Neuroanatomical correlates of macrolinguistic aspects in narrative discourse in unilateral left and right hemisphere stroke: A voxel-based morphometry study

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Abstract

A growing body of literature has demonstrated the importance of discourse assessment in patients who suffered from brain injury, both in the left and in the right hemisphere, as discourse represents a key component of functional communication. However, little is known about the relationship between grey matter density and macrolinguistic processing. This study aimed to investigate this relationship in a group of participants with middle-low to low socioeconomic status. Twenty adults with unilateral left hemisphere (LH, n = 10) or right hemisphere (RH, n = 10) chronic ischemic stroke and 10 matched (age, education and socioeconomic status) healthy controls (HC) produced three oral narratives based on sequential scenes. Voxel-based morphometry (VBM) analysis was conducted using structural magnetic resonance imaging (MRI). Compared to HC, the LH group showed cohesion impairments whereas the RH group showed impairments in coherence and in producing macropropositions. Cohesion positively correlated with grey matter (GM) density in the right primary sensory area (PSA)/precentral gyrus and the *pars opercularis*. Coherence, narrativity, and index of lexical informativeness were positively associated with the left PSA/insula and the superior temporal gyrus (STG). Macropropositions were mostly related to the left PSA/insula and STG, left cingulate, and right primary motor area/insula. Overall, the present results suggest that both hemispheres are implicated in macrolinguistic processes in narrative discourse. Further studies including larger samples and with various socioeconomic status should be conducted.

Keywords: narrative oral production; macrolinguistic processing; cohesion; coherence; lexical informativeness; stroke; left hemisphere; right hemisphere; brain density.

Introduction

The study of complex communication abilities, such as discourse, can contribute to the diagnosis and treatment of atypical language processing, which explains the wide clinical applications of this type of study (Bryant et al., 2017). Besides, some atypical linguistic processes are better documented in discourse production and/or comprehension rather than in isolated words or sentences (Coelho et al., 2012; Thompson et al., 2012). Discourse may be modulated by *linguistic aspects*, such as text genres and complexity, or presentation modality (whether visual or auditory). Discourse may also be modulated by *cognitive aspects*, such as shared and differential processing demands related to comprehension or production (e.g., AbdulSabur et al., 2014), or still by *individual-related aspects*, such as sociodemographic variables, including the level of education and the socioeconomical status (SES).

Regarding age and education, Steibel et al. (2016) investigated the effect of these variables in the memorization of items such as names, pictures and stories using the Rivermead Behavioral Memory Test (Wilson et al., 1985). Their participants were divided according to age (60-69, 70-79 and 80 or more years old), and to education level (less than 8 years or 8 years of more of formal education). Performance improved as the level of education of the participants increased, while advancing age correlated to poorer performance. Similarly, Tripathi et al. (2014) assessed the impact of education and age on neuropsychological functions (episodic memory, attention, executive functions and language) in 180 older adults with no history of cognitive impairment. Education had an effect on all tasks analyzed, while age impacted on three out of 12 tasks. Similarly, SES has been associated with the quality of content and discourse productivity (Snow et al., 1997) as well as with cohesion (Coelho, 2002) in studies involving patients who suffered from a traumatic brain injury (TBI). Coelho (2002) classified the participants (55 patients with a TBI and 47 neurotypical matched controls) based on their SES, as professionally skilled and unskilled workers. The only significant difference between unskilled (i.e., low SES) and professionally skilled workers has been found on intersentential cohesion, regardless of story task. Studies in aphasia have also associated SES to the severity and patterns of recovery. For example, Song et al. (2017) studied the impact of SES - measured by the level of education, occupation and income - on the functional outcome after three months following an ischemic stroke. Their results suggested that people with lower SES present poorer outcome after stroke. Multinomial logistic model analysis also showed that low educational level and manual laboring has a more significant impact on the functional outcome than low-income level. Despite the relevance of studies on the impact of low education level and low SES, such studies are still very scarce both in neurotypical adults and patients suffering from language impairments.

For analyzing oral discourse production, two main approaches have been proposed: (1) *structural* and (2) *functional.* In the *structural approach*, the focus is on discrete linguistic variables, such as phonology, syntax, and lexicon in addition to macrolinguistic variables, such as cohesion, coherence, and macropropositions. *Cohesion* is accomplished by the use of cohesive devices, which are linguistic markers that form the structural and semantic connectivity between elements of speech (Halliday & Hasan, 1976). These authors proposed five categories of cohesive devices: (1) reference, (2) conjunctive, (3) ellipsis, (4) substitution, and (5) lexical. Similarly, Antunes (1996, 2005) pointed out that cohesion builds up a *continuity* of meaning, which is generally expressed by the relationship among *reiteration*, *association*, and *connection*. Yet *coherence* refers to the meaning conveyed by the discourse (Barker et al., 2017). More specifically, coherence builds the "discursive weave" by establishing the connections between its corresponding phrases and propositions, which are globally organized in the macrostructure (Kintsch & van Dijk, 1978). These authors propose that coherence is built at two levels: (1) a local one (the maintenance of abstract links between utterances, for instance, by the use of proper pronouns to link elements), and (2) a global one (the way propositions are organized to reach the global topic or goal of the text, involving the connection of utterances). When global coherence is not reached or maintained, the text may become incongruent, irrelevant, tangential, or repetitive (Sherratt & Bryan, 2012). Finally, *macropropositions* consist of the stages through which a narrative evolves, following a hierarchical structure (van Dijk, 1976, 1980). By definition, macropropositions refer to the 'global' meaning (van Dijk, 1980) or a summary representation (Wood, 2009) of propositions. Macropropositions encompass some hierarchically organized categories, such as setting, complication, resolution, evaluation and conclusion. Knowledge of this schematic structure of stories is important and well-known in everyday communication (van Dijk, 1980).

Complementing the structural approach for analyzing discourse production, the *functional approach* analyzes the ability to convey relevant and meaningful information at the discourse level. *Narrativity*, which is related to the *manner* by which narratives are orally produced, should be taken into consideration to reach a more complete assessment. Narrativity includes the assessment of the causal relations linking the sequence of events of the story, the predominance of narration (in contrast with scene descriptions), the relationship between the fact narrated and the pictures, and characters' recognition. As postulated by Davis et al. (1997), discourse production can be analyzed as a function of the task (e.g., interview, spontaneous, picture-based) or of the type of discourse elicited (e.g., narrative or expository). Furthermore, the type of analyses may vary, being performed in multiple levels, from a more microstructural level to a macrostructural one. Within the later, the authors suggest the inclusion of story structure analysis, or what we will call *narrativity,* together with logical coherence, thematic coherence and general attributes, as an important aspect to be observed in both left hemisphere (LH) and right hemisphere (RH) stroke patients. Being able to detect the sequence of the narrative structure, with its causal implications, is crucial for successful story telling. Davis et al. (1997) postulate that the use of sequences of scenes allows the clinician and the researcher to assess participants' ability to construct narrative ties between the scenes, as opposed to single pictures, which tend to elicit descriptions instead. Moreover, this broader structural type of analysis seems to have been less studied than coherence and cohesion ties connecting sentences or parts of speech. To our knowledge, no previous study investigated narrativity behaviorally nor its neural correlates.

Also within a more functional approach to discourse production analyses, a few different measures have been proposed to investigate the quality of a narrative in terms of lexical informativeness, including lexical information units (LIUs). LIUs are content and function words that are phonologically well-formed and also appropriate from a grammatical and pragmatic point of view (Andreetta & Marini, 2015; Marini, Boewe, et al., 2005; Marini, Carlomagno, et al., 2005; Marini, Galetto, et al., 2011). In this study, an *index of lexical informativeness* was adopted to compare the groups' linguistic performances and brain correlates.

