Brain & Language 121 (2012) 174–184

Contents lists available at SciVerse ScienceDirect

Brain & Language

journal homepage: www.elsevier.com/locate/b&l

Neurofunctional (re)organization underlying narrative discourse processing in aging: Evidence from fNIRS

Lilian Cristine Scherer [a,b,c,*], Rochele Paz Fonseca [c], Francine Giroux [a], Noureddine Senhadji [a], Karine Marcotte [a,b], Lêda Maria Braga Tomitch [d], Habib Benali [e], Frédéric Lesage [a,f], Bernadette Ska [a,b], Yves Joanette [a,b]

[a] Centre de Recherche Institut Universitaire de Gériatrie de Montréal – CRIUGM, Canada
[b] École d'orthophonie, Faculté de médecine, Université de Montréal, Canada
[c] Pontifícia Universidade Católica do Rio Grande do Sul – PUCRS, Brazil
[d] Universidade Federal de Santa Catarina (UFSC), Brazil
[e] Unité 678 INSERM/UPMC, France
[f] École Polytechnique de Montréal, Canada

ARTICLE INFO

Article history:
Available online 17 November 2011

Keywords:
Aging
Cognition
Discourse comprehension
fNIRS
Functional neuroimaging

ABSTRACT

Relatively few studies have analyzed the mechanisms underlying the cognitive changes that affect language in the elderly, and fewer have done so for narrative discourse. The goal of this study was to explore the neurofunctional changes associated with aging for different components of narrative discourse. Functional near-infrared spectroscopy (fNIRS) and behavioral data on 10 younger adults and 10 healthy elderly participants were collected. Ten younger adults in a non-proficient second language condition were included to explore the possibility that the age-related neurofunctional reorganization partly expresses demanding resource allocation. Results show within- and across-hemispheric differences in the neurofunctional pattern of activation in the older participants with reference to the younger ones, partially shared with the low-proficiency young adults, providing support for the recognized mechanisms underlying neural reserve and compensation. fNIRS was shown to be appropriate for studying the age-related neurofunctional reorganization of complex cognitive abilities.

© 2011 Elsevier Inc. All rights reserved.

1. Introduction

The mechanisms and processes underlying cognitive aging have become an increasingly important research issue. However, not all cognitive processes have been investigated in any depth in relation to aging (Sörös, Bose, Sokoloff, Graham, & Stuss, 2011). For example, most studies have been conducted on memory, executive functions or other cognitive abilities, but very few have directly examined linguistic abilities, even though the ability to maintain communication contributes to supporting elderly people's quality of life. Communication depends on a number of language components, and discourse represents one of the most naturalistic and complex ones, since it requires the mobilization of some important abilities, such as inferences for bridging ideas, the use of background knowledge and discourse contexts, as well as pragmatic interpretation, over and above effective working memory abilities (De Beni, Borella, & Carretti, 2007; Ferstl, Neumann, Bogler, & von Cramon, 2008). Thus, it is important to understand how the brain manages to maintain communication abilities in spite of the structural and cognitive changes generated by age (for a review, see Burke & Barnes, 2010; see also Beason-Held, Kraut, & Resnick, 2008; Grady, Springer, Hongwanishkul, McIntosh, & Winocur, 2006).

2. Discourse ability and the neuroanatomical and neurofunctional changes in the aging brain

Discourse comprehension depends on the interplay between various inter- and intrahemispheric regions (Démonet, Thierry, & Cardebat, 2005), which is at the heart of recent investigations into how the brain adapts with age in order to maintain cognitive efficiency (Stern, 2009). Many cognitive capacities known to be influenced by age could impact on discourse abilities, such as changes in attention and executive functions (Collette, Schmidt, Scherrer, Adam, & Salmon, 2007), and in episodic and working memory (De Beni et al., 2007). According to Grady et al. (2006), the most evident declines resulting from aging can be observed in episodic memory, attention and aspects of emotional perception. On the

* Corresponding author. Address: Pontifícia Universidade Católica do Rio Grande do Sul – PUCRS, 6681 Ipiranga Ave., PO Box 1429 – Zip Code 90619-900, Porto Alegre – RS, Brazil. Fax: +55 51 3320 3500x4708.
E-mail address: lilian.scherer@pucrs.br (L.C. Scherer).

0093-934X/$ - see front matter © 2011 Elsevier Inc. All rights reserved.
doi:10.1016/j.bandl.2011.09.008

other hand, no changes have been noted in semantic memory and in aspects of social cognition, such as theory of mind abilities; in some cases, these abilities have even been found to improve. These cognitive changes are related to modifications in the nervous system (Raz, 2000; Rossini, Rossi, Babiloni, & Polich, 2007) and to disturbances in neuroanatomical structures such as the prefrontal cortex (Rajah & D'Esposito, 2005; Raz, 2000). However, despite these anatomical and cognitive changes, most elderly individuals present adequate discourse abilities. The reason for this preservation of discourse abilities has been linked to the presence of suspected compensatory cognitive mechanisms, which appear to be particularly efficient in highly educated elderly adults. These presumed adaptive mechanisms could reflect the occurrence of a neurofunctional reorganization in optimal aging, including both inter- and intrahemispheric reorganization (e.g., Cabeza, 2002; Cabeza, Anderson, Kester, & McIntosh, 2002; Davis, Dennis, Daselaar, Fleck, & Cabeza, 2007; Grady et al., 2006; Li, Moore, Tyner, & Hu, 2009; Park & Reuter-Lorenz, 2009).

3. Discourse ability and the neurofunctional reorganization of the aging brain

Discourse ability is a language component that relies on the integrity of both left and right cerebral hemispheres (Brownell & Joanette, 1993; Perfetti & Frishkoff, 2008). According to Gernsbacher and Kaschak (2003), traditional left-hemisphere (LH) language areas deal mainly with local coherence between and within sentences, while right-hemisphere (RH) brain areas are responsible for global coherence, at the macrostructure of the verbal message. Bilateral activations observed in neuroimaging studies, such as the ERP study by Nieuwland, Otten, and Van Berkum (2007) and the fMRI study by Kuperberg, Lakshmanan, Caplan, and Holcomb (2006), indicate that the construction of a coherent discourse representation requires the participation of different regions within both hemispheres, which need to share and integrate information.

A number of phenomena have been reported to be associated with the preservation of cognitive abilities in aging. One of them is a reduction in hemispheric asymmetry in high-performing older adults (Hemispheric Reduction in OLDer Adults or HAROLD; Cabeza, 2002). This phenomenon had already been reported in earlier studies. For example, Reuter-Lorenz et al. (2000), looking at older and younger adults solving a verbal and spatial working memory task, observed activations that were more left-lateralized for verbal working memory and right-lateralized for spatial working memory in young adults, whereas older adults showed more bilateral activation in the execution of both tasks. Such interhemispheric reorganization is considered in Stern's (2009) model to correspond to the addition of neural reserve, a phenomenon that also occurs when young subjects are faced with increasingly complex tasks (Banich & Weissman, 2000; Maertens & Pollmann, 2005; Weissman & Banich, 2000).

Another pattern of brain reorganization, first proposed by Grady et al. (1994) in a PET study of face and location perception abilities among younger and older adults, delineates an intrahemispheric reorganization taking the form of a posterior–anterior shift in aging (PASA; Davis et al., 2007). This reorganization is interpreted by some researchers as representing the impact of reduced occipital activity due to age-related sensory processing decline, coupled with increased frontal activity. This neurofunctional reorganization is viewed in Stern's (2009) model as a compensation mechanism.

Based on an integrative view of the aging brain, including the PASA and HAROLD phenomena among others, Park and Reuter-Lorenz (2009) proposed the so-called *Scaffolding Theory of Aging and Cognition* (STAC). These authors suggest that the development of scaffolding mechanisms starts in young adulthood, when these mechanisms are built and activated to cope with novel situations and to attain new learning. In aging, scaffolding is invoked by means of increased frontal lobe and/or bilateral activation, representing the response of an adaptive brain engaging in compensatory measures to cope with the decline in neural structures and functions. Thus, neural reserve is used first (mostly expressed by interhemispheric reorganization), followed by neural compensation (mostly expressed by intrahemispheric reorganization). This is a complementary action that the brain takes to achieve a cognitive goal. This action is intrinsically related to aspects such as cognitive engagement and practice, and to low levels of default network engagement.

