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Research Article

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Abstract

Bilingualism modulates structural and functional brain properties and hence sculpts cognition and language. The aim of this study was to evaluate whether this effect of bilingualism on cognition and language processing is preserved when a primary left-dominant hemisphere brain tumor is present. Results from a large sample of individuals ($n = 119$) showed higher performance of bilinguals in lexico-semantic, nonword repetition, verbal fluency and attention/short-term memory tasks at the presurgery assessment. The beneficial effect of bilingualism on semantic knowledge, nonword repetition and phonological verbal fluency was maintained regardless of the type of brain tumor, whereas the bilingual effect on semantic verbal fluency was influenced by the type of tumor. Moreover, the machine learning results indicated that the lexico-semantic association task was the best predictor of bilingualism. Our results provided the first evidence of bilingualism as a protective factor for cognition of patients with a brain tumor diagnosis, most probably for language-learning abilities.

1. Introduction

Bilingualism enables effective communication in two languages through speaking, writing, reading and listening (Mendis et al., 2021). Nowadays, exposure to continuous interaction among different languages is common, given that more than half of the world's population is bilingual (Bialystok et al., 2012). In this sense, bilingualism is not only associated with the acquisition of a second language, but may also have a potential impact on how information is processed during learning (Dal Ben et al., 2022). An influential hypothesis about the potential positive effects of knowing more than one language on executive functions was proposed (Bialystok, 2011) and evaluated at different periods across the lifespan. In particular, studies have reported a beneficial effect of bilingualism on cognitive flexibility (Massa et al., 2020), working memory (Antón et al., 2019; Morales et al., 2013), set shifting with reduced switch costs (e.g., Mas-Herrero et al., 2021) and overall executive control (e.g., (Bialystok et al., 2008), including both attentional (Chung-Fat-Yim et al., 2022) and inhibitory control (Celik et al., 2022; Giovannoli et al., 2020; Incera & McLennan, 2018; Poarch & Bialystok, 2015). In contrast, a disadvantage of second language acquisition has been suggested in language domains where bilingualism may be negatively associated with language development (Kovayazina et al., 2021; see the review by Bylund et al., 2023). Compared with their monolingual peers, bilingual subjects have lower vocabulary (Portocarrero et al., 2007; Roberts et al., 2002) and proficiency (Hope et al., 2015) in each language, and slower responses in object-naming tasks (Gollan et al., 2007; Ivanova & Costa, 2008). Bilinguals also obtain lower scores on semantic verbal fluency tasks (Gollan et al., 2002; Portocarrero et al., 2007; Rosselli et al., 2000; Soltani et al., 2021) and show more effortful language processing (Bialystok et al., 2012). Differential practice and expertise, along with reduced usage for each language in bilingual speakers, could partially explain these differences in language performance, together with an enhanced sensitivity to damage of bilingual language networks due to this reduced premorbid language proficiency (Hope et al., 2015).

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However, research from the last decade and recent meta-analyses (see, e.g., De Bruin *et al.*, 2021; Giovannoli *et al.*, 2020, 2023; Grundy, 2020; Johann *et al.*, 2022; Kousaie *et al.*, 2014; Lehtonen *et al.*, 2018; Paap, 2019; Paap *et al.*, 2015) have not shown coherent results regarding bilingual advantage and conclude that there is no strong or consistent evidence for enhanced executive functioning in bilingual individuals or reduced language abilities. Hence, the bilingual effect on cognition and language is not yet fully understood and appears to be mediated by several factors. On the one hand, individual factors can modulate the intensity of the bilingual effect, such as age (Bialystok *et al.*, 2014), bilingual acquisition variables (Backer & Bortfeld, 2021; Bialystok & Barac, 2012) or the sociolinguistic context (e.g., switching patterns; (Green & Abutalebi, 2013; Rodriguez-Fornells *et al.*, 2002). On the other hand, methodological discrepancies among studies (Bak, 2016; Van Den Noort *et al.*, 2019) also need to be considered. Overall, it seems that the bilingual effect might be overstated or, at the very least, likely to emerge only under restricted and undetermined circumstances defined by previously mentioned modulation factors (Paap *et al.*, 2015).

Considering the ongoing controversy about the influence of bilingualism, the present study aims to provide a detailed account of its consequences on cognition and language in a specific clinical population of patients with a primary brain tumor. In more detail and building on previous ideas about the potential cognitive benefits of bilingualism, we investigated whether bilingualism serves as a protective factor for cognition and language in subjects diagnosed with a brain tumor located in language-eloquent areas of the left-dominant hemisphere.

The bilingual experience involves not only cognitive and linguistic effects – although still under debate – but may also result in structural and functional changes in the brain that underlie these effects (see the review by DeLuca *et al.*, 2020). The acquisition of a second language has an impact on brain functioning, both resting-state and metabolic processes (see the review by Pliatsikas & Luk, 2016; Tao *et al.*, 2021). Specifically in language processing, the recruitment of additional executive function and cognitive control areas – such as the middle prefrontal cortex, the supplementary motor area and the basal ganglia – during language production has been observed in bilingual individuals (Abutalebi, 2008; Rodriguez-Fornells *et al.*, 2005). In addition, bilingualism may affect the structural properties of the brain (see the review by Li *et al.*, 2014), including changes in white matter integrity (López-Barroso *et al.*, 2013; Pliatsikas & Luk, 2016; Vaquero *et al.*, 2017) and gray matter structure (see the review by Taylor *et al.*, 2022). These effects may result in a preserved intrinsic functional network organization in bilinguals that is not observed in monolinguals (Stevens *et al.*, 2023).