The heterogeneity of the extracted variables and the various types of discourse reported in discourse analysis following a stroke limits the comparison between the studies and our understanding of the role of each hemisphere in discourse processing (Stark et al., 2020). Lesions following a cerebrovascular accident (CVA) form a fruitful context in which brain hemisphere specialization can be studied. These lesions may affect each hemisphere differently and thus foster the debate on hemispheric specialization in discourse at the macrolinguistic level. Some of the first studies on discourse that have been conducted with patients with an RH-related lesion (Joanette & Goulet, 1990; Myers, 1999) have demonstrated the relevance of RH participation in comprehension and discourse production. Converging results on this topic have shown that individuals with RH damage present difficulties in cohesion, coherence, and consequently, in discourse organization (see Brownell & Martino, 1998; Hough, 1990; Kempler, 1990; Molloy et al., 1990; Myers, 1999). Davis et al. (1997) compared referential cohesion and logical coherence in an oral narrative production between eight participants with an RH lesion and eight control participants. Samples from six stories were obtained with tasks of cartoon-elicited story telling. Patients with a lesion in the RH produced fewer predicates and their related arguments, fewer cohesive devices, lower logical connection between propositions, and had difficulty in conveying the theme and the structure of the narrative compared to the control group while retelling the stories. More recently, Marini (2012) compared the narrative production at the macrolinguistic (between sentence level) and microstructural levels (within sentence level) of 15 patients with a lesion in the RH to that of 14 healthy participants. All participants were asked to describe stories portrayed in a set of sequential images. In comparison to healthy controls, participants with an RH lesion produced descriptions with normal levels of microlinguistic elements, but they produced more tangential errors and incongruent statements that reduced the levels of conveyed information. Additionally, patients with frontal lesions in the RH presented more difficulties when trying to organize information, which suggests that the frontal cortex in the RH would have a role in the organization of information in narrative discourse.

Although most studies suggest that deficits in cohesion occur when stroke is located in the RH (Marini, Carlomagno, et al., 2005; Sherratt & Bryan, 2012; Stockbridge et al., 2019), others have reported cohesion impairments following a stroke in the LH (Andreetta et al., 2012; Barker et al., 2017; Davis et al., 1997; Ellis et al., 2005; Geranmayeh et al., 2017; Marini, 2012; Stockbridge et al., 2019; Uryase et al., 1991). Among the few existing longitudinal studies, Stockbridge et al. (2019) reported that total cohesive markers were similarly used between LH and RH individuals in the narrative samples obtained from the analyses of the Cookie theft of the Boston Diagnostic Aphasia Examination (BDAE). However, when looking at the acute (< 1 week after stroke) and the chronic (6–12 months after stroke) stages independently, fewer cohesive ties were produced in samples from LH individuals than RH individuals in the acute phase. Conversely, in the chronic phase (6–12 months post-stroke), the two groups seem to use different *types* of cohesive markers although the *number* of cohesive markers did not differ. Barker et al. (2017) investigated cohesion together with textual coherence, attention, and executive functions in non-aphasic individuals after comparing LH and RH lesion. Overall, RH patients showed impaired local and global coherence compared to LH and controls. Similarly, both patient groups made more cohesive errors than the controls with a trend toward greater cohesion impairment in RH patients. Correlations between verbal fluency and cohesion have been reported in a group of older adults (Sherratt & Bryan, 2019) in patients with the behavioral variant of frontotemporal dementia (Ash et al., 2006) and patients with amyotrophic lateral sclerosis (Ash et al., 2014), which suggests that impairment observed in cohesion could also be caused by linguistic impairment rather than by macrolinguistic impairment per se (e.g. Armstrong, 1991; Huber & Gleber, 1982). However, this relation has not been tested in patients who suffered from a stroke, including patients with aphasia.

Regarding the neural correlates of macrolinguistic processing, there is no consensus yet on which brain regions in the LH or RH are responsible. Barker at al. (2017) recently proposed a schematic representation of discourse processing based on current existing models of speech production (e.g., Frederiksen & Stemmer, 1993; Jakobson, 1983; Levelt, 1989, 1993; Levelt et al., 1999) involving three stages: *conceptual preparation* (i.e., macrolinguistic processes), *linguistic formulation* (i.e., microlinguistic processes) and articulation. According to this model, macrolinguistic processes, namely cohesion, local and global coherence as well as novelty, have been traditionally associated with RH regions (e.g., Myers, 1999) whereas microlinguistic processes, namely lexical retrieval, syntax, grammatical encoding and phonological encoding, have been associated with the LH. Specifically regarding macrolinguistic processing, the construction of a preverbal message requires the generation of ideas and their organization, which are highly supported by executive functions. Indeed, non-linguistic cognitive mechanisms such as executive processes and attention, but also more affective aspects like social cognition and emotion are implicated in the *conceptual preparation*. For instance, discourse production has been associated with cognitive constructs, such as working memory (Cahana-Amitay & Jenkins, 2018) and episodic memory (Seixas-Lima et al., 2020). However, the nature of this association still needs to be further elicited, since most studies in stroke (and other atypical) populations have focused on the assessment of linguistic features of discourse, disregarding the impact of the integrity of memory types.

There is only a relatively small number of inconclusive imaging studies compared to the number of behavioral studies, especially addressing the role of each brain hemisphere in the discourse process (e.g., Alyahya et al., 2020; e.g. Belin et al., 2008; Dal Molin et al., 2013). To date, most studies have not compared discourse processing in patients who suffered from a stroke in the left and in the right hemisphere. For instance, a very interesting unified model of discourse processing have been recently proposed by Alyahya et al. (Alyahya et al., 2020) but their study was only comparing patients with post-stroke aphasia (following a stroke in the LH) and controls. Using a principal component analysis, they showed that discourse production was composed of three main components, namely verbal quantity, verbal quality (i.e. the component related to macrolinguistic processing) and motor speech. Using voxel-wise lesion-symptom mapping, they showed that verbal quality, which refers to informativeness in the present study, was associated with widespread frontal regions and superior temporal lobule. These regions have previously been associated with working memory (e.g., Boisgueheneuc et al., 2006) and executive functions (e.g. Humphreys & Lambon Ralph, 2015), and are consistent with the model of Barker et al. (2017) which suggests that the *conceptual preparation* level is supported by non-linguistic cognitive factors.

The present study intended to investigate macrolinguistic variables in oral production of narrative stories in middle-low to low SES adults who suffered from a unilateral stroke in the LH or RH compared to participants with no brain damage. Most studies on discourse processing have been conducted analyzing highly educated adults, with middle-high socio-economic status. Since education and SES relate to cognitive (including linguistic) performance, those studies may not be generalizable for lower educated and lower SES samples. We also aimed to explore the association between narrative measures and their structural correlates in the gray matter (GM). More specifically, partly based on the schematic representation of connected speech of Barker et al. (2017), our exploratory hypothesis is two-fold: 1) individuals who suffered from a left hemisphere (LH) stroke will have a lower performance in within-sentence processes, namely the index of lexical informativeness (%) as compared to the other two groups, and 2) individuals who suffer from a stroke in the RH will have a lower performance on the more "global" macrolinguistic variables, such as cohesion, global coherence, macropropositions, and narrativity as compared to the other two groups (Marini, 2012). We also have two additional exploratory hypotheses. We hypothesize that 3) GM density in the left temporal and left frontal lobes will correlate with lexical informativeness (i.e. within-sentence) processes (Marini & Urgesi, 2012). We also hypothesize that 4) right frontal areas will relate to cohesion, coherence, macropropositions, and narrativity (i.e. between-sentences) based on the hypothesis that the *conceptual preparation* level in the model of Barker et al. (2017) is not yet linguistic and thus also relies on non-linguistic cognitive mechanisms including executive processes and attention (Marini et al., 2005; Sherratt & Bryan, 2012).

