of the costs for switching from a single language to a code-blend, revealed no additional costs associated to the activation of an additional language (Kaufmann & Philipp, 2015; Blanco Elorrieta et al., 2018; see also Emmorey et al., 2020). It is also interesting to note the asymmetry observed in the pattern of code blends; single signs are produced quite frequently during speaking, whereas single words are very rarely produced when sign language is selected as the matrix language (Emmorey et al., 2016). In sum, given that BBs often produce elements of the two languages at the same time, it has been proposed that they do not need to control the activation of the language not in use to the same extent as UBs (Emmorey et al., 2008; 2016). Contrary to such conclusion, some studies have shown a relationship between bimodal bilingualism and executive functions. Kushalnagar et al. (2010) found that high proficient BBs performed better than low proficient bilinguals in an attention switching task. Similarly, Giezen et al. (2015) reported that BBs with higher inhibitory control abilities, measured through the performance in a spatial Stroop task, were less sensitive to cross-language competition than BBs with lower inhibitory control.

Few previous neuroimaging studies directly investigated the effects of sign language experience on the anatomical structure of the brain, often comparing BBs or deaf signers to hearing monolinguals, thus confounding the effect of bilingualism with the effect of sign language experience. Recently, McCullough and Emmorey (2020) tried to isolate the

plasticity effects uniquely due to the experience with sign language from those due to hearing loss or bilingualism comparing deaf signers Vs hearing controls and BBs Vs. hearing controls. Sign language use was associated with a reduction of cortical thickness in the right occipital lobe and with an expansion of the surface area of the left anterior temporal lobe and the left occipital lobe. These effects have been interpreted as the consequence of higher demands of visual-spatial processing related to signed languages, that during comprehension require to constantly and jointly process motion information of the hands producing the sign, and the facial expression of the speaker which conveys relevant syntactic and pragmatic information. Quartarone et al. (2022) used Diffusion Magnetic Resonance Imaging Tractography (DTI) to compare the microstructural properties of the ventral WM tracts in UBs and BBs. The results highlighted both similarities and differences between the two groups. For both UBs and BBs, the degree of bilingualism was associated to the microstructural properties of the right ILF. However, only for BBs the performance on a fluency task in L1 was associated to the microstructural properties of the right Uncinate fasciculus (UF), an anterior white matter tract connecting the most anterior part of the temporal lobe with the Inferior Frontal Gyrus (IFG), suggesting that this tract might be involved in the control of the signed L2 during L1 production. Other studies investigated more directly the effect of bimodal bilingualism on frontal control regions, only partially supporting the idea that BBs may rely to executive control resources to a lesser extent than UBs. Olulade et al. (2016) showed that the differences observed in control regions (bilateral frontal and right parietal) between UBs and monolinguals are not present when comparing BBs and monolinguals. Differently, Zou et al. (2012) and Li, L. et al. (2017) found large structural similarities between UBs and BBs in the same areas.

In conclusion, the amount and the type of control needed for BBs and whether this involves the same processes and structures as for UBs still remain to be fully disclosed. One

of the aims of present study is trying to fill this gap.

1.2 The Frontal Aslant Tract (FAT)

In the present study we focus on the frontal aslant tract. This is a quite newly described intralobar frontal tract (Catani et al., 2012; Thiebault de Schotten et al., 2012) that links the supplementary motor complex of the superior frontal gyrus (the supplementary motor area - SMA - and the pre-SMA), and the most posterior part of Broca's area, the lateral IFG (see Figure 1). Based on the established role of the areas it connects, it has been hypothesized that the FAT is involved in control and executive functions. In a recent review Dick et al., (2019) proposed that this tract is a key component of neural circuit, that together with subcortical and cerebellar regions, is engaged in action control and in particular in planning, timing and coordination of sequential motor movements. Within this network, the FAT would not be simply involved in motor processing, but it would perform a domain-general higher level function, i.e. resolving the conflict among competitor motor programs (see also Shekari & Nozari, 2022). In the same review, Dick and coll. proposed some degree of specialization across the hemispheres. While the left FAT would be part of a circuit specialized for speech action control (Tremblay & Dick, 2016), the right FAT would be part of a circuit specialized for general action control. Neuroimaging studies provided extensive evidence that the areas connected by the left FAT are important components of language processing. In particular, the left IFG seems to be implicated in controlled semantic and lexical retrieval both in spoken and signed language (e.g. Katzev et al., 2013; Emmorey et al., 2007) and the SMA and pre-SMA are associated with the selection and execution of motor programs for speech (Alario et al., 2006; Tremblay & Gracco, 2009; 2010), but also for other non-linguistic domains (Cona & Semenza, 2017). Empirical evidence showing the involvement of the left FAT in language production primarily comes from studies on several

clinical populations reporting a relationship between speech fluency and the microstructural properties of the left FAT (e.g. Catani et al., 2012, Mandelli et al., 2014; Alyahya et al., 2020; Dragoy et al., 2020; Li, M. et al., 2017), and from intraoperative stimulation studies, showing that the direct stimulation of the of the left FAT often causes speech arrests (e.g. Fujii et al., 2015; Kinoshita et al., 2015). Other studies suggested an involvement of FAT in stuttering: the severity of persistent developmental stuttering seems to be correlated with the diffusivity of the FAT (Kronfeld-Duenias et al., 2016). When considering studies on non-clinical populations, there is evidence reporting that FAT's microstructural properties are associated to language tasks not directly related to fluency. Broce et al. (2015) found that the length of the left FAT was correlated with the score on a receptive language battery in typically developing children of 5-8 years. More recently, Vallesi & Babcock (2020) reported that the degree of left-asymmetry of the FAT correlated with lexical decision speed but not with verbal fluency performance in a group of healthy university students (see Kronfeld-Duenias et al., 2016 for a similar null correlation between the properties of the FAT and the fluency task in non-clinical adults).