Functional and structural neuroplasticity associated with bilingualism might contribute to cognitive reserve, suggesting bilingualism as a cognitive reserve factor (Bak *et al.*, 2014; Bialystok *et al.*, 2016; Craik *et al.*, 2010, p. 201; Perani & Abutalebi, 2015; Schweizer *et al.*, 2012). Thus, bilingualism, from this point of view, could be conceptualized as an important contributing factor that enables individuals to deal with a specific pathology for a longer period before it interferes with cognition (Berkes & Bialystok, 2022). However, it remains unclear whether the effects of bilingualism on cognition and language persist in the presence of a brain lesion that implies specific neuroplasticity changes, such as a brain tumor. Primary brain tumors originate from cells within the central nervous system (Lapointe *et al.*, 2018), with gliomas being the most common type (McNeill, 2016). The presence of gliomas involves

neuroplastic mechanisms that result in structural and functional changes within the brain, which vary across tumor types. Gliomas are classified according to an integrated diagnosis comprising tissue-based histological and molecular information (Weller *et al.*, 2024), all of which can be divided into high-grade glioma (HGG) and low-grade glioma (LGG). Just as learning a second language induces changes in brain structure and function, brain tumors also involve the reshaping of these structures and functions. In fact, a multi-level model of glioma-induced plasticity has been proposed, which includes functional network remodeling and compensatory reconfiguration of cognitive processes (Ng *et al.*, 2024). As described in previous literature, and in contrast to HGG, LGG is characterized by slower tumor growth, which allows for greater brain functional reorganization (Desmurget *et al.*, 2007; Herbet *et al.*, 2016). Hence, cognitive changes are particularly prominent in HGG (Acevedo-Vergara *et al.*, 2022), including several cognitive domains (e.g., executive functions, memory or language) and depending on the location of the lesion and the integrity of the disrupted white matter (Acevedo-Vergara *et al.*, 2022). Given that the acquisition of a second language and brain tumors are associated with specific neuroplasticity mechanisms, it is crucial to clarify how these factors interact in shaping individuals' cognitive and language performance. Our sample includes participants with LGG and HGG, classified as bilingual or monolingual, providing a unique opportunity to examine the simultaneous effects of both plasticity mechanisms on language and cognition. Accordingly, this study aims to assess differences in cognition and language by considering not only the number of languages acquired but also the type of brain tumor – classified as either HGG or LGG. In this regard, we aimed to investigate whether bilingualism could be considered a protective factor for cognition and language in patients with brain tumors and, furthermore, if this effect might depend on tumor type.

2. Method

2.1. Participants

Our study sample includes 119 patients who were candidates for an awake brain surgery and met the following inclusion criteria: (1) diagnosis of a primary brain glioma (classified according to the WHO Classification (Louis *et al.*, 2007, 2016, 2021) in the left-hemisphere (dominant for language); (2) the production of Spanish and/or Catalan as native or with a high level of proficiency (see further clarified below); (3) ability and willingness to cooperate during the surgical procedure while awake; (4) awake brain surgery including intraoperative mapping and monitoring of language and cognition. Language acquisition was determined based on the patient's production ability, as demonstrated by performance in an adapted version of the object-naming task to be used intraoperatively. Therefore, a score of more than 65% was considered an indication of a high level of proficiency in the evaluated language, and consequently, optimal acquisition of that language. Participants who achieved this level in both Catalan and Spanish were classified as bilingual, while those who achieved it in only one language were classified as monolingual. Moreover, although we did not perform an objective assessment of the bilingual context using a standardized questionnaire, all assessed languages were reported as functionally relevant to patients' quality of life. Therefore, patients are relatively exposed to and actively use these languages in their daily lives. We excluded individuals with other brain lesions such as cavernous angiomas or metastases, as well as non-Spanish and/or Catalan

Table 1. Clinical description of the sample

	ALL (N = 119)	BL (N = 71)	ML (N = 48)	Group differences
Age, years	46.0 [35.0;57.0]	44.0 [29.5;54.0]	50.5 [41.0;59.2]	$W = 1295^{**}$; $r = -.25$
Gender (female/male)	45/74	27/44	18/30	$\chi^2 = 0$; $V = 0$
Education, years	10.0 [8.0;12.0]	12.0 [10.0;15.0]	8.0 [7.5;10.2]	$W = 2500^{***}$; $r = .40$
Grade of glioma (HGG/LGG)	83/36	43/28	40/8	$\chi^2 = 5.99^{*}$; $V = .22$
Days between baseline assessment and surgery	17.0 [10.0;55.0]	19.0 [11.0;58.0]	15.0 [5.8;34.5]	$W = 1987$; $r = 0.14$

Note: For numerical variables, median [first quartile; third quartile] is indicated. For categorical variables, the number of subjects for each category is indicated. p-value refers to the analysis of the Wilcoxon–Mann–Whitney test or Pearson’s chi-squared test. * indicates level of significance: $^{*}p < 0.05$. $^{**}p < 0.01$. $^{***}p < 0.001$. r indicates effect size for the Wilcoxon test ($r = Z/\sqrt{N}$). V indicates Cramer’s V effect size for Pearson’s chi-squared test ($V = \sqrt{\chi^2/n \cdot df}$).

bilingual (BL) and monolingual subjects (ML). A total of 71 patients were classified as bilinguals, as they have acquired both Catalan and Spanish. Within the monolingual group ($N = 48$), consisting of patients who only have acquired one language, eight were identified as Catalan monolinguals and 40 as Spanish monolinguals. Patients’ demographic, language and lesion characteristics are shown in Table 1. The study protocol was approved by the Research Ethics Committee (REC) of the Hospital Universitari de Bellvitge. The study was carried out in accordance with the provisions of the Declaration of Helsinki (Fortaleza, 2013). Ethical approval was waived by the REC of Hospital Universitari de Bellvitge in view of the retrospective nature of the study, and all the procedures being performed were part of the routine care. The informed consent was waived by the REC. The processing of personal data was adjusted to the current legal regulations for data protection.