Considering all the factors presented above, the goal of the present study was to seek cues regarding a possible neurofunctional reorganization of discourse abilities with age, while distinguishing between different narrative discourse components such as the micropropositional level (the surface representation of the semantic content of the text), the macropropositional level (a higher hierarchical level, demanding simple inferences that are easily deduced from text structure) and the situational model (the representation of the essential and summarized content of the text, based on the reader's prior knowledge). Since part of the neurofunctional reorganization is presumed to rely on neural reserve, which is also required by younger participants who must perform a more complex task, three groups of participants were included in this study: young and elderly high-performing participants, as well as a group of young non-proficient participants placed in a highly complex situation since their proficiency in the testing language (French) was limited. Thus, it was first expected that the elderly participants and non-proficient young bilinguals would perform worse than younger proficient participants in both micro- and macropropositional aspects of narrative recall. It was also expected that the pattern of brain activation in these two groups of participants would be more bihemispheric given the neural recruitment required to handle complexity; however, in light of the results obtained by Gernsbacher and Kaschak (2003) and by Kuperberg et al. (2006), among others, it was expected that this pattern would involve more RH participation for the processing of higher textual levels (macropropositional and situational levels) but more bilateral activation for micropropositional comprehension. In other words, a HAROLD phenomenon was expected for older participants and non-proficient bilinguals, particularly for the micropropositional level of narrative processing, which has been shown to demand extra, probably bilateral, recruitment due to elderly participants' greater difficulty in retrieving details from the text surface as compared to younger adult readers (Radvansky, Curiel, Zwaan, & Copeland, 2001). At the same time, a PASA phenomenon was also expected since higher-order processing also demands extra recruitment, especially in frontal areas, due to the necessity of selecting the most suitable inference and inhibiting the remaining available ones, since inhibiting possible inferences seems to be a difficult task in aging (Radvansky, 1999).

In order to provide the most naturalistic possible environment to test narrative abilities, functional near-infrared spectroscopy (fNIRS) was chosen as the neuroimaging technique. This technology provides a noise-free environment in which participants are seated normally in front of a screen to execute the task.

4. Method

4.1. Participants

A sample of 30 healthy adults took part in this study, divided into three age groups: 10 young adult native speakers of French (YF), 10 elderly adult native speakers of French (EF), and 10 young adult native speakers of English (YE), with limited proficiency in French, the language in which the experiment took place (see Table 1). For

Table 1
Sociodemographic and neuropsychological characterization of the three groups.

Characteristics	YF	EF	YE	p
Sociodemographic data				
Gender M/F	6/4	3/7	6/4	0.387
Age years	26.40 (4.90)	68.10 (3.48)	24.20 (4.87)	⩽0.001
Education	17.70 (2.21)	15.80 (2.70)	16.60 (2.46)	0.348
Neuropsychological data				
Edinburgh index	98.0 (6.32)	97.50 (7.91)	94.50 (8.32)	0.235
Direct digit span	11.80 (2.30)	10.89 (2.9)	10.80 (1.93)	0.524
Indirect digit span	8.40 (2.72)	9.11 (2.80)	8.10 (2.64)	0.822
Direct–indirect digit span	3.40 (1.65)	1.78 (1.99)	2.70 (2.91)	0.327
Stroop 1	10.86 (2.25)	13.1 (2.39)	12.50 (2.35)	0.079
Stroop 2	12.19 (2.90)	17.15 (3.82)	12.80 (1.77)	0.002
Stroop 3	17.78 (4.73)	28.27 (7.87)	19.54 (6.11)	0.005
Buschke free recall 1	10.80 (0.92)	9.50 (1.58)	11.22 (1.30)	0.167
Buschke free recall 2	11.80 (0.42)	11.20 (1.3)	12.22 (0.83)	0.134
Buschke free recall 3	11.90 (0.32)	11.60 (0.52)	13.11 (1.96)	0.307
TMT B time	60.29 (17.60)	102.13 (46.51)	88.24 (50.40)	0.011

Note: YF = young French native speakers, YE = young English native speakers, EF = elderly French native speakers; TMT = Trail Making Test; Numbers represent Mean values while numbers in parentheses indicate standard deviations.

the YE group, the age of second language (French) acquisition varied from 9 to 16 years old (mean = 9.16, ±11.2), and all had received formal education in French (mean = 4.12 years, ±6.6). They were exposed to and used French for hours on a daily basis, and reported using both languages (French and English) regularly and in different contexts, such as at university and at work. They gave themselves a grade of 3, on average (grades ranging from 2 = ''very good'' to 4 = ''fair'') to evaluate their reading comprehension in French (3 = ''good,'' on a scale of 1 = ''excellent'' to 5 = ''poor''). The use of a standard proficiency test (DELF-B2) attested to the intermediate level of proficiency in French reading attained by all YE participants, as their mean performance was 74.8%, with a range of 60–88%. All participants from all three groups were highly educated (⩾12 years of schooling). They were all right-handers, according to the Edinburgh Handedness Inventory (more than +80; Oldfield, 1971), and had no history of neurological or psychiatric disease. They had normal or corrected-to-normal vision.

All participants underwent a neuropsychological screening test in order to assess their attention, short-term memory and working memory (Digit Span; Wechsler, 1997), naming abilities and processing speed (cards 1 and 2 of the Stroop Test; Stroop, 1935), and inhibition and processing speed in card 3 of the Stroop test, episodic verbal memory (Verbal Memory Task; Grober & Buschke, 1987), and inhibitory executive components (Trail Making Test (TMT), part B; Reitan & Wolfson, 1993). Only part B of the TMT was administered with the goal of assessing executive components as quickly and sensitively as possible, in accordance with the procedures adopted in other studies (Ashendorf et al., 2009; Reitan & Wolfson, 2004).

As shown in Table 1, there were no differences between groups regarding gender and years of education. As for neuropsychological performance on the administered screening, there were no differences between groups, except for scores for execution time on the Stroop 2 ($p = .002$) and 3 ($p = .005$), where the YF and YE groups outperformed the EF group ($p < .01$). According to these data, the cognitive profiles of all three groups were at a similar level regarding accuracy, except for processing speed, in which the elderly subjects presented lower scores, as they needed more time to perform at the same level as the younger groups.

4.2. Materials

4.2.1. Functional near-infrared spectroscopy: the technique and the experimental setting

fNIRS is a relatively new imaging technique with several advantages in comparison to other available techniques. For instance, its portability favors its use in hospitals and clinical settings; its cost is far lower than the cost of fMRI, for example; its relative tolerance of movements favors its use with children and clinical populations; its temporal resolution, in the order of milliseconds, as compared to seconds with fMRI, is valuable for several types of studies in which time measures are crucial; and its non-invasiveness allows repeated data acquisitions and task presentations in a more naturalistic and ecologically valid setting, since participants can perform the task in a comfortable position, with no noise and no exposure to a constrained environment. For a more detailed characterization of the technique, refer to Quaresima et al. (2005) and Schecklmann, Ehlis, Plichta, and Fallgatter (2008). Given that our study investigates text processing, fNIRS was the optimal technique, since it favors task presentation and execution in a more naturalistic way, which is crucial considering the nature of our task.

fNIRS provides three measurements of hemodynamics: HbO (oxygenation), HbR (deoxygenation) and HbT (total hemoglobin, which represents the sum of HbO and HbR). In fMRI, one can quantify the equivalent to the HbR value, since it is paramagnetic and thus is sensitive to fMRI's magnetic fields (Hoge et al., 2005). In fNIRS, activation is characterized by an increase in HbO concentration and a decrease in HbR levels (Schecklmann et al., 2008). Deactivation is characterized by the opposite pattern: HbR increases and HbO decreases; thus, the hemodynamic response is the mirror image of activation. In some cases, a decrease in HbO is found (negative activation). This has been mainly related to (a) blood flow redistribution, originating in a steal effect, due to the reallocation of cognitive processing or resources; and (b) an energy decrease induced by the stimulus in the monitored cortical area (Bandettini, Petridou, & Bodurka, 2005).

In this study, a multichannel continuous-wave optical imager (TechEnCW5; see Fig. 2) was used to obtain the measurements. We used a 24-source-detector channel configuration to cover the specific areas of the RH and LH; four laser sources to emit lights at two different wavelengths of 690 and 830 mm for each side with eight avalanche photodiode detectors (Hamamatsu C5460-01) with sensitivity over the 400- to 1000-nm range to receive diffused light over the scalp. The laser intensities were driven at 16 different frequencies, generated by a master clock and separated by approximately 200-Hz steps, so that their signals could be acquired simultaneously. Each laser delivered less than 5 MW to the tissue. A bandpass filter reduced 1/f noise and room light signal and the third harmonics of the square-wave signals. Then an analog-to-digital converter matched the signal levels with the acquisition level within the computer. Individual source signals were separated once the acquisition was done by demodulation software and filtered afterwards by using an infinite-impulse-response filter with a 20-Hz bandpass frequency.

4.2.2. Stimuli

Thirty-six short narratives with their corresponding probes—a short sentence following each paragraph that tapped either the micropropositional, macropropositional or situational level—were constructed for this study, some of them based on the task produced by Renault (2005). The texts and probes were constructed by native speakers of Canadian French and analyzed by specialist judges and non-specialist judges regarding their classification (as explained below). Afterwards, the narratives were piloted with a group of ten volunteers, age-matched to the two age groups in this study.