As for the right FAT, functional neuroimaging studies showed that both the right SMA and pre-SMA and the right IFG are activated in tasks that require stopping behaviors (e.g., Nachev et al., 2008; Garavan et al., 1999). Stimulation of these areas is associated to the inhibition of voluntary fine movements (Luders et al.,1988) Patients with lesions of the SMA and pre-SMA showed deficits in the production of complex sequences of movements (Dick et al., 1986) and patients with lesions in the IFG show impairments in the inhibition of the irrelevant task set (Aaron et al., 2003; 2004). However, patients with resection of the right FAT do not show impairments in the Stroop test performance where inhibition of verbal responses is required (Puglisi et al., 2019), further supporting the hypothesis of at least partial hemispheric specialization of the control network involving the FAT.

All this evidence is consistent with the proposal that the FAT is involved in inhibitory control processes, also for those related to the regulation of the output of speech (Shekari & Nozari, 2022). However, the exact role of the FAT and whether its function is mainly related to domain-general or language-specific processes has not been fully understood. The present study contributes to clarify these issues by investigating, for the first time, to what extent language control processes are independent of language modality.

1.3 The present study

We extracted the microstructural properties of the right and left FAT by means of DTI in two groups of bilinguals. We adopted the Spherical Deconvolution approach (Tournier et al., 2004; Dell'Acqua et al., 2010, 2013) and we characterized the structure of WM fibers using 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 et al., 2013). Higher HMOA values indicate greater fiber integrity in a given direction. We correlated the HMOA of the left and right FAT with the behavioral performance in two language production task and a language comprehension task, performed both in L1 and in L2 by UBs and BBs. Both groups of bilinguals have a spoken language as L1 (Italian) and either English or Italian Sign Language as L2. The correlational approach we adopted had the advantage to highlight 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. In addition, by comparing the correlational pattern obtained for UBs and BBs, we could evaluate the control needs for suppressing L1 (spoken) during the use of L2 (either signed of spoken) and the control needs for suppressing L2 (either signed or spoken) during the use of L1 (spoken).

The two language production tasks were verbal fluency and picture naming. Picture

naming is thought to represent word production as it occurs in more naturalistic situations. After the concept represented in the picture has been identified, the corresponding lexical representation is retrieved from memory and its phonological structure and content are specified. At this point, the articulatory processes can be planned and, finally, the word is uttered. These processes did not occur automatically. Control processes are needed for the selection of the lexical item and its segments, for the initiation of the speech, as well for monitoring the output at different levels (Levelt, et al., 1999; Hartsuiker & Kolk, 2001; Nozari et al., 2011; Tourville & Guenter, 2011). Few recent studies investigated the relationship between picture naming and the FAT. Zhong et al. (2022) estimated FAT integrity in a group of patients with left post-stroke aphasia. They found that lower FAT integrity was associated to better performance picture naming. Troutman & Diaz (2019) showed a positive correlation between the microstructural properties of the dorsal network (comprising the left FAT, the arcuate fasciculus and the superior longitudinal fasciculus) and the accuracy in picture naming in presence of phonological distractors. Higher FA and lower radial diffusivity (RD) of the dorsal pathway predicted lower accuracy. Finally, Troutman et al. (2022) asked a group of healthy adults to name everyday objects and to respond “picture” in the case of abstract images. They found that the FA and the RD of the left FAT predicted the effect of age in picture naming latency, when adjusted for the associated accuracy. The direction of the correlations, however, was somehow puzzling. Higher FA (but also higher RD) were associated to higher efficiency, i.e., shorter adjusted latencies, when naming everyday objects; however, the adjusted latency to abstract images showed an inverse pattern, where higher FA and lower RD were associated to longer latencies. In conclusion, the evidence suggests that the microstructural properties of the left FAT could predict picture naming performance, however the mixed pattern of results does not allow to determine which are the exact processes of this task in which this tract is involved.

Verbal fluency requires participants to retrieve as many words as possible in a minute of time, according to a specific criterion. In the semantic fluency task, participants were asked to retrieve words (or signs) from a given semantic category. In the phonological fluency task, participants were asked to retrieve words beginning with a given phoneme or signs made with a given handshape (or another phonological parameter). Previous findings are quite inconsistent in showing an involvement of the FAT in verbal fluency, some studies reported correlations with both phonological and semantic fluency (Blecher, et al. 2019; Li, M. et al. 2017), some only with phonological fluency (Keser et al., 2020), and some found no correlation at all (Vallesi & Babcock, 2019). The reason for such controversial results might depend on the composite nature of the fluency task. The fluency task involves control processes at several levels such as the active search among lexical items according to a single cue, the selection of the item to be uttered among several activated lexical entries, the sequencing of the activated relevant lexical entries and, finally the monitoring of the output in order to avoid repetitions and invalid responses. Performance in this task depends on vocabulary knowledge and speed of lexical activation, but a relevant component of this tasks relies on executive control. Luo et al., (2010; see also Sandoval et al., 2010) proposed to analyze the time course of word retrieval in the fluency task, in order to dissociate the executive control component from other purely lexical processes and vocabulary knowledge. Generally, in verbal fluency tasks, participants produce many words at the beginning of the 1-minute interval and then the production rate progressively declines until reaching an asymptote. Plotting the number of items generated against time it is possible to define the function representing the rate of recall. The exponential function has been used to describe the decline in free recall tasks (Wixted & Rohrer, 1994); while research on verbal fluency has used the logarithmic function (Luo et al., 2010). The slope of the function reflects how linguistic resources are handled during the interval. As time progresses, more control is

required to search within the active representations in the lexicon and to monitor the production of new items, resist to lexical interference, and contrasting the tendency to perseverate on already produced responses. Therefore, as proposed by Luo et al., (2010) and Friesen, et al., (2015), the slope of this function can be considered an index of the control needs during word production: the flatter the function (i.e., slope close to 0), the stronger the means for controlling and monitoring lexical production. In the present study we used the slope of the recall rate function as an index of the executive control abilities in the fluency task.