2.2. Neuropsychological assessment

A neuropsychological assessment was administered to each participant by a neuropsychologist before surgery ($Md = 17$ days [10.0–55.0]). The cognitive and language evaluation included a specific test to assess handedness (Edinburgh Inventory; Oldfield, 1971), cognition and language. Neuropsychological battery assessment included an evaluation of attention/short-term memory and working memory (Digit Span forward and backward – Test Barcelona (Peña-Casanova et al., 2009b; Tamayo et al., 2012) and verbal fluency (semantic (animals) and phonological (letter “p”)) (Casals-Coll et al., 2013). Additionally, a detailed assessment of language was performed due to the location of lesions in language-eloquent areas. This assessment included the Boston Naming Test (BNT) adapted to the Spanish population (Aranciva et al., 2012; Peña-Casanova et al., 2009a). We also specified and counted the type of errors produced by participants in the naming task, including semantic and phonological paraphasias, circumlocutions, delays and missings (also known as “anomia”). In addition to naming, we evaluated repetition of words and nonwords (Sierpowska et al., 2017), verbal comprehension using the Token Test (De Renzi & Faglioni, 1978) and semantic processing through the semantic pairs task (SPT) (Sierpowska et al., 2019); adapted to Spanish from the original 96-item synonym judgment task (for the original version, see Jefferies et al., 2009) and Pyramids and Palm Trees Test (PPT; Howard & Patterson, 1992). In the SPT task, we did not only consider the overall score, but also created additional categories: low-difficulty (“easy”) items were those of high frequency and high imageability, whereas high-difficulty (“difficult”) items were those of low frequency and low imageability. Not all patients completed every task (see Supplementary Table S1 for the exact number of patients completing each assessment task).

2.3. Statistical analysis

The normative data allowing to score cognitive performance was studied in different ways depending on their availability: (1) Scores on Digit Span (forward and backward), verbal fluency (semantic and phonological), BNT and the Token Test were transformed to Scalar Scores (SS) using norms used for young and adult Spanish speaking population from a large normative multinational project that is NEURONORMA project which consider age and educational level of the subjects (Aranciva et al., 2012; Casals-Coll et al., 2013; Peña-Casanova et al., 2009a, 2009b; Tamayo et al., 2012). That is, subjects varied from 1 to 19 points, with scores below 6 considered pathological, from 6 to 7 as mild difficulties, and above 7 as normal. (2) PPT, SPT and experimental nonword repetition scores were transformed to z -scores, and values equal or below -1.5 were considered impaired; (3) the experimental words repetition task was expressed as absolute values (per 40 items). As reported in previous work (Sierpowska et al., 2017), normal subjects scored maximum for word repetition (40/40) and almost at the maximum for nonwords (98, $56\% \pm 1.43\%$). Hence, any score below 100% for word repetition was considered pathological. The specific naming errors were expressed as absolute values per 60 (number of items composing BNT).

According to the non-normally distributed cognitive and language measures, nonparametric tests were used. First, the Wilcoxon rank sum test was used to study the isolated effect of bilingualism on cognitive and language measures. Then, in order to evaluate the potential impact of the interaction between tumor type and bilingualism on the results, we performed a rank-based estimation regression, including the following predictors: number of languages acquired (monolingualism versus bilingualism), tumor type (HGG versus LGG) and their interaction.

Finally, once we analyzed the effect that bilingualism and tumor type have on our clinical sample, we aimed to identify cognitive markers of bilingualism and determine which task best distinguishes bilingual from monolingual patients. To this end, we employed a data-driven approach using a random forest-based machine learning model. The data were randomly and independently divided using a hold-out method into a training and test set (ratio of 70:30), maintaining the original proportion of BL and ML in both subsets. Then, the training set was used to fit the model. First, we determined the number of randomly drawn candidate variables ($mtry$ value) from which each split is selected to minimize the out-of-bag error (OOB). According to this, the $mtry$ value was set at 3 for the model. Then, we fitted 500 trees since this number of trees stabilized the error rate of our model (Boehmke & Greenwell, 2019). Each cognitive and language task defined a separate feature, and we analyzed the feature’s weights obtained from the training

process. Specifically, the mean decrease in Gini was used to measure the contribution of cognitive and language tests in the RF model (the higher the value, the more important for classification). The accuracy, precision and recall metrics of the RF model were calculated from the confusion matrix of the test. Furthermore, we also analyzed the receiver operating characteristic (ROC) curve and its area under the curve (AUC). For all these analyses, the significance level was set at $p < 0.05$. All statistical analyses were performed using RStudio Desktop (R Core Team, 2021).