Texts were divided into three groups, according to the type of text processing the probes explored. There were 12 texts per group, six whose probe was "false" and six "correct" ones, which were randomly presented to the participants. Three extra texts and probes, constructed and tested in the same way, and thus considered equivalent forms, were developed for the practice session.

The short narratives contained an equivalent number of sentences, words, syllables and letters. The complexity of the sentence structures was controlled for by the use of a simplified syntactic structure, through the use of coordinated short sentences; embedded and passive sentences were avoided. The different topics of the narratives depicted ordinary, daily events, in order to permit the elaboration of a situational model by all participants, independent of their age or background knowledge. Aspects such as irony, indirect speech, metaphors and theory of mind were avoided.

Analyses of variance (ANOVAs) were done to ensure equivalent numbers of words, propositions, syllables and letters among the probes for the three conditions, in order to allow statistical comparisons among them ($p \leqslant .05$). With reference to Kintsch's (1998) model, probes focused either on micropropositions (MIC), macropropositions (MAC) or the situational level (SIT). These sentences required the informative content of the passages to be inferred or condensed from the text and randomly referred to information that was or was not present. In the case of micropropositional probes, the information requested was based on the predicates, not on the arguments of the sentences. Three sample narratives, one per group, with their respective probes, are presented in Appendix A.

4.3. Procedures

4.3.1. Stimulus presentation

Each block started with a 20-s period, when the participants read the instructions displayed in the middle of the computer screen. Then task presentation started with the first text, which was presented in its entirety in the middle of the screen for 14 s. Then the probe was displayed for 5 s; within this period, the participants had to read and judge the sentence, by pressing the green key on the keyboard (if the sentence was true with reference to the text) or the red key (if the sentence was false). A 20-s period followed, in which the participant was asked to look at the black cross in the middle of the screen and continue sitting still, without moving. Presentation of the stimuli lasted 488 s in each block, but they were programmed to last 510 s, since a time period multiple of 3 is demanded by the fNIRS system to organize the data. After each of the first two blocks, there was an interval. The duration of the task, not including the two rest periods, was 25.5 min. Block order was changed for the final five participants in each group (MAC became the first block, while MIC became the last one to be presented) in order to ensure that the order of presentation was not a factor influencing the results. A schema of task presentation and parameters for fNIRS acquisition can be seen in Fig. 1.

4.3.2. General procedure

The study was approved by the ethics committee at the Centre de Recherche, Institut Universitaire de Gériatrie de Montréal (CRIUGM). All participants were given the neuropsychological tests, as well as the questionnaire on bilingualism and the language proficiency test, in the case of the YE group. Then behavioral and imaging data were collected simultaneously, preceded by a practice session to familiarize the participants with the task. Participants were seated comfortably in front of the computer, their heads resting on a chin-rest 70 cm away from the screen. The instructions were presented on the screen in French for the French native speakers and in English for the English native speakers. Participants had to judge the information presented in the probe following each text as being plausible or not according to the content of the text; that is, they had to judge whether the sentence presented after the text was logical and acceptable, according to the content of the narrative. They were instructed to read the probe, judge its plausibility in relation to the narrative and press the corresponding button as fast as possible.

Behavioral data were captured and processed using the EPrime program (http://www.pstnet.com/eprime.cfm). The program

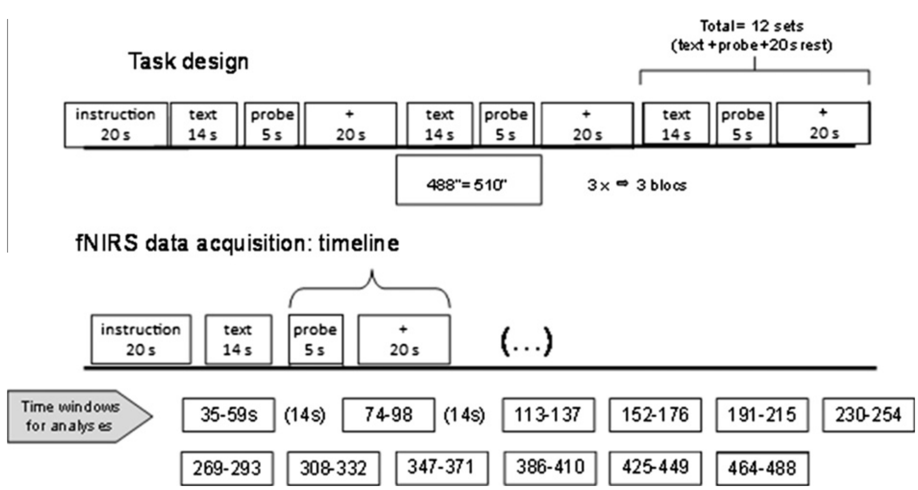

Fig. 1. Schematic presentation of stimuli presentation and parameters for fNIRS data acquisition.

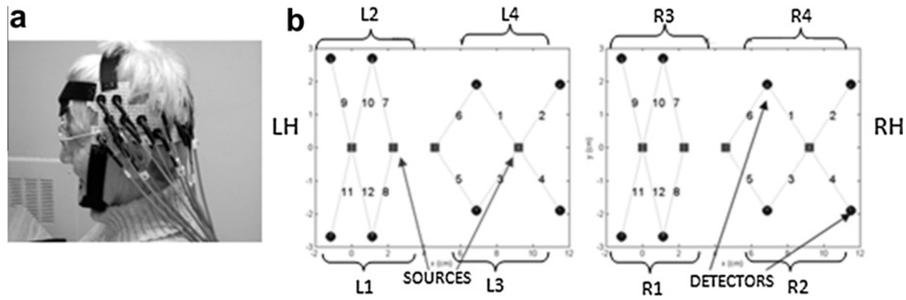

Fig. 2. (a) Participant with electrodes positioned for data acquisition. (b) Location of optical fibers on the left and right hemispheres.

recorded information on accuracy and response time. Moreover, it sent through parallel ports to the fNIRS equipment an indication of the 14-s time window when the participant was expected to answer the question, in order to facilitate the subsequent analyses.fNIRS sources and detectors were placed on flexible plastic probe holders, which were set bilaterally and attached to the head with Velcro (see Fig. 2a). The distribution of sources and detectors observed a minimum distance of 3 cm. The geometry of the probes allowed the simultaneous measurement of frontal and temporal regions, including Broca's and Wernicke's areas in the LH and their contralateral homologues in the RH (see Fig. 2b for probe positioning).

The optical fibers were placed in accordance with the 10×20 system used for EEG (Jasper, 1958). The procedures for plate placement to ensure a focus on Broca's and Wernicke's areas and their homologous areas in the right hemisphere were based on the procedures adopted by other researchers who investigated the same areas with ERP and fNIRS (Coch, Maron, Wolf, & Holcomb, 2002; Friederici, Hahne, & von Cramon, 1998). Four regions of interest (ROIs) per hemisphere were taken: in the LH, L1 (inferior frontal part), L2 (superior frontal part), L3 (inferior temporal part) and L4 (superior temporal part), and the correlated homologues in the RH, denoted as R1, R2, R3 and R4, indicated by brackets in Fig. 2a and b. Thus, Broca's region was defined as the crossing point between T3-Fz and F7-Cz in the LH and T4-Fz and F8-Cz in the RH, in the frontotemporal region approximately within the L1 region and its contralateral R1 region. Wernicke's area was marked at the crossing point between T3-P3 and C3-T5 in the LH and T4-P4 and C4-T6 in the right homologous area, in the posterior-temporal region corresponding approximately to a region within the L3 area and its contralateral R3 region.

fNIRS data analysis was performed by averaging the blood concentration within the 0- to 25-s time window of the three conditions individually. Then, the baseline was subtracted. Baseline averaging was done on the HbO, HbR and HbT concentrations within the 15 s preceding the task presentation and the 15 s of the final pause. Thus, these two time windows were averaged. Signals related to movements were removed during the data analysis. All the data, including baseline data, were normalized by HoMER, a data processing program that allows basic signal processing of near-infrared spectroscopy imaging data of the brain functions (http://nmr.mgh.harvard.edu/PMI).

4.3.3. Data analyses

Neuropsychological screening results were compared among groups with a one-way ANOVA. Behavioral data were analyzed with a mixed ANOVA, comparing the between-subjects group factor (YF, EF and YE) and within-subjects discourse condition factor (macropropositional, micropropositional and situational levels) regarding accuracy and response time in the discourse task. In addition, for neuroimaging data, a mixed ANOVA was conducted with three within-subjects factors (ROI, hemisphere, block/condition) and one between-subjects factor (age/language group). Despite the limited sample size for each group ($n = 10$) regarding multiple comparisons, Bonferroni correction and post-hoc procedures were applied. For each group, in order to better explore the possible effects, one-sample *t*-tests were also performed.