The language comprehension task was a grammaticality judgment of spoken or signed sentences. Bilinguals were presented with one sentence at a time, and, for each, they were required to evaluate the grammatical acceptability of the sentence (acceptable / not acceptable) by pressing one of two keys. Half of the sentences were acceptable sentences, half contained a violation at the lexical, semantic or syntactic level. This task was introduced to investigate whether the neural circuit comprising the FAT is exclusively involved in speech/action control or whether it is also involved in other language processes not directly related to speech motor planning. This issue is still underexplored and empirical evidence on this issue is still scarce.

If the FAT is involved in inhibitory language control, we could expect to find a correlation between the microstructural properties of this tract and the production tasks. This correlation should be evident especially during L2 production, given that interference from L1 to L2 is stronger than the reverse. In addition, control needs should be maximal for less proficient bilinguals who have to override the activation of the stronger and prominent L1. As far as automaticity of lexical access increases even for L2, and as far as the linguistic system adapts to the use of two languages, inhibitory control process becomes less essential, and both languages can be handled with a larger degree of automaticity (Abutalebi & Green,

2007; Grundy et al., 2017; Pliatsikas, et al., 2020). Moreover, if controlling languages within the same modality requires the same neural circuit as controlling languages of different modalities we could expect to find similar correlational patterns for UBs and BBs. Also, if controlling languages within the same modality is more costly than controlling languages of different modalities, we could expect to find stronger correlations for UBs than for BBs. If, instead, the control of signed and spoken language rest on different neural circuits, UBs and BBs would show different correlational patterns, in particular during L1 production when either a spoken or a signed language needs to be suppressed.

2. METHOD

2.1 Participants

Forty-nine bilinguals took part in the study. Data collection was part of a bigger study (see also Quartarone et al., 2022) aimed at investigating structural differences in bilingualism according to modality. They were all right-handed, as verified through the Edinburgh Handedness Inventory Test (Oldfield, 1971) and none had a history of neurological illness. Twenty-four participants had Italian as L1 and Italian Sign language (LIS) as L2. Twenty-five had Italian as L1 and English as L2. UBs had a certified level of English proficiency corresponding at least to the C1 of the Common European Framework of Reference for Languages (CEFR); during the last 5 years they spent at least 6 months in an English-speaking country. BBs had at least the third grade of LIS level, which corresponds to a complete mastery of the language, comparable to the C1 level of English. Both samples had three native bilinguals that have been exposed to the respective L2 before the age of 3, but most of the participants were sequential bilinguals that actively learned L2. At the moment of testing, all participants declared to use the L2 on a daily basis.

Table 1 reports the main features of the participants in the two groups. 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.

Table 1. Means and standard deviations (SD, in parentheses) of the characteristics of the two groups of bilinguals. AoA refers to age of acquisition. 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 – 17 F					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-reported proficiency	7.2 (1.22)					7.8 (1.88)				
% L2 use	47.92 (20.79)					42.08 (24.88)				
% 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

Participants 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.

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-shot, spin-echo, EPI sequence with the following parameters: TR = 8500, TE = 97, FOV = 307.2 x 307.2, matrix size = 128 x 128, 60 slices (no gaps) with isotropic (2.4 x 2.4 x 2.4 mm^3) voxels. The maximum diffusion weighting was 2000 sec/mm2, 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 minutes.

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

Each subject's raw image data were examined before proceeding on to further analyses to detect any outliers in the data, including signal drop-outs, poor signal-to-noise ratio, and image artifacts 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 (http://www.exploredti.com; Leemans et al., 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 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).

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°. 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 Tractography dissections of the frontal aslant tract

To visualize frontal aslant tract and quantify tract-specific measures we used TrackVis software (http://www.trackvis.org; Wang et al., 2007). We used two regions of interest (ROIs) approach according to a dissection method previously described in Budisavljević et al. (2017), Catani et al. (2012) and Rojkova et al. (2015). Two separate frontal ‘AND’ ROIs were manually delineated on the FA maps of each subject in each hemisphere. The ‘AND’ ROI is used to represent an obligatory passage for the tract, and includes the desired

streamlines passing through it. We delineated on axial slices an ‘AND’ ROI around the white matter of the superior frontal gyrus (SFg ROI) and a sagittal ‘AND’ ROI around the white matter of the inferior frontal gyrus (also including the pars opercularis, triangularis and orbitalis) (IFg ROI). An example of tractography reconstructions in a representative subject is shown in Figure 1.

2.3 Behavioral testing

During this session participants performed three experimental tasks: fluency, picture naming and a grammaticality judgment task. All tasks were performed first in L1 and then 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. In the semantic fluency the categories “Animals” and “Transports” were used for Italian and the categories “Food” and “Clothes” for English and LIS; in the phonological fluency the phonemes “F” and “L” were used for in Italian, the phonemes “S” and “P” for English, and the hand configurations “1” and “B” for LIS. The participants 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. Responses were audio-recorded (for Italian and English) and video-recorded (for LIS). For the registration of the vocal response participants wore a pair of Microsoft LifeChat LX-3000 earplugs with a built-in microphone. 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. To estimate the slopes of the fluency tasks, the 1-minute time was divided in 12 bins of 5 seconds each. Analysis were

performed on a participant basis. First, we counted the number of correct responses per participant on each bin of each fluency task. Then, for each the two languages (L1 and L2), we estimated the mean of correct responses in each of the 12 bins, separately for the two phonological and the two semantic tasks. We fitted the 12 bin means with a logarithmic function; the y value of the function was used as the slope value.