3. Results

3.1. Effect of bilingualism on cognition and language of glioma patients at baseline

Our analysis of cognitive and language performance at baseline (see Figures 1 and 2) indicated that BL obtained greater scores than ML, with a small effect of bilingualism, on forward digits ($W = 2046.5$, $p = .04$, $r = -.19$), verbal fluency (semantic: $W = 2075.0$, $p = .04$, $r = -.18$); phonological: $W = 1872.0$, $p = .04$, $r = -.19$), Token Test ($W = 1921.5$, $p = .047$, $r = -.18$) and nonword repetition ($W = 920.5$, $p = .006$, $r = -.25$). Furthermore, BL obtained greater scores than ML, suggesting a medium effect in favor of BL, on overall SPT ($W = 939.5$; $p < .001$, $r = -.33$) and specifically on difficult items (that is low frequency and low imageability; $W = 930.0$, $p < .001$, $r = -.32$). In a more specific analysis, we evaluated differences between ML and BL in the type of naming errors assessed with the BNT. Our results from baseline assessment revealed a greater number of semantic paraphasias ($W = 608.5$, $p = .002$), missings ($W = 659.0$, $p = .007$) and circumlocutions ($W = 710.5$, $p = .02$) in the ML group.

3.2. Effect of bilingualism and grade of tumor on cognition and language of glioma patients before surgery

Results from our rank-based estimation regression (see Table 2), which included glioma grade as a predictor for cognition and language together with the number of languages acquired

(bilingualism or monolingualism), elucidated that bilingualism is associated with higher scores in phonological verbal fluency ($\beta 1.99$; $p = .02$), nonword repetition ($\beta 3.51$; $p = .001$) and semantic knowledge (PPT: $\beta 0.77$; $p = .03$; SPT – overall score: 2.86, $p < .001$; SPT – difficult items: $\beta 2.26$; $p = .03$), independently of which type of tumor is diagnosed. In addition, our results also revealed an interaction between the number of languages acquired and the type of glioma. In this regard, bilinguals with LGG obtained higher scores on semantic verbal fluency ($\beta 3.99$; $p = .02$) but lower scores in PPT ($\beta -2.18$; $p = .003$).

3.3. Prediction of bilingualism based on cognitive and language performance

The random forest model achieved an accuracy of 70% in classifying bilinguals against monolinguals among brain tumor patients, with a precision of 86% and a recall of 75% (Figure 3B). The ROC curve of the model is shown in Figure 3C, with an AUC of 0.84, indicating an excellent ability to distinguish between bilingual and monolingual brain tumor subjects. Furthermore, the model indicated that the most important tasks to predict bilingualism were the overall score of the SPT, followed by performance in difficult items of SPT and nonword repetition, as shown in the feature importance plot (Figure 3A).

4. Discussion

In this study, we were interested in exploring a possible protective effect of bilingualism on the cognition and language of subjects diagnosed with a brain tumor in the left-dominant hemisphere who underwent an awake brain surgery. We hypothesized that bilingual subjects diagnosed with a LGG may exhibit better cognitive status at the time of diagnosis. The most significant finding from our initial analysis – examining potential changes in cognition and language due to bilingualism at the preoperative stage – emerged in relation to semantic knowledge, suggesting a medium effect of bilingualism on this language domain. The bilingual group outperformed the monolingual group on the lexico-semantic association task, as

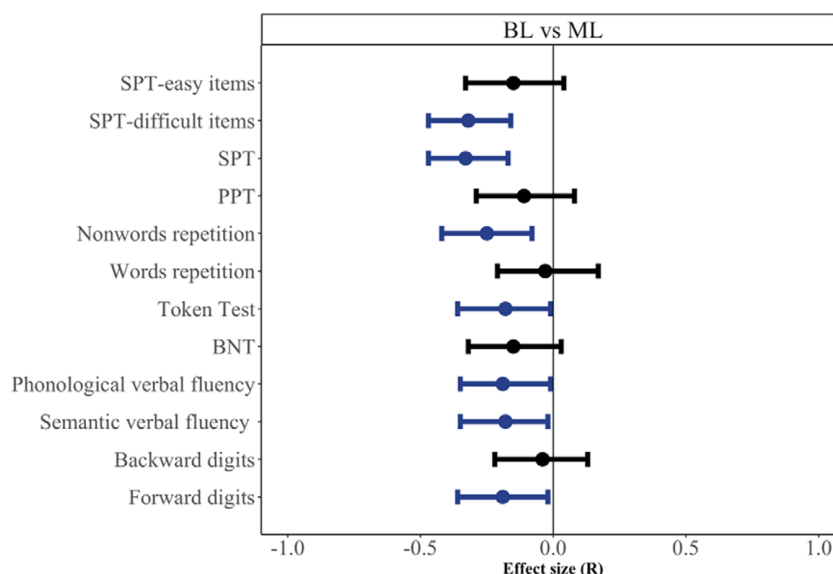


Figure 1. Effect size of group comparison between ML and BL at baseline. Group differences were tested using the Mann–Whitney–Wilcoxon test. The figure shows the effect size for each contrast ($r = Z/\sqrt{N}$), with a 95% confidence interval. $R > 0$: ML scored higher than BL; $R < 0$: ML scored lower than the BL group. Colors represent the significance of the results: blue: significant differences between groups; black: nonsignificant results ($p > 0.05$). SPT = semantic pairs task; PPT = Pyramids and Palm Trees Test; BNT = Boston Naming Test.