Method

Participants

Patients were recruited from a hospital that treats patients from the public health system in a metropolitan area in a southern state in Brazil. Patients' inclusion criteria consisted of first-ever ischemic stroke in the LH or RH and being a native speaker of Brazilian Portuguese. Exclusion criteria consisted of several parameters: (1) a history of major psychiatric disorder(s), (2) learning disabilities, (3) self-reported severe visual and auditory perceptual deficits, (4) additional neurological diagnoses, (5) left-handed or ambidextrous, (6) < 2 years of formal education or > 13 years, and/or (7) bilingualism. All patients were diagnosed by a neurologist and a radiologist. The language and MRI assessments took place at least four months (LH mean = 11.2 ± 5.51; RH mean = 10.5 ± 5.1) after stroke onset.

The age- and schooling-matched control group was recruited at convenience and community centers. In Brazil, recruitment of controls is very challenging, especially with men. Consequently, the control group is unbalanced with both clinical groups regarding the sex variable. Controls reported no history of neurological illness or psychiatric history and were native speakers of Brazilian Portuguese. In addition to the exclusion criteria used with the patients who suffered from a stroke, healthy participants were also excluded if their score on the Mini-Mental State Examination (MMSE) was lower than the age and educational specific cut-off score adapted for the Brazilian population (Brucki et al., 2003). Full written consent was obtained from all subjects. The study was approved by the Ethics Review Board of the Pontifical Catholic University of Rio Grande do Sul (PUCRS) under CAAE # 51099415.6.0000.5336.

Materials and procedures

Neuropsychological assessment

We administered a health conditions questionnaire with socio-demographic and socio-cultural aspects adapted from Fonseca et al. (2012), the Edinburgh Handedness

Inventory (Oldfield, 1971), the Mini-Mental State Examination (MMSE) from Chaves & Izquierdo (1992), and the Geriatric Depression Scale (GDS) from Almeida & Almeida (1999) as adapted from Yesavage et al. (1982). Participants were further characterized by a short neuropsychological assessment using the Digit and Word span working memory tests (Instrumento de Avaliação Neuropsicológica Breve - NEUPSILIN, Fonseca et al., 2009), a short naming task (Montreal-Toulouse-Brasil [MTL-BRASIL], Parente et al., 2016) consisting of 12 nouns and 6 verbs (max = 2 points by stimuli) represented in black and white pictures, and a free (i.e., without constraints) verbal fluency task (Bateria Montreal de Avaliação da Comunicação Breve (MAC-Breve); Ska et al., 2014). Participants also completed a questionnaire developed by the Brazilian Market Research Association (*ABEP - Associação Brasileira de Empresas de Pesquisa*) to capture their SES. This questionnaire allows the calculation of a SES score based on the education level of the head of household and other household characteristics including the number of certain consumer goods and amenities. Descriptive sociodemographic and neuropsychological data of each group are presented in Table 1.

Narrative discourse assessment

All participants were asked to orally narrate three stories supported with sequential pictures: (1) *The dog story* (Hübner et al., 2019), (2) *The car accident* (Joanette et al., 1995), and (3) *The cat story* (Ulatowska et al., 1981). The three stories present a sequence of six or seven scenes in black and white on a strip of paper with each scene measuring 7 x 7 cm. The stories have equivalent length and narrative structure (Adam, 2008) and were randomly presented to participants to balance the order of presentation. Participants were instructed to carefully observe the scenes in order to narrate the stories one at a time after observing that each scene represents a part of the story, which has a beginning, a middle, and an end. Participants were allowed to look at the pictures during narration. Narratives were audio recorded (Sony Digital Flash Voice Recorder (ICD-PX312)) for further transcription and analyses.

Transcription

Audios of each discourse sample were imported and transcribed using the software Transcribe by an experienced linguist and a language student. The narratives were transcribed according to Cultured Linguistic Urban Norm, in Portuguese, Norma Linguística Urbana Culta (NURC) standards (Castilho & Pretti, 1986) by a person who was blind to the group assignment. The segmentation of the narratives into propositions/utterances was made following the rules proposed by Andreetta and Marini (2014). Briefly, a set of acoustic, semantic, grammatical, and phonological parameters that demonstrated high reliability scores (Andreetta & Marini, 2014, p. 73) was used. To be included in the count, the words had to be intelligible in the context, but they did not have to be precise, relevant, or informative in relation to the stimulus. The number of words was verified using the Transcribe software and revised using the statistics provided by Word (Version 2005/Microsoft 365).

Narrative analyses

Two raters blinded to group assignment (RH, LH group and controls) scored the participants' narrative oral productions based on these variables: (1) cohesion, (2) global coherence, (3) macropropositions, (4) narrativity, and (5) index of lexical informativeness. Each discourse measure was reported after combining the three stories together.

Cohesion

For the analysis of the textual cohesion of the narratives produced by the participants, only the narrative sequences were considered. Thus, other types of production over the course of production were excluded. Cohesion was scored according to the textual relations proposed by Antunes (2005): (1) references (grammatical substitution, repetition, lexical substitution, and ellipse); (2) association (lexical selection), and (3) connection (connector). Please see Supplemental Material 2 for examples of the different cohesion relations. Interrater reliability was achieved through agreement. Two experts in the field scored all variables. When a discrepancy was observed between the two reviewers, a third expert resolved the conflict. Cohesion was scored by counting the number of occurrences of cohesion ties. This number was divided by the number of utterances (parts of the narrative produced by the participant) and multiplied by 100.

Global coherence

Global coherence (Kintsch & van Dijk, 1978) refers to the degree by which the propositions/utterances are organized or structured. The global coherence was analyzed through the relationship between each statement (propositions) and the global topic of the presented narrative sequence. For the analysis, complete propositions related to the topic were scored with a score of 1.0; incomplete propositions related to the topic were scored with a score of 0.5. Global coherence was calculated by dividing the sum of these points by the total number of propositions produced and then the results were multiplied by 100 (adapted from Andreetta et al., 2012).

Macropropositions

Each narrative was divided into macropropositions, including story setting, scenario, complication, and resolution (van Dijk, 1980; van Dijj & Kintsch, 1983; see Supplemental Material 1 for the list of the macropropositions used in each story). Four judges participated in the identification of the macropropositions of the cat's and the car accident stories. The dog story followed the division of the macropropositions presented in the Bateria de Avaliação da Linguagem no Envelhecimento or BALE (Hübner et al., 2019). The number of macropropositions produced by each participant was divided by the total number of narrative macropropositions and multiplied by 100. The dog story contained a maximum of six macropropositions, while the car accident and the cat story each contained five.

Narrativity

One point, for a maximum of four points for each story, was attributed for each of the following criteria (according to the norms proposed in BALE [Hübner et al., 2019]) in which observance of the sequence (for example, narrative of the facts in the order they occurred in the story), predominance of narration (as opposite as scene descriptions), relationship of the facts narrated with the pictures (that is, inclusion of intrusive or inexistent aspects), and characters' recognition. A higher narrative score thus reflected a better performance.