For the picture naming task, we selected 100 colored pictures of concrete objects from pre-existing databases (Alario & Ferrand, 1999; Dell'Acqua, Lotto, & Job, 2000; Bonin, et al., 2003). The list of pictures is available in the Supplementary Material. The pictures were presented on the monitor of the computer (PC Acer Intel Core i7, display 17"), one at a time, centered within a white 400x400 mm template, for 2000 ms or until the participant produced a response. Each picture was preceded by a fixation point (+) lasting 500 ms. DMDX software (Forster & Forster, 2003) was used for picture presentation in Italian and English and E-prime 2.0 (Schneider, Eschman, & Zuccolotto, 2002) for LIS. The same set of 50 pictures in each language condition was presented twice, in distinct blocks, with a different randomized order for each block and participant. The two blocks were separated by a brief pause. The experimental blocks were preceded by a 6 trial training. Vocal responses were recorded through the microphone. Mean RTs were calculated checking manually the interval between the appearance of the target picture and the beginning of each correct response, using Check-Vocal software (Protopapas, 2007). Manual responses were video recorder and checked for accuracy. To record the response times, 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. Release times of correct responses, starting from the presentation of the picture were computed. For both vocal and manual responses, response latencies faster than 200 ms or slower than 4000 ms were considered outliers and not included in the RTs analysis.

For the grammaticality judgment task, 90 correct and 90 incorrect sentences (formed

from 4 up to 9 word/signs) have been created ad hoc for each language. All .s had the same structure and were created by a noun and a verb phrase. The incorrect sentences contained at the end either a pseudo word/a pseudo sign, or a semantically incongruent word/sign or a syntactic violation, that in English and Italian was a morphological violation related to number (or gender for Italian) and in LIS was a) a violation of the object-verb/action location concordance, or b) a violation of the negation position. Correct sentences are reported in the Supplementary materials. The sentences in Italian and English were read by a native English bilingual and audio recorded and the sentences in LIS have been signed by a native deaf signer and video recorded. The sentences have been presented using DMDX software. After a fixation cross ("+") lasting 1500 ms, a sentence was presented and participants were instructed to press the "B" or the "N" key when the sentence was correct or incorrect, respectively. Given that the sentences had different durations, we calculated the latency with respect to the duration of the sentence: RT of each correct response / sentence duration. Only latencies to sentences without violations were considered.

After the experimental session we collected demographic data and information about the use and proficiency of L2. At the end of the session, non-verbal intelligence was tested administering 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). In order to control for the L2 AoA, the effect of age, and gender on the HMOA value, we run linear regression models with these variables as predictors. We also added Group (Bimodal Vs. Unimodal bilinguals) as predictor in order to test whether the two groups of bilingual participants showed anatomical differences in the microstructural properties of the FAT

(Syntax: lm(FAT_HMOA ~ Sex + Age + Group + AoA_L2; *lme4* R package, Bates et al., 2015).

As a second step, we assessed the relationship between the DTI data and the language tests. Person's correlations were used. The HMOA of the right and left FAT and the dependent variables extracted from each behavioral task were correlated, both considering the whole group of bilinguals and separately for each group of bilinguals. We calculated the uncorrected and FDR-corrected p-values. Correction was applied according to Benjamini and Hochberg (1995), and separately for each task. 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 & Rounder, 2021). 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). If a given correlation was significant only for one group of bilinguals, we compared the correlation coefficients of the two groups using the r.test() function from the *psych* R package (Revelle, 2021).

3. RESULTS

Tract dissection in a representative participant is shown in Figure 1. Figure 2 reports the HMOA values separately for each tract and for each group of bilinguals.

The linear regression model run on the HMOA values showed no effect of group (left FAT t = 0.485; right FAT t = 0.307), no effect of age (left FAT t = -0.034; right FAT 0 t 0 -0.928), no effect of gender (left FAT = t = -0.307; right FAT t = 0.281) and no effect of L2

AoA (left FAT t = 0.297; right FAT t = -0.443). These variables were no longer considered in the following analyses.

Figure 1. Tractography reconstructions of the left and right frontal aslant tract in a representative subject. Frontal 'AND' ROIs including superior frontal gyrus (SFg ROI) and inferior frontal gyrus (IFg ROI) are shown for the right hemisphere.

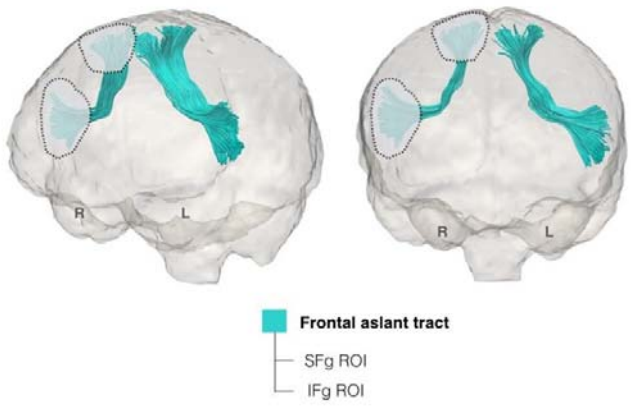


Figure 2. Violin plots of the HMOA values of the right and left FAT extracted form the two groups of bilinguals. Lines represent mean values.

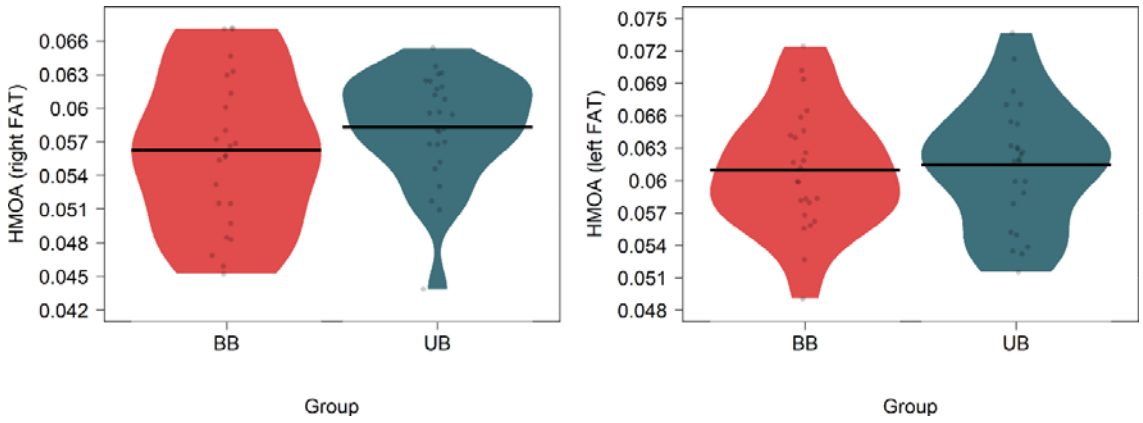


Table 3 reports the performance of the two groups of bilinguals in the behavioral tasks. Two UB participants were excluded from the analyses in the grammaticality judgment task since their mean speed was 2.5 sd lower than the mean.