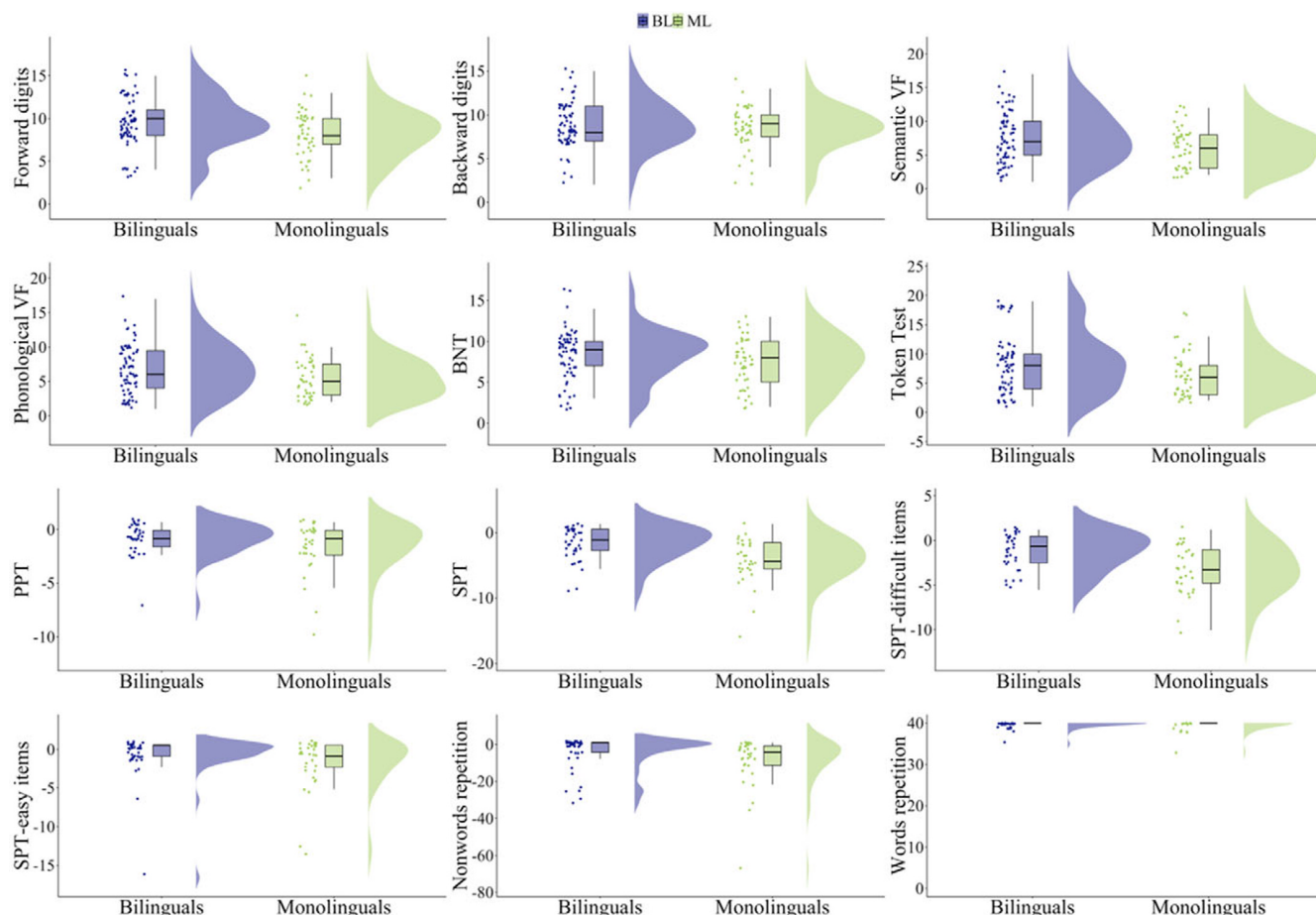


Figure 2. Cognitive and language performance of resulting groups combining the number of languages acquired. For each group, the violin plot shows the distribution of the variable. For each boxplot, the band represents the median value, the box represents the interquartile range, the whiskers show the range of data and black dots represent the outliers. The Y-axis indicates the score of the test (Scalar score, Z score or absolute values, depending on the normative data).

reflected in the overall scores (see Figures 1 and 2). This advantage was particularly evident for more challenging items – those with low imageability and frequency – and remained significant in our second analysis, even after accounting for tumor type. Moreover, the lexico-semantic association task was the best at predicting if a subject is bilingual or not (see Figure 3).

The present results may reflect cognitive and neural mechanisms involved in acquiring a second language (see the review by Rodríguez-Fornells et al., 2009; Gallo et al., 2020; Kroll et al., 2010). New lexical items (L2) are being progressively integrated into existing lexico-semantic networks, likely through direct lexical associations (L1–L2) or new lexico-semantic associations. As in most cases, new lexical forms are integrated into existing semantic networks, bilingual lexico-semantic networks may be reinforced and result in new and strengthened lexico-semantic connections. This strength of lexico-semantic connections due to the acquisition of new L2 concepts could partially explain the better performance of the bilinguals in lexico-semantic association tasks such as the SPT in our study. Within the SPT task, a higher demand for phonological intermediary and semantic-lexical access is present, and hence, more cognitive operations or short-term memory load are needed (Indefrey & Levelt, 2004; Jefferies et al., 2009; Sierpowska et al., 2019). Overall, the superior performance of bilinguals on the SPT, a semantic association task, likely reflects the