5. Results

5.1. Behavioral results

5.1.1. Number of correct responses

The mixed ANOVA showed a main effect of group in two conditions, with no main effect of condition or interaction: in the MAC condition (.001), the YF group made more correct responses than the YE group (.001). In the SIT condition (.047) the same pattern was observed: the YF group performed better than the YE participants (.048). No main effect was found for the MIC condition. There were no statistically important differences in terms of accuracy in the three levels of discourse processing between the EF and YF groups. Fig. 3 shows the performance of the three groups in terms of accuracy and response time.

5.1.2. Response time (RT) patterns

There was a main effect of group in all discourse conditions in relation to RTs, MAC (.005), MIC (.001) and SIT (.001). The YF group performed the tasks in less time than the EF and YE groups ($p < .01$). Fig. 3 presents the comparisons between the groups regarding their RTs for each of the three discourse levels.

5.2. fNIRS results

As an illustration, the mean concentration of HbO (oxyhemoglobin), HbR (deoxyhemoglobin) and HbT (total hemoglobin) for the 10 participants in the EF group, for MAC processing in the RH, inferior frontal region (R1), is displayed in Fig. 4.

Tables 2a–2c represent the averaged changing patterns of HbO, HbR and HbT within the 12 time windows per condition and ROI, obtained with the YF, EF and YE groups, respectively. Fig. 5 represents the patterns of activity in each of the ROIs investigated by condition and group, according to one-sample *t*-test analyses.

The mixed ANOVA showed no main effects of the three within-subjects factors (ROI, hemisphere, block/condition), or of the between-subjects factor (age group). There was a significant hemisphere $\times$ ROI $\times$ age group interaction ($p = .007$). After decomposition using MANOVA syntax, this interaction can be interpreted as indicating greater activation (HbO) in the superior temporal area, RH, in the YE group than in the YF ($p = .009$) and EF ($p = .015$) groups. To better explore the potential results, we conducted one-sample *t*-tests; their effects were interesting, as reported below.

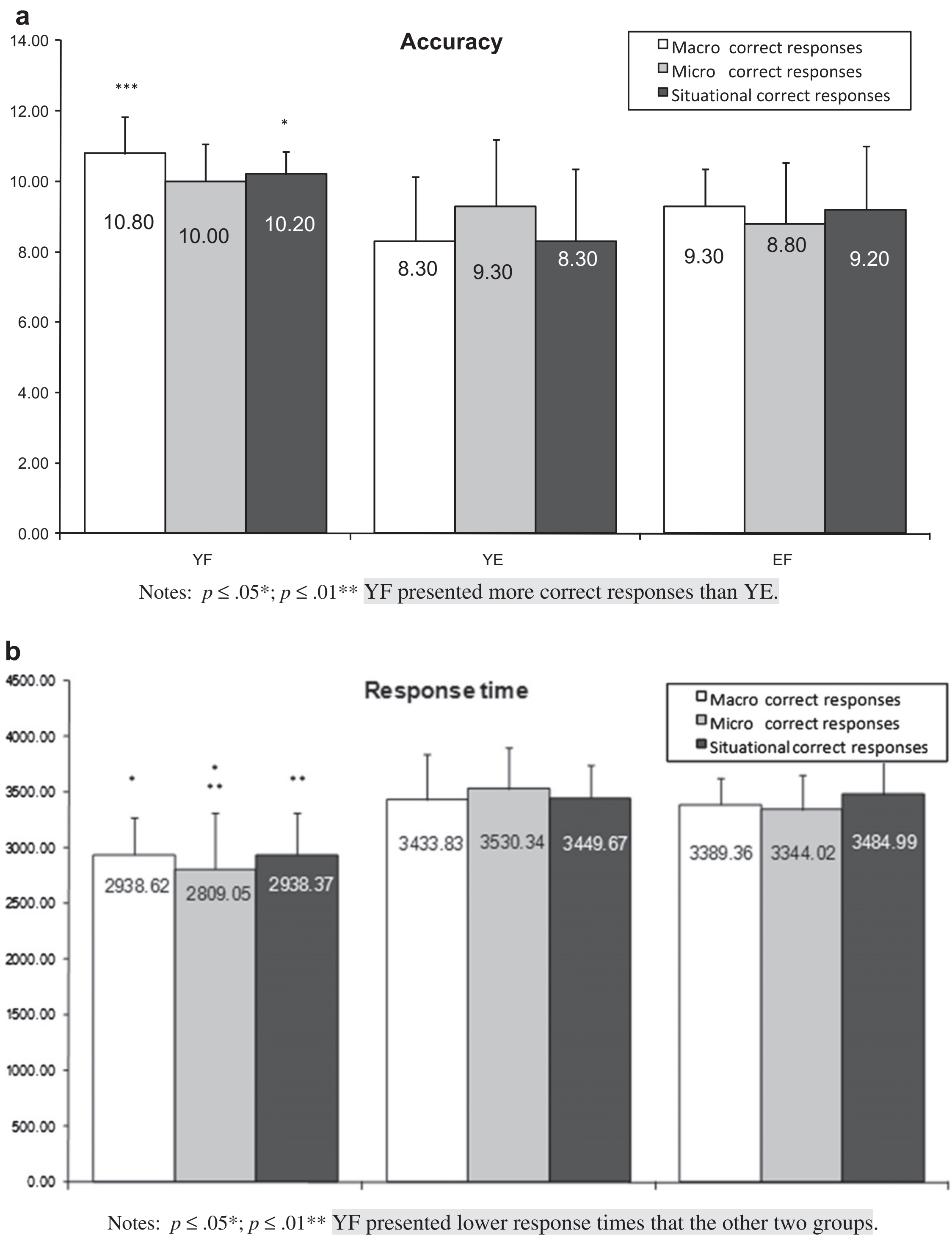

Fig. 3. Accuracy and response time of the three groups of participants on the discourse task.

5.2.1. YF group

An analysis of Table 2a suggests that, for the YF group, overall, several inverted curves occurred, revealing a major decrease in levels of oxygenation in different areas, in both hemispheres. During MIC level processing, a statistically significant inverted curve (that is, a considerable increase in HbR) occurred in the L4 area (temporal region) ($p = .0078$); the same pattern was found in the L3 region in the same hemisphere, although it was not as significant as in the L4 area ($p = .0724$). Thus, no significant activations (that is, increase in HbO levels) were recorded in any of the ROIs in the YF group.

5.2.2. EF group

Data from Table 2b indicate a tendency for HbO levels to increase in the frontal areas bilaterally (mainly in L1, $p = .0784$, and R1, $p = .0961$) for MIC processing. SIT levels showed no statistically significant changes in blood volume in any ROI for the EF group on average. Data for the MAC level revealed significant activation (increase in HbO) in R1 in the EF group ($p = .0215$); the same pattern was observed in R4, although with lower statistical significance ($p = .0670$). Patterns of blood volume changes suggest a tendency to activation in the two frontal areas of the LH as well, although

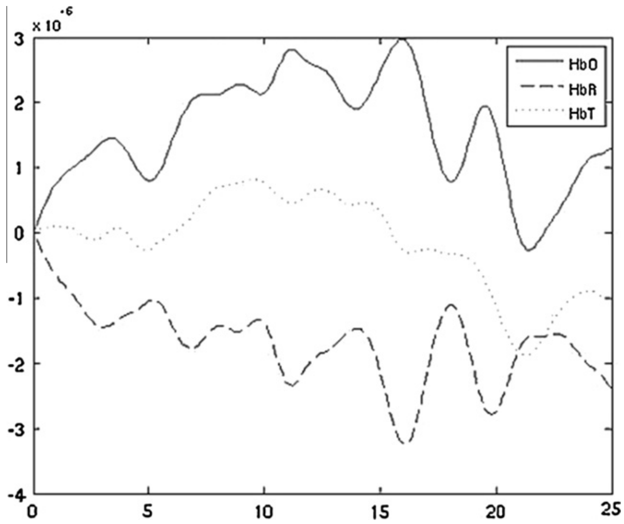

Fig. 4. Sample of a graph with a group mean for the concentration of HbO, HbR and HbT: EF group, MAC processing RH, R1 region.

no statistically significant differences were found when participants' data were averaged as a group.

Finally, another aspect to be mentioned is the occurrence of considerable heterogeneity in the data from this group as compared to the YE and YF groups. In other words, the highest inter-subject variability was recorded in this group of participants.