Table 3. Mean performance and standard deviation (in parenthesis) obtained in the behavioral tasks performed in L1 and in L2 by unimodal (UB) and bimodal (BB) bilinguals. The Slope in the fluency task refers to the slope of the retrieval rate logarithmic function. A slope near to 0 represents a performance where control is deployed all along the minute of time. For the Grammaticality judgment task, we analyzed the responses to acceptable sentences. We used the ratio between the duration of the sentence and the latency of the keypress as an index of the response time.

		SEMANTIC FLUENCY		*PHONOLOGICAL FLUENCY*		*PICTURE NAMING*	*GRAMMATICALITY JUDGMENT*	
		N of Words	Slope	N of Words	Slope	Mean RTS	RTs/Duration	Accuracy
L1	*BB*	17.146 (3.447)	-1.223 (0.414)	14.229 (2.870)	-0.686 (0.315)	789.958 (78.867)	1.254 (0.123)	0.947 (0.035)
	UB	18.16 (2.779)	-1.272 (0.370)	14.12 (3.153)	-0.705 (0.216)	784.8 (91.652)	1.213 (0.11)	0.964 (0.032)
L2	*BB*	14.396 (3.455)	-0.607 (0.222)	8.875 (1.941)	-0.293 (0.177)	1156.646 (399.056)	1.011 (0.063)	0.736 (0.099)
	UB	15.1 (2.905)	-0.905 (0.255)	13.28 (2.292)	-0.577 (0.224)	989.448 (177.396)	1.367 (0.134)	0.834 (0.068)

Table 4. Correlations between the HMOA of the left and right FAT with the behavioral measures extracted from the three tasks performed by participants. For each task, correlations for the whole group, for BBs and UBs are reported, in both L1 and L2. Both uncorrected and FDR-corrected p-values are reported together with the Bayes Factor (BF_{10}). Correlations with p values lower than .05 are marked in bold.

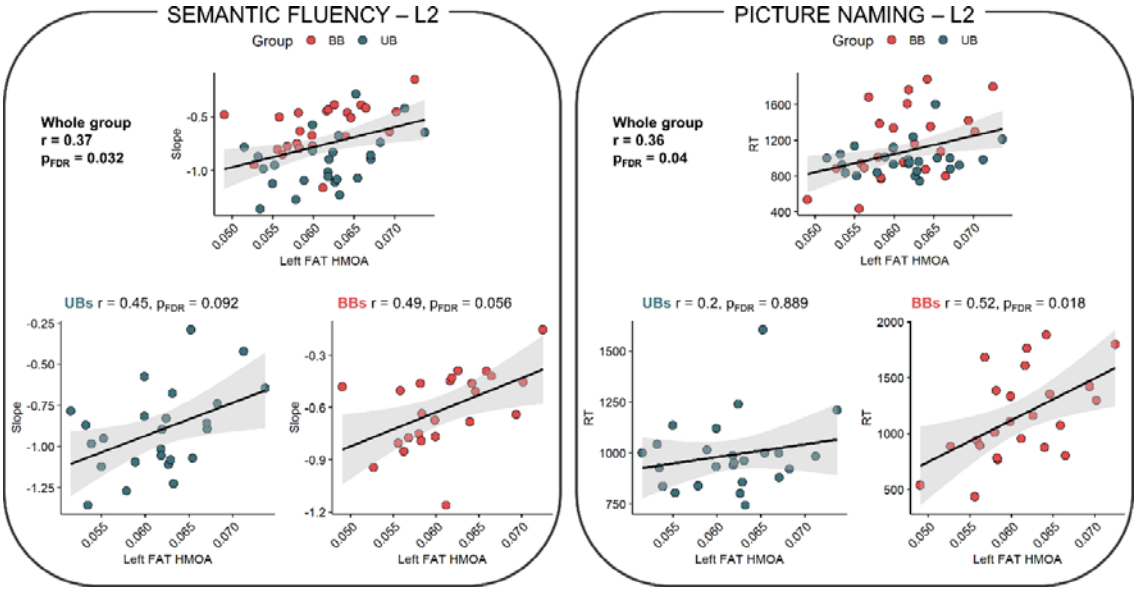
Task	Group	Language	Pearson's r		p_{uncorr}		P_{FDR}		*BF*	
			left FAT	right FAT	left FAT	right FAT	left FAT	right FAT	left FAT	right FAT
Picture naming	Whole group	L1	0.192	0.210	0.187	0.148	0.187	0.187	0.704	0.824
		L2	0.364	0.197	**0.010**	0.175	**0.040**	0.187	6.272	0.735
	BBs	L1	0.448	0.519	**0.028**	**0.009**	**0.037**	**0.018**	3.131	6.836
		L2	0.524	0.377	**0.009**	0.069	**0.018**	0.069	7.331	1.698
	UBs	L1	-0.010	-0.119	0.961	0.572	0.961	0.889	0.433	0.494
		L2	0.204	-0.091	0.329	0.667	0.889	0.889	0.641	0.467
Semantic fluency	Whole group	L1	0.294	0.178	**0.041**	0.222	0.082	0.296	2.12	0.629
		L2	0.372	0.061	**0.008**	0.676	**0.032**	0.672	7.285	0.348
	BBs	L1	0.249	0.358	0.240	0.086	0.240	0.172	0.774	1.464
		L2	0.493	0.258	**0.014**	0.224	0.056	0.240	5.048	0.807
	UBs	L1	0.349	-0.056	0.087	0.790	0.174	0.790	1.444	0.446
		L2	0.452	0.115	**0.023**	0.584	0.092	0.779	3.560	0.490
Phonological fluency	Whole group	L1	0.336	0.232	**0.018**	0.108	0.072	0.145	3.92	1.027
		L2	-0.010	-0.232	0.943	0.109	0.943	0.145	0.322	1.023
	BBs	L1	0.461	0.325	**0.024**	0.121	0.096	0.242	3.556	1.175
		L2	-0.158	-0.240	0.461	0.258	0.461	0.344	0.550	0.742
	UBs	L1	0.187	0.079	0.372	0.707	0.707	0.707	0.601	0.459
		L2	0.150	-0.091	0.473	0.665	0.707	0.707	0.535	0.467
Grammaticality judgment	Whole group	L1	0.09	0.067	0.546	0.655	0.655	0.655	0.351	0.327
		L2	0.135	0.217	0.365	0.142	0.655	0.568	0.453	0.339
	BBs	L1	0.058	0.225	0.788	0.291	0.788	0.582	0.453	0.695
		L2	0.153	0.354	0.475	0.089	0.633	0.356	0.542	1.430
	UBs	L1	0.214	-0.071	0.327	0.748	0.436	0.748	0.662	0.467
		L2	0.251	-0.307	0.248	0.154	0.436	0.436	0.771	1.022