importance of learning mechanisms involved in second language acquisition, particularly those related to the acquisition and integration of lexico-semantic knowledge. Both the integration and the optimal inference of meaning are deemed to be supported by the ventral meaning interface (Rodríguez-Fornells et al., 2009). According to this mechanism, internal and external information is integrated to identify appropriate word–meaning associations, enhancing the recruitment of brain regions involved in the storage and retrieval of conceptual information to ultimately reach the meaning of the word (Ripollés et al., 2017). This ventral meaning interface is in line with the ventral language stream proposed by Hickok and Poeppel (2007) (Hickok & Poeppel, 2007), where brain structures ventral to the Sylvian fissure are in charge of mapping acoustic speech signals onto conceptual and semantic representations. Both mechanisms – the ventral meaning interface and the ventral language stream – are supported by common anatomical structures in perisylvian regions, particularly the middle temporal gyrus, considered a hub for semantic information (Rodríguez-Fornells et al., 2009). Moreover, regions associated with these ventral mechanisms are interconnected with other brain regions through associative pathways, including the inferior fronto-occipital fasciculus (IFOF). Interestingly, previous work of our team suggested that the IFOF plays a role in lexico-semantic processing, as the electrical stimulation mapping applied directly

on the IFOF/ILF intersection interfered with the SPT performance (Sierpowska et al., 2019). The ventral meaning interface and the ventral language stream are reported as triggered in contexts requiring the inference of meaning (Hickok & Poeppel, 2007; Rodríguez-Fornells et al., 2009), such as the SPT. In the SPT, the participant is required to match the target word with one of three alternatives, selecting the option that is most semantically related and thereby inferring the meaning of each lexical item. Based on our results, second language acquisition involves lexico-semantic learning processes that lead to more efficient access to word meaning and, thereby, to greater performance by bilinguals in lexico-semantic association tasks such as the SPT.

In contrast, nonsignificant results were revealed for PPT, a conceptual–semantic association task. In this task, the integrity of the semantic networks is evaluated, with less influence from lexical processing. Considering this pattern of results, we may hypothesize that the effect of bilingualism may be specific to certain levels of

language representation, at the lexical level and not the conceptual one, as it is more influenced by the acquisition of a second language. This is interesting as learning a new language involves a reorganization of the lexico-semantic information, but not necessarily the existing semantic-conceptual information stored in long-term memory.

Surprisingly, our second analysis addressing whether the effect of bilingualism is dependent on the type of brain tumor revealed that bilinguals with LGG obtained lower scores in PPT, showing a detrimental effect of LGG on semantic memory. Initially, this result may be contrary to evidence that LGG, in contrast to HGG, tends to facilitate compensatory mechanisms due to its progressive growth, and hence, slight difficulties in cognition are expected (Duffau et al., 2008). However, we may consider that LGG are generally located in the frontal lobe (Mandal et al., 2020; Romero-Garcia et al., 2023), an area involved in the activation of information stored in temporoparietal cortices, contributing to the selection of semantic information (Binder & Desai, 2011).

Our results also revealed better scores in the nonword repetition task for the bilingual group, an effect maintained after considering also the type of glioma. Initially, nonword repetition was established as a measure of phonological short-term memory, together with digit span (Baddeley, 2003), but its usage evolved as a measure of phonological awareness and representation, lexical knowledge and speech output (Windsor et al., 2010). Hence, nonword learning is positioned as a potential factor for language acquisition, being responsible for up to 44% of language learning (Adlof & Patten, 2017; Gathercole, 2006) and crucial for long-term learning of lexico-semantic representation of verbal information in the aphasia population (Peñaloza et al., 2017). This learning ability mediated by the nonword repetition function has been associated with the structural and functional integrity of the arcuate fasciculus (AF) (López-Barroso et al., 2013; Sierpowska et al., 2017; Vaquero et al., 2017). Meanwhile, the AF is influenced by language learning, as early exposure to L2 increases levels of functional anisotropy along the AF (Hämäläinen et al., 2017). The beneficial effect of bilingualism on nonword repetition indicates a positive modulation of second language acquisition on the dorsal audio–motor interface (Hickok & Poeppel, 2007; López-Barroso et al., 2013; Rodríguez-Fornells et al., 2009), which is mainly associated with acoustic–articulatory linguistic representations to map sound to articulation.

Table 2. Results from rank-based estimation regression: Overall regression results

	Multiple R^2	F value	p value
SPT-easy items	0	0	1
SPT-difficult items	.13	3.26	.03
SPT	.21	5.83	.001
PPT	.12	2.99	.04
Nonword repetition	.17	4.68	.005
Word repetition	0	0	1
Token Test	.03	1.30	.28
BNT	.02	.82	.48
Phonological verbal fluency	.05	2.01	.11
Semantic verbal fluency	.09	3.81	.01
Backward digits	.02	.72	.54
Forward digits	.03	1.39	.25

Note: Bold values indicate statistically significant results. SPT = Semantic Pairs Task; PPT = Pyramids and Palm Trees Test; BNT = Boston Naming Test.