5.2.3. YE group

An analysis of Table 2c indicates a very significant activation (HbO increase) in all ROIs in the LH (L1: $p = .0007$; L2: $p = .0012$; L4: $p = .0018$; L3: $p = .0034$) for MIC level processing. In the RH, a considerable tendency toward the production of inverted curves (HbR increase) was recorded in all four ROIs. No statistically significant changes in blood volume were observed during SIT level processing. Inverted curves (that is, a reduction in the levels of HbO) were seen in the RH while the opposite pattern (increase in HbO) was observed in the LH, similarly to what was observed in MIC processing by this group of participants. MAC level data showed a significant change in blood volume in the RH temporal regions, R4 ($p = .0219$) and R3 ($p = .0510$).

Thus, the statistically most prominent activations were observed in this group, for MIC and MAC processing. An overall analysis of the data from the YE group points to the existence of different patterns of blood changes in both hemispheres: while higher levels of HbO occurred in the LH, in the RH an increase in HbR levels seems to have appeared.

6. Discussion

The goal of this study was to explore the neurofunctional changes associated with aging for different components of narrative discourse processing (microstructure, macrostructure and situational level). In terms of behavioral performance, there were statistically significant differences between the two young adult groups, with the YF group outperforming YE participants at the MAC and SIT levels in terms of accuracy. Regarding response time, YF needed significantly less time in all three conditions than both YE and EF groups. The main fNIRS results showed no main effects of the three within-subjects factors (ROI, hemisphere, block/condition) or of the between-subjects factor (age group). However, there was a significant interaction between hemisphere, ROI and age group, with greater activation (HbO) in the superior temporal area of the RH, in the YE group than in the YF and EF groups. The data

Table 2a
fNIRS data on YF group per condition and per brain site within hemispheres; the three rows of values correspond to the concentration of HbO, HbR and HbT, respectively.

	LH				RH			
	L2	L1	L4	L3	R2	R1	R4	R3
BLOCK	−0.1703	−0.0662	**−0.3761**[*]	**−0.2458**[*]	−0.0170	−0.2404	−0.4657	−0.4629
1	0.0161	0.1115	0.1389	0.1099	−0.0547	−0.0162	0.1087	0.1023
MIC	−0.1542	0.0454	−0.2373	−0.1359	−0.0718	−0.2566	−0.3570	−0.3607
BLOCK	−0.3172	−0.2417	−0.3974	−0.3193	0.2306	0.1198	0.1523	0.1752
2	−0.0254	0.0245	0.0386	0.0292	0.0316	−0.0059	−0.0291	−0.0114
SIT	−0.3426	−0.2172	−0.3588	−0.2900	0.2621	0.1139	0.1232	0.1639
BLOCK	−0.4623	−0.2579	−0.5252	−0.4450	−0.1294	−0.3116	−0.3488	−0.3728
3	0.1472	0.2047	0.2788	0.2514	0.0432	−0.0232	0.0390	0.0502
MAC	−0.3151	−0.0532	−0.2464	−0.1936	−0.0861	−0.3348	−0.3098	−0.3226

* $p \leqslant .08$ and $\geqslant .05$.
** $p \leqslant .05$.

Table 2b
NIRS data on EF group per condition and per brain site within hemispheres; the three rows of values correspond to the concentration of HbO, HbR and HbT, respectively.

	LH				RH			
	L2	L1	L4	L3	R2	R1	R4	R3
BLOCK	0.0751	0.1832	−0.0701	−0.0625	0.1545	0.2238	−0.0024	0.0033
1	−0.0256	−0.0498	0.0123	0.0313	−0.0566	−0.0753	−0.0709	−0.0517
MIC	0.0495	**0.1333**[*]	−0.0578	−0.0312	0.0979	0.1485	−0.0733	−0.0484
BLOCK	0.0985	0.1414	−0.0796	−0.0948	−0.0094	0.0852	−0.1729	−0.2068
2	−0.0303	−0.0479	−0.0095	0.0115	−0.1032	−0.0826	−0.0164	−0.0124
SIT	0.0682	0.0935	−0.0891	−0.0833	−0.1126	0.0026	−0.1893	−0.2192
BLOCK	0.2093	0.2397	0.0000	−0.0170	**0.3656**[*]	**0.4594**[**]	0.1632	0.1370
3	0.0012	0.0142	0.0217	0.0528	−0.2624	−0.3334	−0.1923	−0.1878
MAC	0.2105	0.2539	0.0217	0.0358	0.1032	0.1260	−0.0291	−0.0508

* $p \leqslant .08$ and $\geqslant .05$.
** $p \leqslant .05$.

Table 2c
NIRS data on YE group per condition and per brain site within hemispheres; the three rows of values correspond to the concentration of HbO, HbR and HbT, respectively.

	LH				RH			
	L2	L1	L4	L3	R2	R1	R4	R3
BLOCK	**0.7640**[**]	**0.7343**[**]	**0.6975**[**]	**0.6748**[**]	**−0.5181**[*]	−0.5875	−0.4632	−0.4734
1	−0.1643	−0.1573	−0.1854	−0.1844	0.1732	0.1009	0.0018	0.0252
MIC	0.5997	0.5769	0.5122	0.4905	−0.3449	−0.4865	−0.4614	−0.4481
BLOCK	0.1019	0.0015	0.0542	0.0676	−0.3516	−0.2871	−0.3284	−0.4477
2	0.1617	0.2120	0.2179	0.1990	−0.0152	−0.1789	−0.1419	−0.1381
SIT	0.2636	0.2136	0.2721	0.2665	−0.3668	−0.4660	−0.4703	−0.5858
BLOCK	0.3269	0.4491	0.2410	0.2577	−0.0778	**−0.0925**[*]	**−0.0916**[*]	**−0.1021**[*]
3	0.1768	0.2478	0.2028	0.2045	0.0010	−0.0005	−0.0022	0.0026
MAC	0.5037	0.6968	0.4438	0.4622	−0.0768	−0.0930	−0.0938	−0.0994

Note: The values in Tables 2a–2c represent the average blood changes within a time window of 0–25 s when the task corresponding to the three conditions (MIC, MAC, SIT) was performed.
[*] $p \leqslant .08$ and $\geqslant .05$.
[**] $p \leqslant .05$.

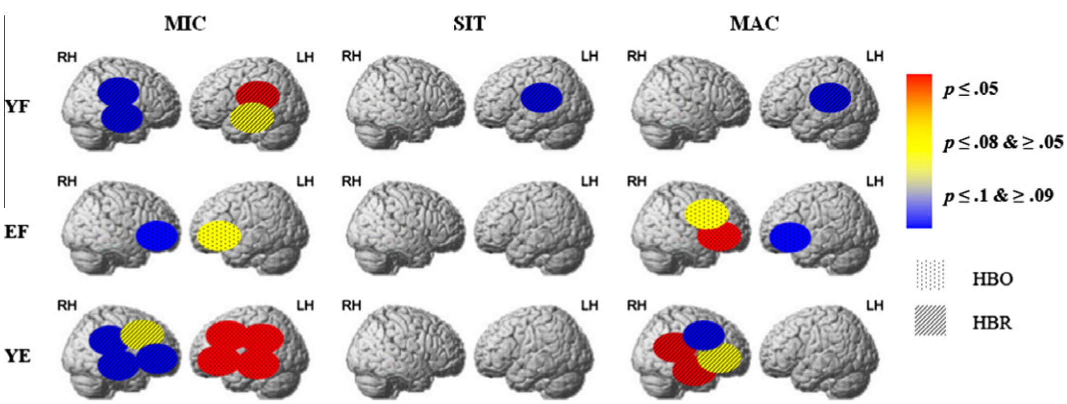

Fig. 5. Representation of patterns of blood changes in ROIs per group and condition. *Notes*: MIC = micropropositional level; SIT = situational level; MAC = macropropositional level; YF = young adults, French native speakers; EF = elderly adults, French native speakers; YE = young adults, English native speakers; RH = right hemisphere; LH = left hemisphere; data show simple *t*-tests results in each ROI per condition and group.

also indicated a more prominent frontal and RH activation in the elderly participants for MAC processing, as compared to the young native speakers of French. This pattern corroborates the PASA and HAROLD phenomena, does not rule out the STAC Model, and seems to reflect a reorganization of the brain circuitry for discourse processing, not necessarily linked to an increase in task difficulty, since the high behavioral scores achieved by the elderly group reflect the fact that the task was relatively easy to perform; their performance was comparable to that of the young group, also made up of French native speakers. At the same time, the native speakers of English who spoke French as their second language seemed to show considerable activation (increase in HbO levels) in all four regions of the LH for MIC processing, probably due to their greater difficulty coping with a task in a language in which they were not fully proficient.