Table 4 reports the correlations we obtained between the HMOA values of the FAT and the behavioral variables extracted from the language tasks. We focused on the slope of the function describing retrieval rate during the fluency tasks, the picture naming latency, and the latency in the grammaticality judgment task.

3.1 Left FAT

We obtained significant correlations (FDR corrected) between the HMOA of the left FAT and the performance in the semantic fluency task and in the picture naming task, when performed in L2 for the whole sample of bilinguals (see Figure 3). The slope of the retrieval rate function was positively correlated to the HMOA value. The pattern seems to be present for both UBs and BBs, however separate correlations within each group were not significant after FDR correction.

Figure 3. *Production tasks in L2*. On the left, the correlations between the HMOA of the left FAT with the slope of the recall function in the semantic fluency task. On the right the correlation between the HMOA of the left FAT and the mean response times (in ms) obtained in the picture naming task in L2 (i.e. English and LIS for unimodal and bimodal bilinguals, respectively). The upper graph represents the whole group of bilinguals and the lower graphs the unimodal and bimodal bilinguals, separately. Red dots represent bimodal bilinguals and green dots unimodal bilinguals.



Picture naming latency in L2 was also positively correlated with the HOMA value. When analyzed separately, the correlation was significant for BBs but not for UBs. When

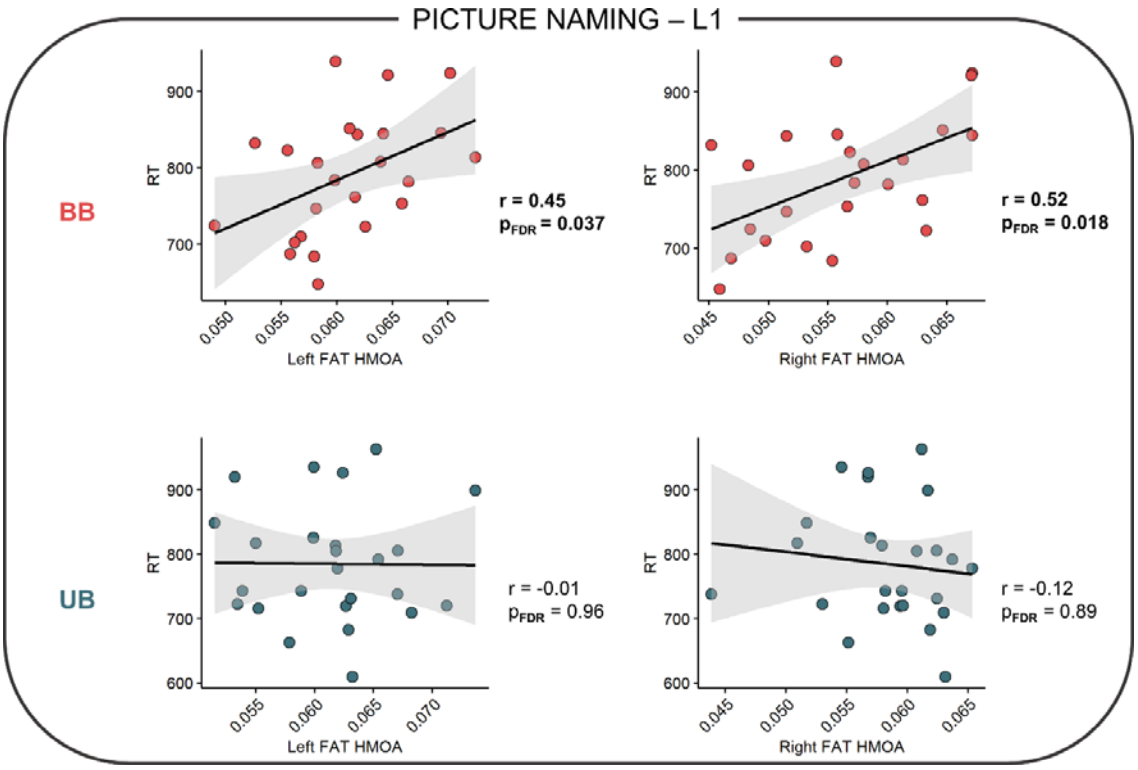
compared, the correlation coefficients of the two groups were not significantly different (z-value = 1.225, p = 0.221).

Only for the BB group, the HMOA of the left FAT correlated with picture naming latency in L1 (Figure 4). 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 did not observe a statistically significant difference (z-value = 1.622, p = 0.105).

3.2 Right FAT

A similar difference between BBs and UBs concerned the relation between the right FAT and picture naming in L1 (Figure 4). Again, for BBs, the HMOA of the right FAT was positively correlated with the response times, but such correlation was not present for UBs.