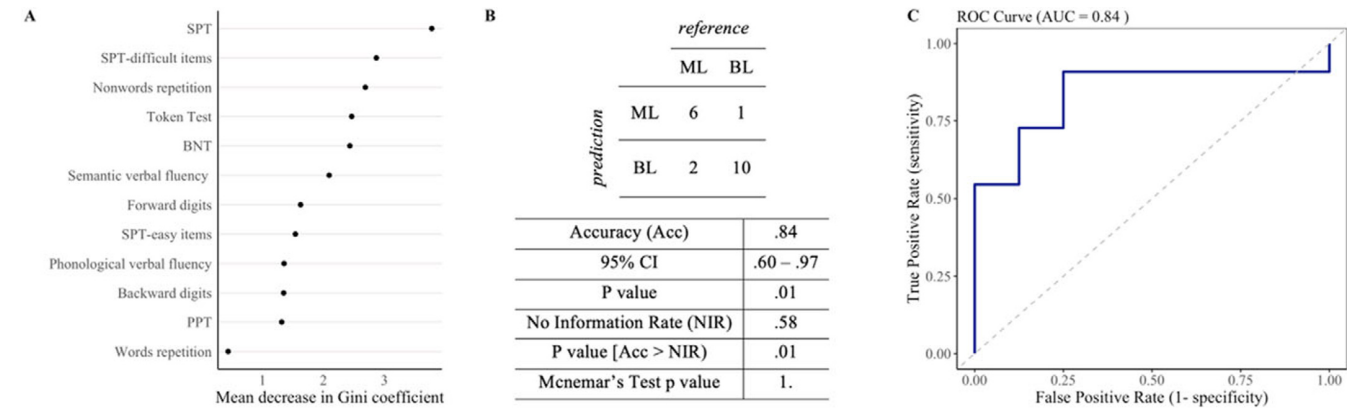


Figure 3. Performance and variable importance of the random forest model used for the classification of bilinguals. (A) The cognitive and language variables, ranked by their contribution to the model's accuracy. Each point, connected by a horizontal line, indicates the average decrease in Gini impurity that results from splits involving that variable, averaged over all the trees in the forest. (B) Confusion matrix of the model. (C) ROC curve of the model.

From our first analysis in the brain tumor sample, bilingual subjects also obtained higher scores in attention/short-term memory tests, confirming previous studies on it (Dash et al., 2019; Ljungberg et al., 2013; Rosselli et al., 2000; Stafford, 2011; Wodniecka et al., 2010). Attention has been identified as a key factor in the cognitive functioning of bilinguals. Second language acquisition is described as a modulator of attentional processes, highly influenced by the language context (Birulés et al., 2019; Dash et al., 2022, p. 202; Olguin et al., 2019; Timmer et al., 2021). Specifically, recent evidence states that bilingualism may be associated with an enhancement of attentional process (see the review by Chung-Fat-Yim et al., 2022). Moreover, the bilingual environment might promote a domain-general benefit in attentional control to cope with an enriched language context composed of constant competition between languages (Bialystok & Craik, 2022). In addition, our results also revealed better scores for the bilingual group in the Token Test, a tool widely used to examine verbal comprehension. However, the Token Test has been highly associated with auditory-verbal/span and auditory working memory tests (Basagni et al., 2022), this association was also confirmed in our study ($r_s(113) = .34; p < .001$). The Token Test is composed of items of increasing difficulty, and the last section is made up of commands of higher syntactic complexity and working memory demand. Thus, we may consider this result as attentional/short-term-memory benefits of bilingualism, and not so much to verbal comprehension per se.

The efficiency in word retrieval, mainly assessed with verbal fluency, has been one of the most studied cognitive domains within the bilingual population. In our study, bilinguals showed a better performance in verbal fluency tasks, which may reflect a better ability to use categorization strategies defined within the bilingual population (Giovannoli et al., 2023). There are several discrepancies on this topic in the existing literature, as some studies confirm a robust bilingual advantage on verbal fluency emergent in adulthood (Friesen et al., 2015), whereas other studies revealed a lower performance or even no effect of bilingualism (Gollan et al., 2002; Portocarrero et al., 2007; Rosselli et al., 2000). In fact, a recent meta-analysis showed that the bilingual effect on verbal fluency is modulated by additional variables such as choice of stimulus or individuals' sociodemographic characteristics (Friesen et al., 2021). The complexity of the different results observed in the verbal fluency task highlights the need for a specific evaluation of the performance for our population of interest.

Our second analysis, considering also tumor grade only revealed a positive effect of bilingualism on phonological verbal fluency, being the effect on semantic verbal fluency specific for the LGG group. Despite the consideration of verbal fluency as a construct, its different modalities (semantic versus phonological) are two independent entities with specific cognitive processes involved. Semantic verbal fluency has been shown to be more associated with vocabulary size (Shao et al., 2014), whereas phonological verbal fluency with executive control, due to the role of inhibition (Patra et al., 2020). Therefore, due to the potential advantage of bilingualism in executive functioning, a higher performance of phonological verbal fluency may be expected. Regarding LGG, tumor grade-related network reorganization of language and control networks appears to be associated with different levels of language impairments (Nieberlein et al., 2023). There is evidence of a more severe disruption of language and control networks in HGG patients (Nieberlein et al., 2023), with a weaker within- and between-hemispheric language-network connectivity (Yuan et al., 2020) which results in a poor network reorganization for language compensation in HGG subjects. This

decreased connectivity can reduce the probability of having a beneficial effect of bilingualism in the HGG group for semantic verbal fluency. In addition, the bilingual brain may exhibit enhanced loading on language networks and so increased sensitivity to damage within that network (Hope et al., 2015). Overall, the present results point to the potential influence of bilingualism on phonological verbal fluency, mediated by cognitive control, and even in the presence of a brain tumor, whereas for semantic verbal fluency, this effect was modulated by the lesion.