6.1. Micropropositional level

Contrary to studies that found a significant difference in the performance of younger and older adults on microstructural processing (Radvansky et al., 2001; Stine-Morrow, Loveless, & Soederberg, 1996), with the younger ones outperforming the elderly ones, in this study no statistical differences were observed at this level. According to the literature, there is a tendency for elderly participants to take longer to solve cognitive tasks, such as text comprehension (Ska & Joanette, 2006; Stine-Morrow, Miller, & Leno, 2001; Stine-Morrow et al., 1996); this was the case in this study, where the elderly subjects took more time to solve all three text processing conditions.

The fNIRS results showed prominent LH participation in processing MIC structure in the YE group. It has already been postulated that the LH plays a supportive role in text comprehension, especially in more text-based processing (Beeman, Bowden, & Gernsbacher, 2000). Due to its specialization for processing vocabulary in a more focal, narrow way (Waldie & Mosley, 2000), the LH plays an important role in semantic processing at the micropropositional level (Gernsbacher & Kaschak, 2003). The YE group recruited all four ROIs (temporal and frontal) in the LH for MIC processing. The very significant recruitment of frontal regions by this group might have occurred due to the demands of the task, since they were reading in their non-proficient language. No statistically important activation was recorded in the elderly group for MIC processing. This result corroborates the behavioral data, which showed no statistical differences between elderly and young French native speakers at this level.

The YF and YE groups presented different patterns of blood changes: while in the YE group (and the EF group) the changes mainly affected HbO levels, in the YF subjects they affected HbR levels, suggesting that there is an age-related difference in hemodynamics (as well as a difference related to proficiency), as suggested by Herrmann, Walter, Ehlis, and Fallgatter (2006) and Ajmani et al. (2000). If this result is further verified, it would mean that the use of fMRI—based on the BOLD effect, itself linked to the concentration of HbR—could be insufficient for comparing younger and older participants. Be that as it may, most previous fNIRS studies have taken HbO measurements to represent activation patterns.

Finally, it is important to note that the most heterogeneous signals captured by fNIRS at all three levels of discourse processing, not only in MIC, were generated by the EF group, as observed in the changing patterns of HbO and HbR curves; they were followed by those of the YE group. The higher standard deviation levels in the elderly group reflect their greater behavioral heterogeneity (similar to what was reported in the study by Duong, Giroux, Tardif, and Ska (2005)), and physiological heterogeneity, as reported in studies of the differences between default modes in younger and older adults (e.g., Grady et al., 2010; Rajah et al., 2009) and of semantic encoding verified by fMRI (Vandenbroucke et al., 2004).

6.2. Macropropositional level

Both the YE and EF groups showed considerable activation during MAC processing. In the elderly French native speakers' group (EF), substantial participation by the RH in MAC processing was recorded, corroborating the findings of previous studies, which have pointed to the prominent participation of the RH, mainly frontal areas, in tasks demanding the construction of story representations (Gernsbacher & Kaschak, 2003), the integration of information in a coherent and holistic way (Hough, 1990), and the drawing of inferences and establishment of global coherence (Beeman et al., 2000; Federmeier & Kutas, 1999; Friese, Rutschmann, Raabe, & Schmalhofer, 2008; Robertson et al., 2000).

Elderly participants activated a large area in the RH frontal region (R1), and R2 was also relevant for processing at the MAC level in this group, while no significant changes were observed in these areas in the younger French native speakers. The fact that no major changes in hemodynamic patterns were observed in the YF group's MAC processing may suggest that this group constructed this higher level of text comprehension automatically and effortlessly. As Kintsch (1998) notes, this is the case when textual information easily permits the elaboration of inferences necessary for macrostructure construction. The high frontal RH activation and significantly higher RTs in MAC processing by the elderly group, as compared to the YF group, may result from a reduced ability to inhibit irrelevant information and to select the most appropriate inference from among all the possible ones which might be considered (Beeman, 1998; Radvansky, 1999; Radvansky et al., 2001). Thus, both behavioral and neuroimaging data corroborated the hypothesis that processing the MAC level made higher demands on the elderly group.

In the group of young English speakers (YE), statistically significant blood changes were recorded in both RH temporal regions (R3 and R4). St. George, Kutas, Martinez, and Sereno (1999) associated the participation of middle temporal regions, mainly in the RH, with integrative processes for global coherence. In the same way, the fMRI study developed by Friese et al. (2008) demonstrated the association of left and right temporal lobes with comparison processes that are based on propositional representations of context sentences.

In this study, elderly adults reflected no significant activation in temporal regions in any of the three conditions, reflecting a greater reliance on frontal areas; in this regard, they differed from both the YE participants, who significantly activated the temporal areas, and the YF group, who also showed a tendency to higher activation in temporal than in frontal regions. This shift from more posterior to frontal areas in aging seems to corroborate the ideas postulated by the PASA Model, which has presented evidence of a shift from parietal and occipital regions to frontal ones. The model postulates that this shift occurs no matter what the level of the cognitive activity may be. In other words, a posterior–anterior shift occurs regardless of whether the participant is performing a harder or an easier task. It represents a neurofunctional change, which enables older adults to cope with cognitive tasks.

6.3. Situational level

Comprehension at the situational level relies on extratextual knowledge, that is, on world knowledge, acquired from intertextual pieces of information to which one has previously been exposed (Kintsch, 1998). Although both SIT and MAC represent higher levels in text processing, more prominent activations were recorded only in MAC in the elderly group. There are two possible explanations of this finding. First, as suggested by the HAROLD and PASA phenomena, frontal areas tend to strongly recruited when high-performing elderly subjects are accomplishing cognitive tasks, whereas this is not the case for younger adults. Considering that MAC processing is strongly associated with frontal areas, and that elderly participants tend to have reduced inhibitory control, which affects the generation and choice of appropriate inferences, the frontal area of the RH should be highly recruited by elderly readers when they must solve a reading task at the MAC level. The second explanation relates to the nature of SIT model processing. In order to build up the SIT model, the reader needs to link the incoming information from the text—which must be maintained in working memory, an attribute strongly related to the frontal lobes, as already mentioned—to extratextual information, which is related to world knowledge already stored in memory—an attribute strongly related to temporal areas, among others. Thus, the computation of the SIT model calls on a wider brain network, comprising frontal and temporal areas (as well as other areas not investigated in this study). According to Martín-Loeches, Casado, Hernández-Tamames, and Álvarez-Linera (2008, p. 621), "the same content [of a narrative] can also give place to different situation models as a function of the degree of global coherence achieved by the reader or listener." In other words, these authors suggest that multimodal areas may be activated, as they probably relate to activities described in the short texts, and are accessed in a personally represented space. Similarly, Mason and Just (2006) postulate that text representation in the situational model is diffused and distributed over many brain regions, depending on the nature of the information (for instance, spatial in the right parietal region, emotional in the amygdala/fronto-medial cortex, etc.). The changing hemodynamic patterns in this distributed network may have become non-significant, and therefore were not considered in the fNIRS statistical analysis. To corroborate this possible explanation, one may consider the fact that SIT model processing did not lead to significant changes in any hemisphere for any group of participants, not even for the YE group, whose low scores on this task reflected their problems coping with the task, and probably the consequent high demands on brain activity.

Taken together, the findings of this study, by comparing the processing of three textual levels by three groups of participants, indicate some possible conclusions. First, discourse processing in aging, according to our data, seems to rely mainly on RH frontal areas. This involvement of frontal areas is coherent with the PASA phenomenon, and does not contradict the HAROLD phenomenon, which also emphasizes the greater participation of frontal areas in high-performing older adults. Secondly, the increased participation of the RH frontal region in older adults (EF) may not have occurred due to high task demands, since the behavioral results did not show statistically significantly lower accuracy in the processing of MAC—or the other textual levels investigated in this study—by the elderly group compared to the younger adults (YF). Thirdly, a tendency to contralateral activation in MIC processing and extra recruitment of areas for MIC and MAC processing (the latter with significant activation in comparison to the other two groups of participants) was noticed in the performance of the YE group, composed of non-native speakers, which is in line with Stern's (2009) assumption that a bilateral brain contribution is triggered by increased tasks demands in young adults, as well as with Banich and colleagues' hypothesis that there is a bilateral distribution advantage (BDA) (Weissman & Banich, 2000). Due to the difficulties imposed by the English speakers' limited proficiency in French, confirmed by their behavioral data and proficiency test results, an extra effort to cope with the reading comprehension tasks may have been demanded, generating bilateral recruitment, as well as wider network recruitment. Thus, in this study, both the HAROLD and PASA phenomena, as well as the STAC frame of reference, could account for the data from the elderly group. Stern's theory and the BDA model may explain the YE data on MIC and MAC processing, since cooperation between correlated interhemispheric areas was observed while the YE participants performed the tasks that demanded reading processing at these two text levels.

