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Syntactic processing in bilinguals: An fNIRS study

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ABSTRACT

The study of the neural basis of syntactic processing has greatly benefited from neuroimaging techniques. Research on syntactic processing in bilinguals has used a variety of techniques, including mainly functional magnetic resonance imaging (fMRI) and event-related potentials (ERP). This paper reports on a functional near-infrared spectroscopy (fNIRS) study on syntactic processing in highly proficient young adult speakers of Portuguese (mother tongue) (L1) and French (second language) (L2). They made a syntactic judgment of visually presented sentences, which either did or did not contain noun–verb agreement violations. The results showed that syntactic processing in both languages resulted in significant activation in anterior frontal regions of the left hemisphere and in the temporal superior posterior areas of the right hemisphere, with a more prominent activation for L2 in some areas. These findings corroborate previously reported neuroimaging evidence, showing the suitability of fNIRS for the study of syntactic processing in the bilingual brain.

1. Introduction

For a message to be conveyed, it is important that the speakers or writers master the mental lexicon, as well as the rules that govern language structure. There is considerable debate regarding the extent to which these two language dimensions are distinguishable enough to be broken apart (Palolahti, Leino, Jokela, Kopra, & Paavilainen, 2005). For instance, event-related potential (ERP) evidence has shown that the P600, which initially was only found to be strongly associated with syntactic violations, has also been recorded in semantic verb-argument violations, even in the absence of any syntactic violations or ambiguities (Kuperberg, 2007). When it comes to the organization of two or more languages in the brain, the distinction between structure and meaning becomes even more complex, because two (or more) language systems are involved and need to be selected and retrieved, or inhibited, according to the context in which the message is generated. The study presented here aimed to investigate the behavioral and neural correlates of syntactic processing in young bilingual adults by using functional near-infrared spectroscopy (fNIRS). This emerging neuroimaging technique measures the hemodynamic response to stimuli at two levels: oxygenation (HbO) and deoxygenation (HbR) (see Quaresima & Ferrari in this issue for a review of the technical aspects of fNIRS).

1.1. Neuroimaging evidence on syntactic processing in bilinguals

Considering that most studies on syntactic processing have focused on monolingual populations, an important conclusion drawn by this literature is that syntactic processing is not restricted to left frontal activations. Thus, several studies show both frontal and temporal left hemisphere (LH) activations, as well as significant activations in homologous right hemisphere (RH) areas. For instance, Fiebach, Schlesewsky, Lohmann, von Cramon, and Friederici (2005) reported significant activations in the posterior inferior frontal gyrus (IFG) and superior temporal regions when their monolingual participants read non-canonical sentences in which the verb argument was dislocated to a relatively long distance. The authors suggest that these activations reflected increasing working memory loads, resulting from the processing demands entailed by the non-canonical structure of the sentences. In bilinguals, there is evidence

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that similar cortical regions sustain semantic processing in the first language (L1) and the second languages (L2), given the reliance on a shared lexical storage system (Abutalebi et al., 2005). Conversely, with regards to syntactic processing, the L1–L2 overlap seems to be less complete, as languages may show distinct activation patterns (Rüschemeyer, Zysset, & Friederici, 2006), even in highly proficient bilinguals. In another study, Suh et al. (2007) assessed syntactic processing in a sample of late bilingual Korean (L1) and English (L2) speakers. The authors (Suh et al., 2007) reported overlapping L1/L2 significant left IFG activation, together with significant bilateral activations in the inferior parietal gyrus and the occipital lobes including the cuneus and the lingual gyrus. However, in L1 greater activation in the IFG was observed for embedded sentences as compared to conjoined sentences, whereas no such difference was observed in L2. Thus, Suh et al. (2007) concluded that, although areas involved in L1 and L2 syntactic processing may be shared, distinct patterns of activation reflect different underlying processing mechanisms across languages. These differences have been related to the factors of age of acquisition (AoA) and proficiency level (Wartenburger et al., 2003), as well as daily amount of L2 use, or years of formal education in L2 (Flege, Yeni-Komishiann, & Liu, 1999). Still, some studies contest the impact of AoA on the neural organization for syntactic processing and report similar patterns of activation for syntactic processing in L1 and L2 late bilinguals (Kotz, 2009; Rossi, Gugler, Friederici, & Hahne, 2006).