Index of lexical informativeness

The definition, selection, and analysis of words and the index of lexical informativeness were performed based on Marini et al. (2011), Nicholas and Brookshire (1993), and Lira et al. (2014). Lexical informativeness refers to content and functional words that are not only phonologically well-formed but also appropriate from a grammatical and pragmatic point of view. Informative nouns and verbs were extracted using AntConc 3.4.4w (Anthony, 2016a), a freeware which has been adapted to Brazilian Portuguese. The index of lexical informativeness was calculated by dividing the number of informative nouns and verbs produced by each participant by the total number of words produced and multiplied by 100 (Andreetta & Marini, 2015; Marini, Andreetta, et al., 2011; Marini, Carlomagno, et al., 2005).

Inter-rater reliability

Inter-rater reliability (IRR) was conducted on the transcriptions of three participants (10% of the transcripts) for all three stories independently (n=12 transcriptions) by a second rater. Two-way random effects intraclass correlation coefficients (ICC) were calculated on the raw scores of cohesion, coherence, macropropositions and narrativity to determine consistency between raters. ICCs were not calculated for the index of lexical informativeness as the informative words were extracted by a freeware (Anthony, 2016b). The ICC is a statistical metric commonly used to assess inter-rater reliability. ICC values range from 0 to 1 and can be categorized into four levels of test-retest reliability: excellent (ICC > .75), good (ICC = .60 to .74), fair (ICC = .40 to .59), and poor (ICC > .40) (Fleiss et al., 2003). An excellent degree of reliability was found between raters for cohesion (ICC = .907; 95% confidence interval (CI) = [.589, .979]) and macropropositions (ICC = .750; 95% CI = [-.108, .944]). A good degree of reliability was found between raters for narrativity (ICC = .608; 95% CI = [.231, .800], whereas reliability was fair for coherence (ICC = .497; 95% CI = [-1.229, .887]).

MRI protocol

Participants underwent two meetings in two days that included an MRI scan and a language assessment. The MRI protocol was acquired using a GE Healthcare 3.0T HDxt MRI scanner at the Radiology Department at InsCer (Brain Institute). One high-resolution three-dimensional (3D) T1-weighted scan was acquired using a Magnetization Prepared Rapid Gradient Echo (MP-RAGE) sequence (TR = 6272 msec, TE = 2255 msec, TI = 500 msec, voxel size = 1x1x1 mm^3, matrix = 240 x 240, 196 slices) and an 8-channel skull coil.

Lesion segmentation

The lesion delineation was performed using a semi-automated demarcation performed with *Clusterize* SPM's toolbox (Clas et al., 2012) from http://www.medizin.uni-tuebingen.de/kinder/en/research/neuroimaging/software and verified by a fully manual method. First, *Clusterize* was used to semi-automatically delineate the lesion on the T1 map of each patient. Agreement between manual segmentation and the semi-automated lesion maps obtained with *Clusterize* has been shown to be excellent in chronic stroke delineation (de Haan et al., 2015). *Clusterize* automatically computes hypo-intensity clusters of voxels. Cluster(s)-of-interest corresponding to the lesion were manually selected and adjusted to fit the lesion in each slice by a team member. Finally, the entire lesion was extracted for each subject. Second, each lesion file was adjusted (if needed) with MI-brain software (Imeka Solutions Inc.; www.imeka.ca). The rater was blind to the behavioral scores and to the severity of language impairment. Lesion volume was estimated in milliliters.

Voxel-based morphometry pre-processing

Voxel-based morphometry (VBM) pre-processing was performed using Clinical Toolbox Version 7/7/2016 running on SPM12. We used the MR segment-normalize function. The template for normalization was obtained from 30 healthy subjects (mean age: 61.3 years, seven men; see Rorden et al., [2012] for details). Enantiomorphic normalization (6-tissue new segment), an alternative non-linear registration method that corrects the signal within the lesion using information from the undamaged contralesional region, has been used because it has been shown to be superior to the traditional cost-masking function (Nachev et al., 2008). Lesion maps were entered into the normalization step. The pre-processing of the control group followed the same procedures of brain-damaged patients without including the lesion since control brains were not damaged. The GM tissue images obtained from the segmentation of normalized images were then smoothed with an 8-mm full-width-half-maximum Gaussian filter.

Statistical analyses

Behavioral analyses

The index of lexical informativeness, cohesion, macropropositions, and global coherence showed a normal distribution according to the Shapiro–Wilk normality test ($p > 0.05$). The narrativity variable showed a non-normal distribution according to the Shapiro–Wilk normality test ($p < 0.05$). Analysis of variances (ANOVAs) were conducted for variables with a normal distribution with Bonferroni post-hoc comparisons. A non-parametrical Kruskal–Wallis test with Bonferroni post-hoc comparisons were conducted for the narrativity variable.

Previous studies have shown that story grammar (Mozeiko et al., 2011) and global coherence (Barker et al., 2017; Wright et al., 2014) correlated with measures of executive function and that cohesive ties positively correlated with verbal fluency (Sherratt & Bryan, 2019). Others have reported associations between working memory and discourse measures in clinical populations. Namely, spoken discourse measures at the macro-level were correlated with working memory in post-stroke aphasia, whereas measures at the micro-level were not (Cahana-Amitay & Jenkins, 2018). Working memory was also reported to be associated with efficiency and cohesion in patients who suffered from a traumatic brain injury (Hartley & Jensen, 1991). Exploratory correlations were thus performed to assess the possible association between the discursive variables and two lexical formal tasks (i.e., the naming and the free verbal fluency tasks, which also rely on executive functions) as well as with two working memory tasks (digit and word span). The naming task showed a non-normal distribution according to the Shapiro–Wilk normality test ($p < 0.05$), and therefore, we used non-parametric correlations with this task. The free lexical task and the working memory tasks showed a normal distribution according to the Shapiro–Wilk normality test ($p > 0.05$). Therefore, Spearman's correlations were conducted between the free lexical fluency task, digit span, word span and the index of lexical informativeness, cohesion, macropropositions, and global coherence, whereas Kendall's tau correlation was conducted with the narrativity variable, which yielded a non-normal distribution. A Bonferroni correction was made for multiple comparisons, resulting in an alpha level of 0.01 for each family of tests.

Neuroimaging analyses

A factorial analysis model was used to compare GM density at the voxel level between controls, LH, and RH. Regression models were performed using the linguistic discursive measures scores as dependent outcome. Age, years of education, and total intra-cranial volume were considered as covariates. A family-wise error (FWE) correction at $p < 0.05$ at the cluster level was applied, using an arbitrary cluster-forming uncorrected threshold of $p < 0.001$. Additionally, effect sizes for significant comparisons were calculated using the T-statistics (t) and the degrees of freedom (df) in the formula $\sqrt[2]{t^2/(t^2+df))}$ (Lukic et al., 2017).

Results

Participants

Table 1 presents demographic information and mean neuropsychological evaluation scores for both patient and control groups. One-way ANOVAs showed that no significant differences in age, education, or socioeconomic status between the three groups. Time of stroke onset was also comparable between the LH and RH groups. A short language assessment was conducted by a speech language pathologist who concluded that one participant in the LH group suffered from mild conduction aphasia. This participant was included in this study since his performance was comparable to the other patients of the LH group.

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Insert Table 1 approximately here

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Behavioral results

A significant effect of group on the cohesion score was found (F (2,27) = 7.17, p = 0.003) for which the LH patients had a lower performance than healthy controls. A significant effect of group on the macropropositions score was also found (F (2,27) = 3.90; p = 0.032), and post-hoc comparisons showed that patients with an RH stroke had a lower performance than healthy controls. Similarly, a significant effect of group on the global coherence score was found ($F (2,27) = 5.47$, $p = 0.010$) with post-hoc comparisons showing that patients with an RH stroke had a lower performance than healthy controls. No group effect for the index of lexical informativeness and narrativity was found. Mean and standard deviations (mean ± SD) for each group are reported in Table 2 in addition to the statistical values of the tests.