7. Conclusion

The study here reported showed that older and younger French native speakers did not differ in terms of accuracy when processing the three discourse levels under analysis, while the young group significantly differed from the young English native speakers at the macropropositional and situational levels. In terms of response time, young adult native speakers of French were significantly faster than the other two groups of participants in all three analyzed levels. fNIRS data showed considerable activation (HbO increase) in the right frontal region in the elderly group during macropropositional processing, while the group of young English native speakers showed several areas with high activation: left frontal and temporal regions during micropropositional processing and a very significant right temporal area activation while processing the macropropositional level in comparison to the other two groups. These results seem to point to an inter- and intra-hemispheric (re)organization in the elderly group to maintain their good performance at text processing, specifically at the macropropositional level. There is evidence suggesting that this reorganization is more linked to cognitive, strategic and/or neurobiological compensation than to task difficulty, since the elderly adults in this study did not show any decrease in accuracy in text processing in the comparison to the young adult native speakers.

Much research has lately been done on the neurofunctional changes related to the elderly population's performance on cognitive tasks and on the changes that take place over a lifespan. By now, a considerable body of evidence has suggested the occurrence of compensatory or adaptive mechanisms through the reallocation of brain regions to cope with declining abilities in aging, as shown by a large number of studies reporting the existence of different brain circuitry for cognitive activities in older and younger adults which, to some extent, was corroborated by this study. However, much of the evidence reported so far on this neurofunctional reorganization seems to be compatible with a variety of reported phenomena and frameworks. Further studies are needed to better investigate the relative impact of maintained cognitive performance on neurofunctional restructuring in aging, and the influence of level of task difficulty. Moreover, the interplay between performance of cognitive activities and important cognitive components such as attention, inhibitory control and working memory capacity should be analyzed while elderly adults are processing language, and discourse in particular, a research field in which neuroimaging investigations are very recent. Finally, the use of the fNIRS technique should be further exploited, since it has been demonstrated to be a useful tool for investigating brain circuitry in cognitive processing in a more naturalistic way, and thus is especially suited for the study of discourse processing.

Acknowledgments

The first author gratefully acknowledges the support given by CAPES, the Brazilian Funding Agency, by means of a scholarship received during her doctoral training period (Process BEX 3323/04-8) and a post-doctoral scholarship (Process BEX 2231/09-3), which contributed to the development of the research presented here and the preparation of this manuscript. The work was supported by a grant from the Canadian Institutes of Health Research (CIHR # MOP-93542) to YJ and BS.

Appendix A

Samples of the task: examples of three short narratives with their corresponding probes, each one dealing with one of the three levels of text comprehension investigated in the study (MIC, MAC and SIT)

A.1. Micropropositional level

TEXT: Michaël est propriétaire d'une voiture verte depuis douze ans. Il l'aime bien et l'appelle Pierrette. La voiture de Michaël est très vieille et tombe en panne. Michaël est triste parce qu'il va devoir acheter une autre voiture.

Michaël has owned a green car for 12 years. He loves it and calls it Pierrette. Michaël's car is very old and breaks down. Michaël is sad because he will need to buy another car.

PROBE: La vieille voiture de Michaël est de couleur bleue. (F)

Michaël's old car is blue. (F)

A.2. Macropropositional level

TEXT: Joanne a l'habitude d'être malade durant ses voyages, mais aujourd'hui elle se sent bien. Soudain, la plus jeune de ses filles tombe. Heureusement, un autre touriste la ramène à bord en la tirant par son gilet de sauvetage.

Joanne usually gets sick during her trips, but today she feels well. Suddenly, her youngest daughter falls. Fortunately, another tourist brings her back on board by pulling her by her life jacket.

PROBE: Joanne et sa fille sont des touristes en croisière sur un bateau. (V)

Joanne and her daughter are tourists traveling on a boat. (T)

A.3. Situational model

TEXT: Marie ne parle pas couramment le français. Elle a lu une offre d'emploi de réceptionniste dans un hôtel de Montréal. Elle va à l'entrevue mais sa candidature n'est pas retenue. Marie décide de prendre des cours de français.

Marie does not speak French fluently. She has read a job offer to work as a receptionist in a hotel in Montreal. She goes for the interview, but her application is not accepted. Marie decides to take French courses.

PROBE: Marie étudiera le français parce qu'elle adore cette langue. (F)

Marie is going to study French because she loves this language. (F)

References

Ajmani, R. S., Metter, E. J., Jaykumar, R., Ingram, D. K., Spangler, E. L., Abugo, O. O., et al. (2000). Hemodynamic changes during aging associated with cerebral blood flow and impaired cognitive function. *Neurobiology of Aging, 21*, 257–269.

Ashendorf, L., Jefferson, A., O'Connor, M. K., Chaisson, C., Green, R. C., & Stern, R. A. (2009). Trail Making Test errors in normal aging, mild cognitive impairment, and dementia. *Archives of Neuropsychology, 23*(2), 129–137.

Bandettini, P. A., Petridou, N., & Bodurka, J. (2005). Direct detection of neuronal activity with MRI: Fantasy, possibility, or reality? *Applied Magnetic Resonance, 29*(1), 65–88.

Banich, M. T., & Weissman, D. H. (2000). One of the twenty questions for the twenty-first century: How do brain regions interact and integrate information? *Brain and Cognition, 42*, 29–32.

Beason-Held, L. L., Kraut, M. A., & Resnick, S. M. (2008). Longitudinal changes in aging brain function. *Neurobiology of Aging, 29*, 483–496.

Beeman, M. J. (1998). Coarse semantic coding and discourse comprehension. In M. Beeman & C. Chiarello (Eds.), *Right hemisphere language comprehension: Perspectives from cognitive neuroscience* (pp. 255–284). Mahwah, NJ: Erlbaum.

Beeman, M. J., Bowden, E. M., & Gernsbacher, M. A. (2000). Right and left hemisphere cooperation for drawing predictive and coherence inferences during normal story comprehension. *Brain and Language, 71*, 310–336.

Brownell, H. H., & Joanette, Y. (1993). *Narrative discourse in neurologically impaired and normal aging adults*. San Diego: Singular.

Burke, S. N., & Barnes, C. A. (2010). Senescent synapses and hippocampal circuit dynamics. *Trends in Neurosciences, 33*, 153–161.

Cabeza, R. (2002). Hemispheric asymmetry reduction in older adults: The HAROLD model. *Psychology and Aging, 17*, 85–100.

Cabeza, R., Anderson, N. D., Kester, J., & McIntosh, A. R. (2002). Aging gracefully: Compensatory brain activity in high performing older adults. *NeuroImage, 17*, 1394–1402.

Coch, D., Maron, L., Wolf, M., & Holcomb, P. J. (2002). Word and picture processing in children: An event-related potential study. *Development Neuropsychology, 22*, 373–406.

Collette, F., Schmidt, C., Scherrer, C., Adam, S., & Salmon, E. (2007). Specificity of inhibitory deficits in normal aging and Alzheimer's disease. *Neurobiology of Aging, 30*, 875–889.

Davis, S. W., Dennis, N. A., Daselaar, S. M., Fleck, M. S., & Cabeza, R. (2007). Qué PASA? The posterior-anterior shift in aging. *Cerebral Cortex, 8*, 2007.

De Beni, R., Borella, E., & Carretti, B. (2007). Reading comprehension in aging: The role of working memory and metacomprehension. *Aging, Neuropsychology, and Cognition, 14*, 189–212.

Démonet, J.-F., Thierry, G., & Cardebat, D. (2005). Renewal of the neurophysiology of language: Functional neuroimaging. *Physiological Reviews, 85*, 49–95.

Duong, A., Giroux, F., Tardif, A., & Ska, B. (2005). The heterogeneity of picture-supported narratives in Alzheimer's disease. *Brain and Language, 93*, 173–184.

Federmeier, K. D., & Kutas, M. (1999). Right words and left words: Electrophysiological evidence for hemispheric differences in meaning processing. *Cognitive Brain Research, 8*, 373–392.

Ferstl, E. C., Neumann, J., Bogler, C., & von Cramon, D. Y. (2008). The extended language network: A meta-analysis of neuroimaging studies on text comprehension. *Human Brain Mapping, 29*, 581–593.

Friederici, A. D., Hahne, A., & von Cramon, D. Y. (1998). First-pass versus second-pass parsing processes in a Wernicke's and a Broca's aphasic: Electrophysiological evidence for a double dissociation. *Brain and Language, 62*, 311–341.

Friese, U., Rutschmann, R., Raabe, M., & Schmalhofer, F. (2008). Neural indicators of inference processes in text comprehension: An event-related functional magnetic resonance imaging study. *Journal of Cognitive Neuroscience, 20*, 2110–2124.

George, M., St., Kutas, M., Martinez, A., & Sereno, M. I. (1999). Semantic integration in reading: Engagement of the right hemisphere during discourse processing. *Brain, 122*, 1317–1325.