Despite the evidence found to date regarding how the bilingual brain processes syntax, there is considerably less work on syntactic processing, as compared to studies of semantic processing in bilinguals (Hartsuiker & Pickering, 2008; Kotz, 2009).

There is evidence suggesting that RH areas are recruited whenever a syntactic task is particularly demanding (Fiebach et al., 2005) or when there is a need to repair an error to solve the task (Meyer, Friederici, & von Cramon, 2000). In line with this claim, Rossi et al. (2006) report distinct activation patterns comparing several ERP components such as the LAN and the P600, both in monolingual and bilingual populations, during syntactic tasks of syntactic violation. According to Friederici (2002), three distinguishable components of syntactic processing relate to different stages and their corresponding neural substrates: first, there is a word category assignment stage (ELAN), sustained by the left anterior regions; the second stage corresponds to morphosyntactic and/or semantic/thematic role assignment (LAN/N400), which entails a significant central-parietal activation, mainly in the RH. Finally, the third stage corresponds to syntactic reanalysis or repair phase (P600), which concerns error correction and is associated with central parietal processing (Friederici, 2002). In the same line, Meyer et al. (2000) argued that there is a left-dominant component for early syntactic structure building and a bilaterally distributed late component responsible for syntactic reanalysis and repair. Thus, in BOLD-based neuroimaging techniques such as fMRI and fNIRS, all of these activated areas could be observed as a consequence of the larger temporal window examined.

In summary, most neuroimaging studies on syntax processing have focused on monolingual populations, and show that syntax processing is sustained by a bilateral fronto-temporal network, similarly to what has been reported in studies on the comparison between L1 and L2 syntactic processing (Raettig, Frisch, Friederici, & Kotz, 2010; Grodzinsky & Friederici, 2006; Friederici, Rüschemeyer, Hahne, & Fiebach, 2003; Friederici, Meyer, & von Cramon, 2000). In bilinguals, studies have focused on the degree of overlap between L1/L2 activation patterns. Specifically with regards to syntax processing, some overlap is expected in cases of equivalent L1_l2 proficiency (Rüschemeyer et al., 2006; Suh et al., 2007); however, the overlap is not as complete as observed in semantic processing, given that syntax processing may entail different underlying processing mechanisms across languages (Suh et al., 2007). Thus, specific L1–L2 activations observed during syntax processing have been related to individual factors, such as age of acquisition and degree of consolidation in syntax processing (Wartenburger et al., 2003), but there is no general agreement on this issue.

The present study aimed to identify the neural correlates of syntactic processing in high-proficient bilingual adults with fNIRS. Specifically, the purpose was to bench-test the suitability of fNIRS in studies of syntactic processing in bilinguals. In line with previous functional neuroimaging research (e.g., Friederici et al., 2003), it was expected that syntactic processing would significantly activate left fronto-temporal brain areas, with a more bilateral distribution in the temporal regions. Also, in line with previous reports (Rüschemeyer et al., 2006; Suh et al., 2007), it was expected that L1 and L2 activation maps would show a considerable overlap, although L2 maps would be more widespread.

2. Method

2.1. Participants

Ten young bilingual right-handed adults who were native speakers of Portuguese (L1) and highly proficient in French participated (L2) in the study. Table 1 presents the participants' sociodemographic and bilingual characteristics, as well as their performance on a neuropsychological battery. The participants used both Portuguese and French consistently on a daily basis, at work, at home and/or at the university. The majority of the participants were married to a French speaking person, and all received formal education in French. They had no history of neurological or psychiatric disease and had normal or corrected-to-normal vision. All participants received financial compensation for their time. The study was approved by the ethics committee of the CER – Comité mixte scientifique et d'ethique du Centre de Recherche de l'Institut Universitaire de Gériatrie de Montréal, affiliated to the University of Montreal.