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Insert Table 2 approximately here

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Exploratory correlations were performed to assess the possible association of the discursive variables with two lexical formal tasks as well as with two working memory tasks. The statistical details of the correlations are reported in Table 3. Four correlations were found to be significant, and three survived the Bonferonni correction. Namely, the narrativity score was significantly correlated with the naming task score ($r = 0.420$; $p = 0.004$), the digit span score ($r=.453$; $p=.001$) and the word span score ($r=.459$; $p=.001$).

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Insert Table 3 approximately here

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Imaging results

Linear regression-based analysis of narratives variables

Significant associations between all five discourse variables and regional GM volume as measured by whole brain VBM were computed using regression-based analyses after controlling for age, education, and total intracranial volume. The anatomical labelings of the clusters are listed in Table 4, and the areas are shown in Figure 1.

Cohesion

One significant cluster located in the right primary sensory area, precentral gyrus, and the interior frontal gyrus (IFG, *pars opercularis)* significantly and positively correlated (p = .011) with the cohesion score.

Global Coherence

Similarly, one significant cluster located in the left superior frontal gyrus (STG) and the primary sensory area was significantly positively correlated (p = .002) with the global coherence score.

Macropropositions

GM density positively correlated with the macro-positions score mainly with brain areas located in the left hemisphere. The most significant clusters were located in the left cingulate *(p* < .001*),* the left STG *(p* < .001*)*, the left MTG (p = .040), and the left inferior frontal gyrus (p = .001). A cluster including the primary motor area, the primary sensory area, and the insula in the right hemisphere (p =.003) also significantly and positively correlated with the macropropositions score.

Narrativity

One significant cluster also located in the left primary sensory area, the left insula, and the left STG significantly and positively correlated (p = .001) with the narrative structure score.

Index of lexical informativeness

One significant cluster located in the left primary sensory area and the left insula significantly and positively correlated (p = .020) with the lexical informativeness score.

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Insert Table 4 approximately here

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Insert Figure 1 approximately here

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Discussion

This study was designed to explore the association between different aspects of connected speech and their GM structural correlates in participants with a unilateral stroke in the LH or the RH and a group of healthy controls, all having middle-low to low SES. Behaviorally, individuals with a LH stroke presented impairment in cohesion, whereas individuals with a RH stroke presented impairments in coherence and macropropositions. The groups did not differ in terms of narrativity and lexical informativeness. As hypothesized, this study demonstrated that cohesion is associated with greater GM density in the RH. Surprisingly, the other more "global" macrolinguistic processes (i.e., coherence, macropropositions and narrativity) were associated with GM density in the LH, although macropropositions were as well associated to GM density in the primary motor area and the insula in the RH. Moreover, lexical informativeness, which is a more functional, but also more "local" macrolinguistic process, presented neural correlates similar to those of coherence, macropropositions, and narrativity. Interestingly, and consistent with our hypotheses, both behavioral and imaging results were very similar between coherence and macropropositional processing since both constructs are intrinsically and deeply connected.

Both the LH and RH groups produced fewer proportions of cohesive ties than the healthy controls, but the difference was only significant between the LH group and controls. Consistent with previous findings (Uryase et al., 1991), LH participants produced a lower proportion of cohesive ties per utterance than RH participants, but the difference between these clinical groups was not significant considering the large score range in our participants. One possible explanation for the differences between the studies is the severity of linguistic impairments in patients with an LH stroke at the time of testing. Barker et al. (2017) hypothesized that the impairments observed in cohesion in LH individuals might be caused by linguistic impairments rather than by macro-linguistic impairments per se. Consistent with this hypothesis, the number of cohesive ties was moderately and positively correlated with verbal fluency in a group of older adults (Sherratt & Bryan, 2019). Similarly, correlations between verbal fluency and global and local connectedness have also been reported in patients with the behavioral variant FTD (Ash et al., 2006) and patients with amyotrophic lateral sclerosis (Ash et al., 2014). To the best of our knowledge, this relationship has not yet been tested in stroke patients. Our exploratory analysis does not support this hypothesis. A weak correlation between cohesion and the naming task was found, but it did not survive the multiple testing corrections, and the correlation with the verbal fluency task was not significant. However, one must note that in Sherratt and Bryan (2019), the *total* number of cohesive ties in the picture sequence samples, similar to the samples used in the present study, did not significantly correlate with the verbal fluency task. Nevertheless, after examining each type of lexical ties more specifically, one of the strongest correlations was between the *lexical* ties in the picture sequence samples and the verbal fluency task. Considering the sample size in the present study, we decided to only look at the total number of cohesive ties and not to separately investigate each type of cohesion ties. Thus, the relationship between verbal fluency and cohesion still requires further attention as it seems to depend on the nature of the discourse task and the type of cohesive ties that were analyzed.

Consistent with previous studies conducted in different clinical populations (Ash et al., 2006, 2014; Troiani et al., 2008), the present results support an association between non-linguistic brain areas and discourse cohesion in which executive functions play a decisive role. The cohesion score was positively associated with GM density in the right primary sensory area/precentral gyrus and the *pars opercularis*. A correlation between local connectedness and cortical atrophy was found significant in the right frontal and anterior temporal areas in non-aphasic patients with a disorder of social behavior and executive functioning (i.e., the behavioral variant of FTD) (Ash et al., 2006)). Based on their results, the authors concluded that discourse impairment is largely caused by language impairment which is strongly associated with poor executive functioning. Similar results were obtained in patients with amyotrophic lateral sclerosis who presented impaired discourse adequacy including local connectedness (i.e., a measure of discourse coherence) and maintenance of the theme (Ash et al., 2014). Impaired local connectedness was associated with bilateral atrophy in the inferior frontal area, but also with reduced fractional anisotropy in the genu of the corpus callosum and in the right uncinate, which connects the anterior temporal area to the inferior frontal area. Bilateral inferior frontal activations have also been reported in healthy adults in an fMRI study in which story narration was contrasted to the description of unordered pictures (Troiani et al., 2008). These studies are also in line with the schematic representation of discourse processing of Barker et al. (2017). In the present study, correlations observed between cohesion and GM density in the right primary sensory area/precentral gyrus and the *pars opercularis* could be interpreted as non-linguistic functions in support of discourse cohesion (Marini, Carlomagno, et al., 2005; Sherratt & Bryan, 2012). Additional work is needed to determine whether the present results could be replicated in a larger group of patients who have suffered from a stroke.

Global coherence is one of the most studied variables in discourse (Ellis et al., 2016), but relatively few studies have compared patients with unilateral LH and RH stroke individuals, especially when it comes to combine behavioral and brain imaging data. Consistent with previous evidence, global coherence was significantly affected in RH compared to healthy controls (Barker et al., 2017; Bartels-Tobin & Hinckley, 2005; Davis et al., 1997; Marini, 2012). However, the performance in global coherence was positively associated with GM density mainly in the LH, which contrasts with previous findings. Nevertheless, bilateral activations in BA45 were positively correlated with coherence during speech production in healthy older adults using fMRI (Hoffman, 2019). Behaviorally, previous findings tend to support the implication of executive functions in maintaining global coherence in connected speech, which are usually associated with frontal activation (Barker et al., 2017; Wright et al., 2014). Our VBM results demonstrated greater GM density in the left primary sensory area/insula and STG, which are not classically associated with executive functions. Thus, we could hypothesize, based on the discourse representation model proposed by Barker et al. (2017), that these areas could be considered as part of non-linguistic cognitive network supporting macrolinguistic functions. As highlighted by Ellis et al. (2016), more investigations are needed to address a comprehensive portrait of neural correlates associated with global discourse coherence.