Figure 4. *Production task in L1*. Correlations between the HMOA of the FAT and the latency in the picture naming task. The graphs on the left concern left FAT, on the right, the right FAT. The upper portion of the Figure represents the correlations found for the BBs, and the lower portion the correlations for the UBs.



The contrast between correlation coefficients revealed a statistically significant difference between the two groups (z-value = 2.284, p = 0.022).

No significant correlations emerged for the grammaticality judgment task.

In sum, production in L2 resulted to be related to the microstructural properties of the left FAT. This occurs for the whole group of participants, i.e., independently of the modality of the L2. The HMOA decreases as the slope of the recall rate function of the semantic fluency task decreases. Consistently, we found a positive correlation with HMOA and picture naming latencies, showing that lower HMOA values were associated to faster response times.

Performance in L1, and specifically in picture naming, is related to the properties of the right and left FAT, only for bimodal bilinguals. For the right FAT, the correlational pattern obtained in BBs was significantly different from the one observed in UBs. The effect seems to be modality specific, i.e., related to the modality of the L2 during the use of the L1. The neural circuit involving the FAT seems to be strongly involved during L1 production when activation of a signed L2 needs to be controlled. Again, all significant correlations are positive, so that lower HMOA values are associated to faster response times.

4. DISCUSSION

Functional neuroimaging studies showed that multilingual speakers activate areas that are not comprised in the classical perisylvian language network, suggesting that a specific control pathway specializes to enable bilinguals to use the target language while monitoring the interference from constantly active units of the unintended language (Branzi et al., 2016; Calabria et al., 2018). The IFG and the SMA complex are among these areas. The results of the present study showed that the FAT, the WM tract connecting these two areas, is involved in bilingualism and, by comparing unimodal and bimodal bilinguals, they provided novel hints to better specify the role of this tract within the control network.

4.1 The left FAT and L2 production

The results showed that the left FAT is involved in L2 production, independently of L2 modality. Both groups of bilinguals seem to rely on the neural circuit comprising the left FAT when producing words/signs in L2, suggesting that the type of process mediated by this tract is independent of L2 modality. When performing a semantic fluency task or a picture naming task in L2, bilinguals need to select a lexical entry in L2 and control for the interference exerted by semantically related co-activated language entries in L1. For both unimodal and bimodal bilinguals of the present study, L1 was spoken. One possible interpretation, therefore, is that the left FAT, is involved in the suppression of the speech actions. According to such view, the left FAT specializes for the selection and inhibition of speech motor plans, congruently with recent studies showing that the left FAT has a direct role in speech motor planning (e.g., Troutman et al., 2022; Zhong et al., 2022). Troutman et al. (2022), showed that the microstructural properties of the left FAT correlated not only with picture naming times but also with the response times to a less demanding production task in which participants were asked to produce the word "picture" in response to any picture. Zhong et al. (2022) reported a direct association between the severity of speech apraxia and the level of damage of left FAT in stroke patients.

Primarily based of the role of the left IFG which is associated with controlled lexical retrieval and phonological activation/selection in several linguistic tasks (e.g., Katzev et al., 2013; Krieger-Redwood & Jefferies, 2014; Klaus & Hartwigsen, 2019), it has been hypothesizes a role of the left FAT also in this type of processes. The results of the present study are not consistent with such hypothesis, given that a similar involvement of the left FAT is present during L2 production for UBs and BBs, i.e., both when the active lexical/phonological representations belong to the same (spoken) modality and when they

belong to different modalities (signed Vs. spoken). As a matter of fact, direct evidence of the involvement of the FAT in lexical selection is still lacking. Zyranov et al. (2020) analyzed the effects of FAT volume on lexical selection measures using a picture-word interference task in post stroke patients and failed to find a relationship between the two variables. It could be possible that the activation of the left IFG in lexical and phonological selection is mainly related to activation in temporal areas as suggested by a recent study investigating the pattern of functional connectivity during a covert naming task (Rivas-Fernandez et al., 2021). Interestingly, both groups of bilinguals showed a positive relationship between the HMOA of the left FAT and L2 naming times. The longer were the naming times in L2, the higher was the HMOA. In line with our predictions, this relationship suggests that less proficient bilinguals seem to rely heavily on the active suppression of the native language when speaking/signing the L2. As far as automaticity of lexical access increases even in L2, and as far as the linguistic system adapts to the use of two languages, inhibitory control process become less essential and/or control is displaced at other (earlier) levels of processing. In line with this conclusion, we found a positive correlation between the HMOA value and the slope of the function describing the amount of words produced as a function of time in the semantic fluency task, reflecting the rate of declining in performance during the minute of time. Higher HMOA values are associated to slow declining rates., i.e., superior control abilities. Congruent with views envisaging the structural changes related to bilingualism as the result of a learning process, during the initial stages of learning, when processes are not yet automatized more marked changes of the frontal areas of the brain involved in control and executive functions are expected (Green & Abutalebi, 2013). However, as far as proficiency increases, L2 lexical activation/selection becomes more and more automatic, frontal involvement is not yet required and the changes in this part of the brain progressively disappear, in favor of changes in most posterior parts of the brain (Grundy et al., 2017).

Consistently with this conclusion Quartarone et al. (2022) found in the same group of UBs and BBs a correlation between the proficiency/amount of use of L2 and the microstructural properties of the Inferior Longitudinal fasciculus, a WM ventral tract connecting the occipitals and the temporal lobes.

While we found significant correlations between the microstructure of the left FAT and performance in the semantic fluency task in L2, no correlations were found for phonological fluency in L2. Generally, phonological fluency is thought to strongly reflect executive control, given that the search based on the phonological cue is more artificial than the search based on a semantic cue. However, it is possible that the task is highly demanding when performed in L2, and the control resources are primarily deployed to the search for the target words/signs and less to the inhibition of competing candidates, thus involving neural circuits not comprising the FAT.