Gernsbacher, M. A., & Kaschak, M. P. (2003). Neuroimaging studies of language production and comprehension. *Annual Review of Psychology, 54*, 91–114.

Grady, C. L., Maisog, J. M., Horwitz, B., Ungerleider, L. G., Mentis, M. J., Salerno, J. A., et al. (1994). Age-related changes in cortical blood flow activation during visual processing of faces and location. *Journal of Neurosciences, 14*, 1450–1462.

Grady, C. L., Protzner, A. B., Kovacevic, N., Strother, S. C., Afshin-Pour, B., Wojtowicz, M., et al. (2010). A multivariate analysis of age-related differences in default mode and task-positive networks across multiple cognitive domains. *Cerebral Cortex, 20*, 1432–1447.

Grady, C. L., Springer, M. V., Hongwanishkul, D., McIntosh, A. R., & Winocur, G. (2006). Age-related changes in brain activity across the adult lifespan. *Journal of Cognitive Neuroscience, 18*, 227–241.

Grober, E., & Buschke, H. (1987). Genuine memory deficits in dementia. *Developmental Neuropsychology, 3*, 13–36.

Herrmann, M. J., Walter, A., Ehlis, A.-C., & Fallgatter, A. J. (2006). Cerebral oxygenation changes in the prefrontal cortex: Effects of age and gender. *Neurobiology of Aging, 27*, 888–894.

Hoge, R. D., Franceschini, M. A., Covolan, R. J., Huppert, T., Mandeville, J. B., & Boas, D. A. (2005). Simultaneous recording of task-induced changes in blood oxygenation, volume, and flow using diffuse optical imaging and arterial spin-labeling MRI. *NeuroImage, 25*, 701–707. <http://www.nmr.mgh.harvard.edu/PMI/PDF/2005/Hoge_NI_25_701_2005.pdf>.

Hough, M. S. (1990). Narrative comprehension in adults with right and left hemisphere brain-damage: Theme organization. *Brain and Language, 38*, 253–277.

Jasper, H. H. (1958). The ten-twenty electrode system of the International Federation. *Electroencephalography and Clinical Neurophysiology, 10*, 371–375.

Kintsch, W. (1998). *Comprehension: A paradigm for cognition*. New York: Cambridge University Press.

Kuperberg, G. R., Lakshmanan, B. M., Caplan, D. N., & Holcomb, P. J. (2006). Making sense of discourse: An fMRI study of causal inferencing across sentences. *NeuroImage, 33*, 343–361.

Li, Z., Moore, A. B., Tyner, C., & Hu, X. (2009). Asymmetric connectivity reduction and its relationship to "HAROLD" in aging brain. *Brain Research, 1295*, 149–158.

Maertens, M., & Pollmann, S. (2005). Interhemispheric resource sharing: Decreasing benefits with increasing processing efficiency. *Brain and Cognition, 58*, 183–192.

Martín-Loeches, M., Casado, P., Hernández-Tamames, J. A., & Álvarez-Linera, J. (2008). Brain activation in discourse comprehension: A 3t fMRI study. *NeuroImage, 41*, 614–622.

Mason, R. A., & Just, M. A. (2006). Neuroimaging contributions to the understanding of discourse processes. In M. Traxler & M. A. Gernsbacher (Eds.), *Handbook of psycholinguistics* (pp. 765–799). Amsterdam: Elsevier.

Nieuwland, M. S., Otten, M., & Van Berkum, J. J. A. (2007). Who are you talking about? Tracking discourse-level referential processes with ERPs. *The Journal of Cognitive Neuroscience, 19*, 1–9.

Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia, 9*, 97–113.

Park, D. C., & Reuter-Lorenz, P. (2009). The adaptive brain: Aging and neurocognitive scaffolding. *Annual Review of Psychology, 60*, 173–196.

Perfetti, C. A., & Frishkoff, G. A. (2008). The neural bases of text and discourse processing. In B. Stemmer & H. A. Whitaker (Eds.), *Handbook of the neuroscience of language* (pp. 165–174). Cambridge, MA: Elsevier.

Quaresima, V., Ferrari, M., Torricelli, A., Spinelli, L., Pifferi, A., & Cubeddu, R. (2005). Bilateral prefrontal cortex oxygenation responses to a verbal fluency task: A multichannel time-resolved near-infrared topography study. *Journal of Biomedical Optics, 10*, 11012.

Radvansky, G. (1999). Aging, memory, and comprehension. *Current Directions in Psychological Science, 8*, 49–53.

Radvansky, G., Curiel, J. M., Zwaan, R. A., & Copeland, D. E. (2001). Situation models and aging. *Psychology and Aging, 16*, 145–160.

Rajah, M. N., Bastianetto, S., Bromley-Brits, K., Cools, R., D'Esposito, M., Grady, C. L., et al. (2009). Biological changes associated with healthy versus pathological aging: A symposium review. *Aging Research Reviews, 8*, 140–146.

Rajah, M. N., & D'Esposito, M. (2005). Region-specific changes in prefrontal function with age: A review of PET and fMRI studies on working and episodic memory. *Brain, 128*, 1964–1983.

Raz, N. (2000). Aging and the brain and its impact on cognitive performance. Integration of structural and functional findings. In F. I. M. Craik & T. A. Salthouse (Eds.), *The handbook of aging and cognition* (pp. 1–90). Mahwah, NJ: Erlbaum.

Reitan, R. M., & Wolfson, D. (1993). *The Halstead-Reitan neuropsychology battery: Theory and clinical interpretation*. Tucson, AZ: Neuropsychology Press.

Reitan, R. M., & Wolfson, D. (2004). The trail making test as an initial screening procedure for neuropsychological impairment in older children. *Archives of Clinical Neuropsychology, 19*, 281–288.

Renault, A. -S. (2005). *Construction d'une tâche pour localiser la compréhension du discours en imagerie par résonance magnétique: étude de la complexité du discours en fonction de l'âge des sujets*. Unpublished thesis, Université Claude Bernard, Lyon, Institut Technique de Réadaptation.

Reuter-Lorenz, P. A., Jonides, J., Smith, E. E., Hartley, A., Miller, A., Marshuetz, C., et al. (2000). Age differences in the frontal lateralization of verbal and spatial working memory revealed by PET. *Journal of Cognitive Neuroscience, 12*, 174–187.

Robertson, D. A., Gernsbacher, M. A., Guidotti, S. J., Robertson, R. R. W., Irwin, W., Mock, B. J., et al. (2000). Functional neuroanatomy of the cognitive process of mapping during discourse processing. *Psychological Science, 11*, 255–260.

Rossini, P. M., Rossi, S., Babiloni, V. C., & Polich, J. (2007). Clinical neurophysiology of aging brain: From normal aging to neurodegeneration. *Progress in Neurobiology, 83*, 375–400.

Schecklmann, M., Ehlis, A.-C., Plichta, M. M., & Fallgatter, A. J. (2008). Functional near-infrared spectroscopy: A long-term reliable tool for measuring brain activity during verbal fluency. *NeuroImage, 43*, 147–155.

Ska, B., & Joanette, Y. (2006). Vieillissement normal et cognition. *Medecine Sciences: Vieillissement, 3*, 284–287.

Sörös, P., Bose, A., Sokoloff, L. G., Graham, S. J., & Stuss, D. T. (2011). Age-related changes in the functional neuroanatomy of overt speech production. *Neurobiology of Aging, 32*, 1505–1513.

Stern, Y. (2009). Cognitive reserve. *Neuropsychologia, 47*, 2015–2028.

Stine-Morrow, E. A. L., Loveless, M. K., & Soederberg, L. M. (1996). Resource allocation in on-line reading by younger and older adults. *Psychology and Aging, 11*, 475–486.

Stine-Morrow, E. A. L., Miller, L. M. S., & Leno, R. (2001). Patterns of on-line resource allocation to narrative text by younger and older readers. *Aging, Neuropsychology, and Cognition, 8*, 36–53.

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology, 18*, 643–662.

Vandenbroucke, M. W. G., Goekoop, R., Duschek, E. E. J., Netelenbos, C., Kuijer, J. P. A., Barkhof, F., et al. (2004). Interindividual differences of medial temporal lobe activation during encoding in an elderly population studied by fMRI. *NeuroImage, 21*, 173–180.

Waldie, K., & Mosley, J. L. (2000). Hemispheric specialization for reading. *Brain and Language, 75*, 108–122.

Wechsler, D. (1997). *WAIS-III: Administration and scoring manual*. San Antonio, TX: The Psychological Corporation.

Weissman, D. H., & Banich, M. T. (2000). The cerebral hemispheres cooperate to perform complex but not simple tasks. *Neuropsychology, 14*, 41–59.