In line with the results found regarding global coherence, both the LH and RH groups produced fewer macropropositions than the healthy controls did, but the difference was only significant between the RH group and the control group. Although considered as an important aspect of discourse (Davis et al., 1997), the assessment of story structure - the macropopositions in this study – is relatively uncommon in both left hemisphere (LH) and right hemisphere (RH) stroke patients. As expected, GM density was associated with both coherence and macropositions in similar areas. In addition, macropropositions were positively associated with GM density in the left primary sensory area/insula and STG. The left insula has been associated to articulatory planning, while the primary sensory area is involved with sensory-to-motor mappings, which includes the temporal cortex and other areas in the dorsal tract (Cahana-Amitay & Jenkins, 2018). As for the results found with coherence, we could hypothesize that the areas associated with macropropositions could be considered as part of a non-linguistic cognitive network as they are less traditionally associated with language processing. Behavioral evidence tends to support this hypothesis. For instance, positive correlations between story grammar, a variable similar to the macroproposition measure used in the present study, and measures of executive functions, which are usually associated with frontal activation, have been reported (Mozeiko et al., 2011). Additionally, Cannizzaro and Coelho (2013) examined the relationship between executive functions and story grammar in 46 neurotypical adults (18-98 years old). They reported that the number of story grammar elements were negatively correlated with age as well as with linguistic and non-linguistic measures of executive functions. Thus, similarly to the discussion developed regarding global coherence, the relationship between macroproposition processing, executive functions and a non-linguistic cognitive network supporting macrolinguistic functions should be further explored.

Narrativity encompassed the assessment of the causal sequence of events in the story, the predominance of narration (as opposed to description), the relationship between the story scenes and the facts narrated, as well as characters' recognition. Thus, it is a macrolinguistic discourse ability, which relates to story structure (macropropositions), and includes crucial abilities for the construction of a globally coherent narrative (van Dijk, 1980). The confluence of story structure, logical coherence, thematic coherence and general attributes should be further investigated comparing RH and LH stroke (Davis et al., 1997). As with coherence and macropropositions – also more "macro" abilities – narrativity correlated more strongly to LH areas as opposed to RH ones, namely the left insula and the STG. Moreover, although no significant differences between the three groups were observed behaviorally, narrativity was the only macrolinguistic measure that correlated with naming (semantic memory) and working memory. Due to the novelty of this construct in oral narrative production analyses, further studies should investigate the association between narrativity and story planning and monitoring as executive tasks, as well as its neural correlates.

The index of lexical informativeness as calculated by Marini et al. (Andreetta et al., 2012; Marini, 2012; Marini et al., 2007; Marini et al., 2011) did not show a significant difference among the three groups. Among the few studies that compared individuals with an LH and RH stroke, Agis et al. (2016) investigated the index of lexical informativeness using the measure of content units (Yorkston & Beukelman, 1980) in the description of the Cookie Theft picture from the BDAE-3 (Goodglass et al., 2001) within 48 hours of stroke onset. The two patient groups in that study did not differ from each other as in the present study, but they differed from the group of healthy controls. The most probable explanation for this difference is the timing of the assessments. The patients recruited in the present study were in the sub-acute/chronic phase of recovery, at least four months post-onset, whereas the patients in Agis et al. (2016) were in the acute phase of recovery. The heterogeneity of the results (large standard deviations) in both patient groups also explains the lack of statistical difference with the controls. Another possible explanation for the absence of a difference between the patient groups and controls could be the SES of the participants. Our participants presented a middle-low to low SES, which has been associated with a reduced content and discourse productivity (Snow et al., 1997; Yorkston et al., 1993) in addition to a reduction in cohesive adequacy (Coelho, 2002). Similarly, Coelho (2002) reported that professional and skilled workers had better scores on cohesion measures than unskilled workers, but no differences were found in sentence production and story grammar measures. However, participants in our sample had much lower education levels than those in these previous studies (2–13 years of education in the present study versus 9–14 years in the study by Coelho). Previous findings have also shown that the SES has an impact on outcome after stroke (Song et al., 2017). This underlines the importance of assessing SES in various language tasks, in both clinical populations and neurotypical controls, in order to have a clearer idea of the impact of SES after stroke. It also reinforces the need for a larger study focusing on the impact of SES in individuals with a wider range of SES. The study of low SES samples brings important contributions for future research and clinical outcomes since this population represents most of the people in the world who are living in mainly underdeveloped countries.

Surprisingly, lexical informativeness, a more “local” process, was associated with similar patterns of GM density than the processes of coherence, macropropositions, and narrativity, which are generally associated with more “global” processing. However, these results are consistent with previous evidence. Among the few studies conducted on the neural basis of lexical informativeness, Agis et al. (2016) reported that in LH stroke, total content units produced were independently associated with the volume of the lesion and damage to the left inferior temporal gyrus, close to the left insula, which was positively associated with lexical informativeness in the present study. Similar to our results, no area was independently related to total content units (CU) in RH stroke.

Some limitations of our study should be noted. First, the sample sizes of our groups were relatively small, and it is therefore difficult to generalize the present results to all patients who underwent LH or RH stroke. Another aspect to consider is the issue of sex differences in cognition. In our study, groups were not balanced according to sex due to the difficulties in recruiting participants who would fulfil all of the inclusion criteria to join the behavioral and imaging data acquisition. We did not use sex as a covariate in the present analysis because the use of intracranial volume significantly reduces the gender differences (Pell et al., 2008). These authors also reported multi-collinearity between intracranial volume and gender, and thus recommended not to use gender as an additional covariate and use intracranial volume, which shows the most consistent effects. Nevertheless, we acknowledge that it would have been optimal to have groups matched on the sex variable. Third, inter-rater reliability for coherence was found to be fair. More extensive training or refinement of coherence measurement is thus required to improve the reliability of coherence. Finally, to fully understand the neural basis of oral narratives, future studies should not only investigate the structural correlates but also look the functional and anatomical connectivity to have a better understanding of the role of the language network in discourse processing.

Conclusion

The present results underline the importance of conducting studies in both LH and RH patients and of combining both cognitive and language assessments to better specify the characteristics of connected speech. Our results support the assumption that both hemispheres are essential in connected speech but at different macrolinguistic processes. A better behavioral and neuroanatomical comprehension of the macrolinguistic processes in patients with various types of communication impairment will aid in the development of early detection and management protocols, particularly in patients who suffered from a RH stroke. Furthermore, our study highlights the need for studying middle-low SES samples, which represent the majority of older adults in underdeveloped countries worldwide and of those served by the public health system in many countries.

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Table 1 – Mean sociodemographic descriptive data and neuropsychological results for participants with a LH stroke, participants with a RH stroke and age-matched healthy participants.