4.2. The role of the FAT in L1 production

The results showed an involvement of the FAT in L1 production for BBs. We observed that increased HMOA values corresponded to longer response times in picture naming for this group of bilinguals only. This pattern suggests that BBs exert specific control of L2 (signed) when they name pictures in L1. Differently from UBs, who need to select one phonological (spoken) representation at a time, BBs do not experience between-language competition until later levels of processing, and the word and the sign phonology could be both activated by the presentation of a picture. At a given point, however, the spoken modality must be selected and/or the signed modality must be inhibited. This process seems to involve a neural circuit comprising the FAT. It is possible that this tract plays a role in the control of hand movements, stopping the activation of the motor plans related to the sign phonology. In line with this hypothesis, Budisavljević et al. (2017) showed an association

between the microstructural properties of the bilateral FAT and the hand kinematics in the grasping and reaching-to grasp movements, performed with the right hand. This proposal aligns well with the hypothesis that the FAT is primarily involved in the selection and control of the appropriate plan for motor action, consistently with what suggested by recent literature about the role of this tract (Dick et al., 2019; Shekari & Nozari, 2022). The fact that in BBs the inhibition of the signed modality involves both the right and the left FAT, while the inhibition of the spoken modality only involves the left FAT, further supports the idea that, on the left side, the FAT specializes for the control of speech actions (Dick et al., 2019).

Similar to what reported for L2, the correlations between L1 naming times and the HMOA values of the FAT were positive. We interpret this result as indicating that highly proficient bilinguals maintain their language output without – or with minimal interference – from the language not in use. Such conclusion is corroborated by the fact that in BBs speed in picture naming correlates with speed of picture signing ($r = .294$, $p = .004$), suggesting that the most proficient speakers are also the most proficient signers.

Previous evidence in favor of that fact that the FAT is involved in language production mainly derives from work examining clinical populations (e.g., Basilakos et al. 2014; Blecher et al., 2019; Catani et al. 2013; Keser et al., 2020; Kinoshita et al. 2015; Li, M. et al., 2017). The studies with healthy participants failed to find a direct association between the performance in native language word production and the FAT (Babock & Vallesi, 2020; Kronfeld-Duenias et al., 2016). Similarly, here for UBs, we did not find correlations between the microstructural properties of the FAT and the performance in the production tasks in L1. When UBs (or monolinguals) speak in their native language, lexical selection among competing units might occur before the activation of motor plans, at least in the great majority of occasions. Inhibitory control may be exerted during the activation of lexical/phonological representations trough neural circuits not involving the FAT (for a

review see de Zubicaray & Piai, 2019). Alternatively, it might be hypothesized that when a language is fully acquired and handled, lexical selection does not require inhibitory control mechanisms and the most active phonological unit is readily and automatically selected for articulation (Dell, 1986; Costa, 2005). Independently of the dynamic and the processing architecture of lexical selection, our results seem to suggest that, in the native language, speaking does not entail conflict at the motor level, at least for bilinguals of two spoken languages who have to produce one utterance at a time. The case is different for bimodal bilinguals. Due to the different output modality, active phonological representations pre-activate the motor plans needed for their articulation. The non-target action must be inhibited and stopped. The results of the present study clearly indicate that such control processes are supported by the FAT.

Quartarone et al. (2022) reported a significant correlation between L1 production and the microstructural properties of the right UF. Paralleling the results here reported, the correlation was present for BBs but not for UBs. This convergence might point to some neural adaptation of the (right) frontal regions/networks in the control of the signed modality for BBs, consistent with evidence showing differences in control needs between BBs and UBs (for a review, see Emmorey et al., 2016)

4.3 Concluding remarks

The present study demonstrated for the first time a direct relationship between the microstructure of the bilateral frontal aslant tract and language control in bilingual individuals. No evidence of the involvement of this tract was found in the comprehension task of grammaticality judgment, suggesting a primary role of the FAT in processes related to bilingual language production. The comparison between unimodal and bimodal bilinguals allowed us to further specify the nature of the control mechanism supported by the FAT.

Or results confirm the hypothesis that the FAT is mainly involved in the control of action. Specifically, this tract might have a role in resolving the competition among motor programs of language production, either by inhibiting the non-target action and/or selecting the appropriate one (Dick et al., 2019; Shekari & Nozari, 2022). We observed that the competition might occur even among actions performed with different effectors. Production performance of either a spoken or a signed L2 is correlated with the microstructural properties of the left FAT. In addition, the fact that for BBs - but not for UBs – a correlation is found between the FAT's microstructure and production in L1, suggests that when the two languages activate different modalities the control over the unintended language might occur at later levels of processing than when the competition occurs between representations having the same phonological format. Interestingly, we found evidence for some hemispheric specialization in bilingual language control. The left FAT seems primarily involved in controlling the activation of the spoken dominant language during the production of L2 words or signs; the right FAT is involved in the control of the signed language and/or in the control of hand movements during speech. Finally, the competition between languages seems to be stronger for less proficient bilinguals, indicating that for more balanced bilinguals the control network adapts in such a way that either language competition it is not experienced or that the conflict is resolved before activating motor representations, likely involving other brain regions and/or other tracts of the neural network engaged in language control.

The present study has some limitations, primarily due to the difficulty of finding BBs and UBs paired for the year of first L2 exposure. Hearing people not born from deaf parents usually come in touch with sign language during adolescence, whereas L2 learning of a spoken language often starts earlier, during primary school. For this reason, the two samples were not fully matched for this variable. Despite this, we think it is unlikely that AoA

confounded the effects here reported, given that this variable did not have any effects on the microstructural properties of the FAT.

APPENDIX

Appendix A and B are available at
https://osf.io/bv8fm/?view_only=2adaabcc68ab4465af57dc76f0c36e30

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DATA AVAILABILITY

The data with identifying information removed are available at
https://osf.io/bv8fm/?view_only=2adaabcc68ab4465af57dc76f0c36e30
To request the full data set contact francesca.peressotti@unipd.it

COMPETING INTERESTS

The authors declare none.

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