2.2. Material

The participants were assessed with an extensive background battery with the aim of documenting proficiency level in both languages. Thus, a Portuguese adaptation of the questionnaire

Table 1
Participants' sociodemographic and bilingual characteristics and neuropsychological assessment.

Sociodemographic data	
Gender (m/f)	5/5
Age (years)	27.90 (5.23)
Education	17.20(2.44)
Bilingual assessment	
Age of acquisition (AoA) of French	21.20 (6.47)
Years of formal education in French	3.70 (1.15)
Mean scores in DELF B2	93.44 (2.29)
Mean scores in grammatical judgment test	96.95 (6.84)
Neuropsychological data	
Edinburgh index	98.0 (6.32)
Direct digit span	11.80 (2.30)
Indirect digit span	8.40 (2.72)
Direct–indirect digit span	3.40 (1.65)
Stroop 1	10.86 (2.25)
Stroop 2	12.19 (2.90)
Stroop 3	17.78 (4.73)
Buschke free recall 1	10.80 (0.92)
Buschke free recall 2	11.80 (0.42)
Buschke free recall 3	11.90 (0.32)
Trail making test – part B time	60.29 (17.60)

created by Marian, Blumenfeld, and Kaushanskaya (2007) was used to gather information on individual factors known to have an impact on the profile of bilingualism (e.g., age of L2 acquisition, parents and caretakers' languages, mode of L2 acquisition, number of years living in a country where the L2 is spoken, number of years of formal education in the L2, history of L1 and L2 use, daily use of both languages, etc.). Furthermore, together with the administration of a standardized French proficiency test (DELF B2 – Diplôme d'études en langue française), a self-rating scale on writing, reading and oral comprehension in both languages was also included. Finally, participants' syntactic judgment ability was assessed by means of 24 written sentences in French, 12 of which contained subject–verb agreement errors.

2.2.1. Neuropsychological baseline assessment

To rule out any cognitive deficit, participants were assessed for short-term memory and working memory (Digit Span; Wechsler, 1997); episodic verbal memory (Grober and Buschke Verbal Memory Task (Grober & Buschke, 1987)); attention, inhibition, mental flexibility and processing speed related to inhibitory executive components (Stroop Test (Stroop, 1935)); and Trail Making Test, Part B (Reitan & Wolfson, 1993). Their scores were above average compared to the respective normative groups. Means and standard deviations for the neuropsychological data are shown in Table 1.

2.2.2. Experimental stimuli and task

Eighty sentences (40 in French and 40 in Portuguese) were developed. Half of the sentences (20 in each language) were syntactically correct, whereas the other half included a subject-verb violation, that is, a verbal agreement violation. None of the sentences included relative clauses, embedded sentences, indirect order or passive voice, since these conditions impose extra demands on working memory during syntactic processing. All verbs were chosen from a set of very frequent and highly pictorial verbs in both languages. Sentences included only present tense transitive verbs, with different types of transitivity (direct, indirect or both); no copula verbs were used. The sentences were constructed so that there were at least two pairs of sentences with exactly the same structure in both languages; two of them were correct and two incorrect. Literal translations from one language to the other where avoided when possible to minimize the possibility of repetition effects. In order to allow for data comparisons across languages, the number of words, propositions, syllables and letters was statistically controlled. A training set of 12 similarly constructed sentences was constructed for a training session. All sentences were judged and validated by a group of 90 undergraduate psychology students at the Université de Montréal. Examples of correct and anomalous sentences in both languages are presented below, followed by their translations into English. The $*$ represents the incorrect version of the sentence.