	LH n=10			RH n=10			Controls n=10			*p* value
Sociodemographic data										
	Mean	**SD**	**Range**	**Mean**	**SD**	**Range**	**Mean**	**SD**	**Range**	
Age (years)	67.80	7.64	57-76	67.6	9.73	50-79	66.3	8.73	52-78	H(2) = .89, p=.235†
Education (years)	7.3	3.26	2-11	7.6	2.99	3-11	6.1	3.93	2-13	F(2,27) = .52, p=.599
Sex	9M, 1F	-	-	4M, 6F	-	-	1M, 9F	-	-	-
Time Post-stroke	15.1	8.67	6-30	10.5	5.1	4-18	-	-	-	t=1.45, p=.165
Socioeconomic status (SES)	25.8	6.37	17-35	27.5	5.4	19-36	27.3	7.09	15-38	F(2,27) = .21, p=.813
Neuropsychological assessment										
Mini-mental state examination (/30)	23.5	3.47	16-27	25.5	3.34	23-29	28.1	1.91	25-30	H(2) = 9.57, p=.008†[a]
Geriatric Depression Scale (/15)	1.90	2.51	0-8	3.60	3.50	0-10	1.00	1.49	0-4	H(2) = 4.53, p=.104†
Naming subtest (MTL-Brasil; /30)	24.20	6.19	8-30	28.40	1.78	24-30	29.50	0.71	28-30	H(2) = 12.64, p=.002†[a]
Free verbal fluency (MAC-Breve; no maximum)	29.10	19.79	4-67	32.30	14.48	10-63	45.60	21.16	26-89	F(2,27) = 2.10, p=.142
Digitspan	10.20	3.88	3-16	8.90	2.38	6-14	9.70	2.03	7-13	F(2,27) = .52, p=.599
Wordspan	8.50	5.66	0-18	10.00	5.33	3-19	14.30	3.91	9-19	F(2,27) = 3.59, p=.042 [a]

LH= left hemisphere stroke patients; RH= Right hemisphere stroke patients; M= Male; F= Female; SES = socioeconomic status as calculated by a questionnaire developped by Associação Brasileira de Empresas de Pesquisa in 2015: Class A = 45 - 100 points, B1 = 38 – 44 points, B2 = 29 - 37 points, C1 = 23 - 28 points, C2 = 17 - 22 points, D-E = 0 – 16 points)

† Non-parametric test statistics reported because this measure showed a non-normal distribution.

[a] LH significantly different from controls <.01

Table 2 – Mean behavioral results for participants with a LH stroke, participants with a RH stroke and age-matched healthy participants.

	LH n=10		RH n=10		Controls n=10		*p* value
Cohesion (#cohesion ties/# utterances * 100)	67.1	31.5	83.0	33.4	115.4	20.8	F(2,27) = 7.17, p=.003[a]
Coherence (#propositions/# narrative propositions * 100)	52.8	31.2	38.0	18.3	69.6	11.5	F(2,27) = 5.47, p=.010[b]
% Macropropositions (#macroprop./#total macroprop * 100)	48.1	33.9	41.25	24.9	71.3	11.5	F(2,27) = 3.90, p=.032[b]
Narrativity (max. 12)	6.0	5.1	8.2	3.4	10.4	2.2	H(2) = 4.63, p=.099
% Index of lexical informativeness (IU/#words * 100)	18.0	10.9	19.2	9.2	24.8	5.1	F(2,27) = 1.73, p=.198

LH= left hemisphere stroke patients; RH= Right hemisphere stroke patients.

[a] LH significantly different from controls <.005

[b] RH significantly different from controls <.05

Table 3. Correlations between discursive variables and formal lexical and working memory tasks.

Variables	Statistics	Cohesion	Coherence	% Macropropositions	Narrativity	% Index of lexical informativeness
Naming task BNT (/30)	r	.295	.190	.262	.420	.190
	p	.034*	.172	.066	.004**	.172
	n	30	30	30	30	30
Free verbal fluency (MAC-Breve)	r	.012	.002	.005	.236	-.096
	p	.929	.986	.971	.087	.463
	n	30	30	30	30	30
Digit span (NEUPSILIN)	r	.064	.126	.053	.453	.075
	p	.736	.507	.780	.001**	.695
	n	30	30	30	30	30
Word span (NEUPSILIN)	r	.003	.152	.120	.459	.164
	p	.986	.422	.528	.001**	.387
	n	30	30	30	30	30

** p< .005; * p<.05, but did not survive the Bonferonni correction

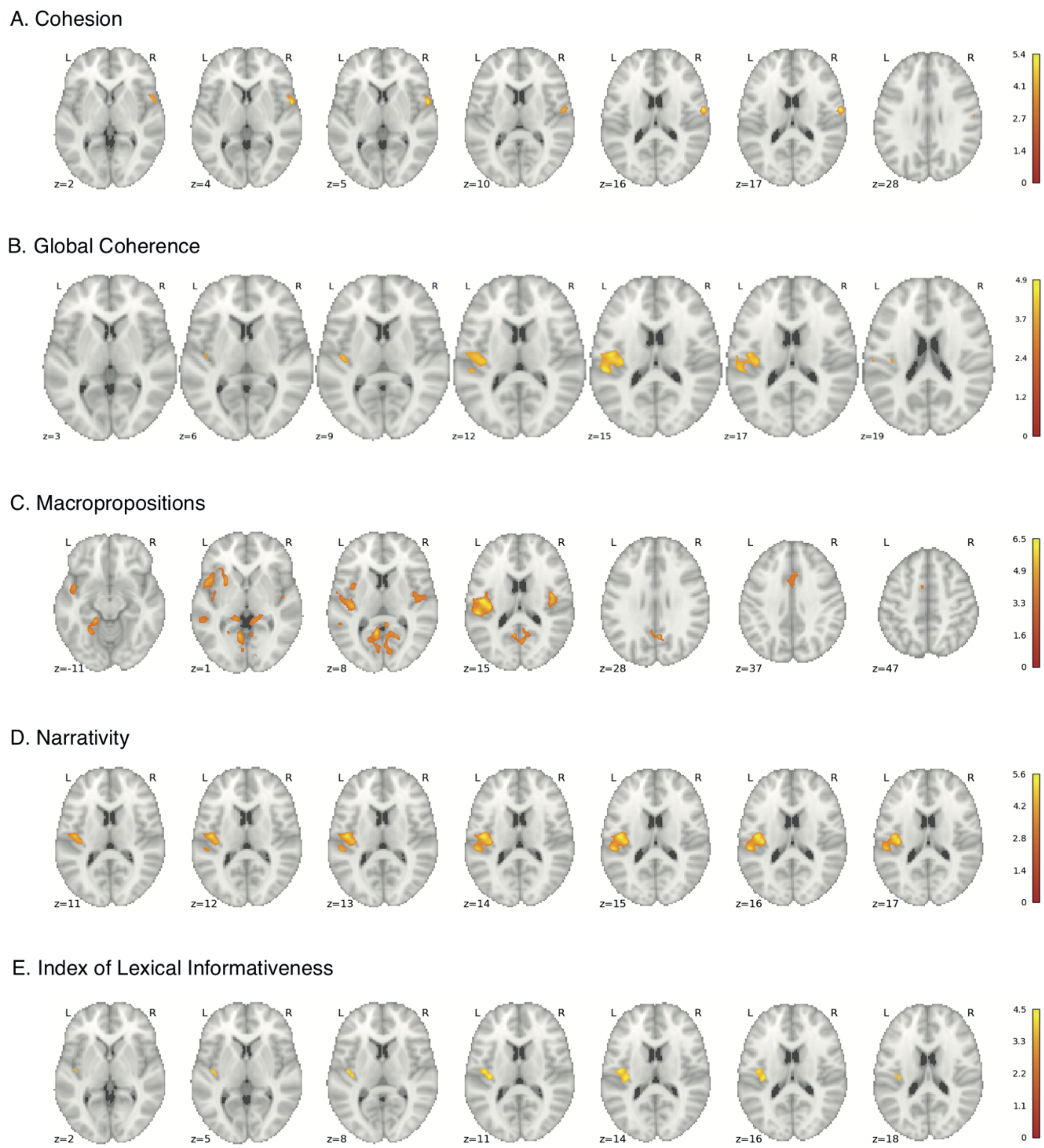
Table 4. Stereotactic locations and Brodmann's areas (BA) of the multiple regressions with the narrative measures.