The cognitive and language effects of bilingualism in patients diagnosed with brain tumors should be considered alongside how languages are organized and represented in the bilingual brain. In this regard, language localization in bilingual individuals may differ between languages (Boerner et al., 2023), including common and distinct cortical areas for each language (Fernández-Coello et al., 2017; Roux & Trémoulet, 2002), and with weaker left-hemisphere language lateralization compared to monolingual individuals (Połczyńska et al., 2017). More specifically, recent research has demonstrated that acquiring multiple writing systems associated with different languages can modulate the visual cortex in bilinguals, potentially leading to the development of cortical regions specialized for a single language (Zhan et al., 2023). Thus, an extended language network composed of not only common but also distinct language areas may be present in bilingual subjects. The presence of extended regions may result from a greater engagement of the cognitive and linguistic processes involved in dual-language acquisition. Specifically, bilingualism is associated with a greater engagement of phonological processes, supported by increased neural integrity in areas related to auditory-phonological processing (e.g., inferior parietal lobe or superior temporal gyrus) (Li et al., 2014; Pliatsikas et al., 2015). Supporting this dynamic view, findings from bilinguals with temporal lobe epilepsy show that L2 is more likely than L1 to shift lateralization in response to left-hemisphere damage, suggesting that bilingual language networks – particularly for the second language – are more flexible and capable of compensatory reorganization (Stassenko et al., 2025). All in all, contributing to the resilience of related cognitive functions such as phonological verbal fluency and nonword repetition, which remained stable across tumor type in our study. It should also be noted that all our results pertain to performance in the native language. Given the potential differences in language organization, future studies should include an L2 assessment to evaluate whether the effect of bilingualism is maintained, regardless of the language evaluated.

It is noteworthy that most of our findings supporting a protective effect of bilingualism were observed irrespective of tumor type, which may be consistent with existing evidence reported across different neurological conditions associated with distinct temporal trajectories and pathophysiological processes. LGG, characterized by slow growth and prolonged disease progression, may share temporal similarities with neurodegenerative disorders such as dementia, in which gradual neural changes permit the development of compensatory and adaptive processes over time, as may also occur in LGG. Within this framework, bilingualism has consistently been proposed as a contributor to cognitive reserve in mild cognitive impairment, being associated with preserved cognitive functioning and delayed cognitive decline (Calabria et al., 2020; de Leon et al., 2020; Rosselli et al., 2019). Moreover, bilingualism has also been implicated in Alzheimer's disease-related pathophysiological mechanisms (Bao et al., 2026; Tablante et al., 2025), with a neuroprotective effect against neurodegeneration (Perani et al., 2017; Schweizer et al., 2012). Conversely, HGG, characterized by

rapid growth and therefore more limited opportunities for lesion-induced functional reorganization, may more closely resemble less progressive neurological conditions such as stroke. Despite the abrupt nature of stroke, bilingualism has likewise been associated with protective effects in poststroke aphasia (Ardila et al., 2023), with reduced severity in bilingual individuals (Alladi et al., 2016; Paplikar et al., 2019). Taken together, the convergence of findings across neurologically heterogeneous conditions supports the interpretation that the beneficial effects associated with bilingualism in our cohort may reflect domain-general neurocognitive and neuroprotective mechanisms that transcend specific disease entities and pathophysiological processes. Given the existing evidence regarding the influence of bilingualism on disease progression and prognosis across other neurological conditions, together with the potential protective role of bilingualism observed at baseline in brain tumor patients, future studies should investigate the impact of bilingualism on the longitudinal evolution of cognitive and language functions throughout disease progression.

4.1. Strengths and limitations of the study

The main strength of this study is the large sample of bilingual brain tumor population and their language characteristics. In this regard, all the bilinguals are Spanish–Catalan bilinguals, and the monolinguals acquired either Spanish or Catalan. The resemblance between languages of both bilingual and monolingual groups allows us to control for a possible effect of distance between languages when comparing the groups. However, several limitations of the current research must be mentioned. The brain tumor location is mainly within language-related areas in the left-dominant hemisphere, and hence, the neuropsychological assessment is mainly focused on language evaluation. Therefore, other cognitive domains, especially relevant in the study of bilingualism (e.g., executive function), may be underrepresented. Future studies may consider the inclusion of other neuropsychological tests addressing a more fine-grained assessment of executive functions, or additional cognitive domains like verbal memory. We are up-to-date about the importance of considering bilingualism placed along a continuum and not as a dichotomous variable. Due to the retrospective character of the study and the unfortunately limited survival associated with HGG (the most prevalent type of tumor in our study), we were not able to collect this type of information. Future studies addressing the effect of bilingualism may consider providing a more detailed description of the bilingual experience. A definition of variables such as age of acquisition or level of exposure may be included to analyze how these specific features associated with bilingualism can influence cognition and language of brain tumor patients.

5. Conclusions

Our study demonstrates how bilingualism interacts with brain tumors in defining the cognition and language of individuals. Despite the existence of a brain tumor, which potentially influences the structure and functionality of the brain, bilingualism is stated as a protective factor for executive functioning and semantic processing. However, the type of lesion and specifically HGG may reduce the potential effect of bilingualism on language-specific function. Overall, our results encourage clinicians to consider bilingualism as a protective factor for cognition and language in brain tumor patients at the preoperative stage, which may define in part postoperative status.

Supplementary material. The supplementary material for this article can be found at <http://doi.org/10.1017/S1366728926101539>.

Data availability statement. In accordance with the guidelines of the Clinical Research Ethics Committee, patient research data cannot be openly shared in a public repository.

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Competing interests. The authors declare none.

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