Discourse measure	Location	Cluster size (k)	MNI 152 coordinates x	y	z	T	df	FWE correction	Effect size
Cohesion	Primary sensory area	1856	62	-6	17	5.43	25	.011	.984
	Precentral gyrus		57	4	5	5.31	25		.964
	Inferior frontal gyrus, *pars opercularis*		52	11	1	4.22			.781
Coherence	Superior temporal gyrus	2583	-52	-30	15	4.97	25	.002	1.042
	Primary sensory area		-45	-14	15	4.60	25		.843
Macropropositions	Anterior cingulate	8372	-12	-69	-34	6.64	25	.000	1.180
	Lingual gyrus		v	-56	11	6.51	25		1.160
	Cingulate		-9	-59	1	5.48	25		.993
			9	-56	22	5.44	25		.986
			5	-60	28	5.27	25		.958
			7	-58	25	5.11	25		.931
			18	-60	9	4.65	25		.854
	Parahippocampal gyrus		6	-45	8	4.58	25		.842
	Cuneus		14	-36	-3	5.20	25		.946
			-6	-75	5	5.01	25		.915
	Precuneus		12	-80	6	4.74	25		.869
			14	-63	23	4.33	25		.800
	Superior temporal gyrus	7251	-45	-15	15	6.51	25	.000	1.160
			-39	-21	12	6.15	25		1.102
	Putamen		-52	-30	15	6.06	25		1.087
	Precentral gyrus		-25	11	1	4.94	25		.903
			-55	-4	5	4.34	25		.801
	Primary sensory area		-4	-56	28	4.30	25		.794
	Insula		-37	3	9	4.24	25		.784
			-32	25	-2	4.24	25		.784
			-32	8	5	4.08	25		.757
			-29	23	0	3.90	25		.725
			-42	-4	14	3.89	25		.724
	Primary motor area	2349	42	-7	13	6.12	25	.003	1.097
	Primary sensory area		52	-11	10	4.59	25		.844
	Insula		-39	-4	1	3.67	25		.685
	Middle temporal gyrus	1370	-55	-28	-5	5.36	25	.040	.973
			47	-9	1	3.67	25		.685
	Inferior frontal gyrus, *pars opercularis*	2777	-42	18	5	5.30	25	.001	.963

	Inferior frontal gyrus, *pars triangularis*		-55	-41	4	5.21	25		.948
	Superior temporal gyrus		-46	12	1	4.99	25		.911
	Fusiform gyrus	2146	-17	-39	-11	4.73	25	.005	.867
			-45	2	-10	4.52	25		.832
	Cingulate gyrus	1633	-25	-52	-10	4.90	25	.019	.896
			3	14	32	4.90	25		.896
	Precentral gyrus		-9	-21	41	4.08	25		.757
Narrativity	Primary sensory area	2675	-44	-15	15	5.67	25	.001	1.024
	Insula		-37	-21	17	5.27	25		.958
	Superior temporal gyrus		-52	-30	16	5.18	25		.943
Index of lexical informativeness	Primary sensory area	1640	-36	-23	14	4.46	25	.020	.821
	Insula		-43	-14	14	4.35	25		.800

Note : Table 3 summarizes regions where GM volume was significantly associated with performance in each discourse measures. A family-wise error (FWE) correction at $p < 0.05$ at the cluster level was applied, using an arbitrary cluster-forming uncorrected threshold of $p < 0.001$. Significant peak regions are reported with corresponding MNI coordinates, T and p values, degrees of freedom, and effect sizes ($\sqrt[2]{t^2/(t^2+df)}$).

Figure 1. Three-dimensional surface rendering showing regions of grey matter associated with A) cohesion; B) global coherence; C) macropropositions; D) narrativity and E) index of lexical informativeness. Results are shown using a family-wise error correction at $p < 0.05$ at the cluster level, using an arbitrary cluster-forming uncorrected threshold $p < 0.001$.



Supplementary Material 1.

Macropropositions of narratives

The dog story (Le Boeuf, 1976)	
A boy sees a dog (lost puppy) on the street / sidewalk	scenario
The boy takes (decides to take) the dog home	scenario
The boy hides the dog in the wardrobe/closet	scenario
The mother finds the dog	complication
The mother asks the boy for some explanations / The boy begs the mother to keep the dog	complication
The mother allows the boy to keep the dog / The mother helps the child/the boy builds the dog house	resolution
The car accident (Joanette et al., 1995)	
A woman/mother drives the car and takes two children/her two children	scenario
The woman/mother parks the car/goes to an establishment and leaves the two children (the two small children) in the car	scenario
The boy gets into the driver's seat and moves the steering/lever of the car	complication
The car goes down the slope and hits a lamppost	complication
The woman/mother leaves the establishment and realizes what happened	resolution
The cat story (Ulatowska, Doyel, Stern, Haynes, & North, 1983).	
A girl/a daughter cries and asks a man/father for help because a cat/his cat is stuck on the branch of a tree	scenario
The man/father climbs the tree to remove the cat	scenario
The man / father leans on the branch and reaches the cat	complication
The man/father throws the cat from the tree towards the girl (the cat jumps towards the girl)	complication
The man / father gets stuck on the branch by his jacket and a fireman comes to rescue him	resolution

Supplementary Material 2.

Cohesion Relations (Examples)			
Participant	**Brazilian Portuguese**	**English**	**Explanations**
RH210 (participant right hemisphere # 210)	*essa historinha aqui/* *é de uma mãe/* *é meio distraída/* *saiu com as criança/* *estacionou em algum lugar/* *saiu pra fazer qualquer coisa/* *e deixou as criança dentro do carro*	this story here/ is about a mother/ who is a little distracted/ she went out with **the children**/ parked somewhere/ went out to do something and left **the children** in the car	This is an example of **reiteration** through **repetition** - repetition is necessary for reference, avoiding ambiguity
PLH6 (participant left hemisphere # 6	*guri* achou o cachorro na rua/* *Ø levou Ø para casa*	boy found the dog on the street/ **Ø** took **Ø** home	In this example, the symbol **Ø** represents an ellipsis. According to Antunes (2005), an ellipsis is a type of referencing. In Portuguese, the subject, or even the object in certain circumstances, does not have to be repeated. In this example, an English speaker would have said '**the boy took the dog home'**. In Portuguese, the pronoun ele **(he)** would have been used in both cases and would not have resolved the ambiguity: '**ele** levou **ele** para casa' (in Portuguese).
PLH 7 (participant left hemisphere # 7	***ele*** *viu um cachorrinho.../* *vira-lata de cachorro de rua/* ***ele*** *gosta muito de cachorro*	***he*** *saw a puppy ... /* *a stray dog /* ***he*** *likes dogs a lot*	In this case, the pronoun **he** - which refers to the boy in the story - does not have a reference. The pronoun does not have a reference, which we call a textual cohesion error.
RH205 (participant right hemisphere # 205	*deve tá pedindo pra mãe deixar o cachorro dentro de casa*	*must be asking the mother to leave the dog inside the house*	A cohesion error is produced in this case because the subject **(the boy)** is missing. In other cases, the subject can be easily taken up by the context, but this was not the case in this example.

* Expression used in southern Brazil, synonymous of young boy