French:	*L'artiste* ***montre*** *ses toiles à un acheteur.* 'The artist **shows** his/her paintings to a customer.' *Le jardinier* ***montrent*** *son jardin au touriste.** 'The gardener **show** his garden to the tourist.*'
Portuguese:	*O pintor* ***mostra*** *os quadros ao comprador.* *O jardineiro* ***mostram*** *o jardim ao turista.**

The stimuli were displayed on a computer screen, by means of E-Prime (v 1.1) software. They were presented in a block design, with a total of four blocks, including randomly presented correct and incorrect sentences, within each block. A baseline 60 s was recorded before the recording of the first block. Each sentence was displayed in black on a white screen for 4 s, during which the participant had to read and judge whether the sentence was grammatically correct or not, and answer by pressing the green button on the keyboard if the presented sentence was syntactically correct, or the red button if it was syntactically incorrect/anomalous. A black cross was displayed on the middle of the screen for 1000 ms between sentence presentations, to achieve fixation, and a 20-s fixation period was included after presentation of each block. Task design is illustrated in Fig. 1.

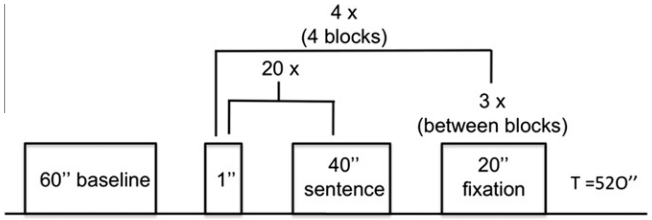


Fig. 1. Experimental task conducted during fNIRS acquisition. Each run lasted 520 s (1 run per language), thus totaling 1040 s.

The experimental task comprised two runs of 8.66 min, one with L1 sentences and the other one with L2 sentences. To control for language presentation order effects, half of the participants were first tested in French, whereas the other half were first tested in Portuguese. In all, the experimental task lasted for 1040 s (17.33 min).

2.2.3. fNIRS study and equipment

The reason why fNIRS was chosen for the present study relates to a given number of fNIRS advantages, in comparison to other neuroimaging techniques. It is non-expensive in comparison to other neuroimaging techniques such as fMRI or PET, for example. As it tolerates a certain level of movement, fNIRs is particularly suitable to study children, elderly and clinical populations. fNIRS has a good temporal resolution, and a relatively good spatial resolution. It is non-invasive, allowing researchers and clinicians to take repeated data acquisitions and task presentations in a more naturalistic and ecologically more valid setting (for a deeper characterization of the technique please refer to Quaresima et al. in this issue). Moreover, this technique provides three measurements of haemodynamics: HbO (oxygenation), HbR (deoxygenation), which is comparable to fMRI's BOLD sign, and HbT (total hemoglobin, which represents the addition of HbO to HbR) Activation is characterized by an increase in HbO concentration, and a decrease in HbR levels.

For the present study, fNIRS data were collected with a multichannel continuous-wave optical imager (TechEnCW5) with a 24 source-detector configuration, covering RH and LH frontal and temporal areas. The system includes four laser sources emitting lights in the 690- and 830-mm wavelengths for each side with eight avalanche photodiode detectors (Hamamatsu C5460-01), and an optical bandwidth of 400–1000 mm, to receive the diffused light. The laser intensities were driven at 16 different frequencies, generated by a master clock and separated by approximately 200-Hz steps for simultaneous acquisition. Each laser delivered less than 5 MW to the tissue. A bandpass filter reduced $1/f$ noise, room light signal and the third harmonics of the square-wave signals. An analog-to-digital converter matched the signal levels with the acquisition level within the computer. Individual source signals were separated by demodulation software and filtered with an infinite-impulse-response filter with a 20-Hz bandpass frequency.

2.3. Procedures for behavioral and fNIRS data acquisition

Data acquisition occurred in two sessions. During the first session, the participants underwent the language and neuropsy-

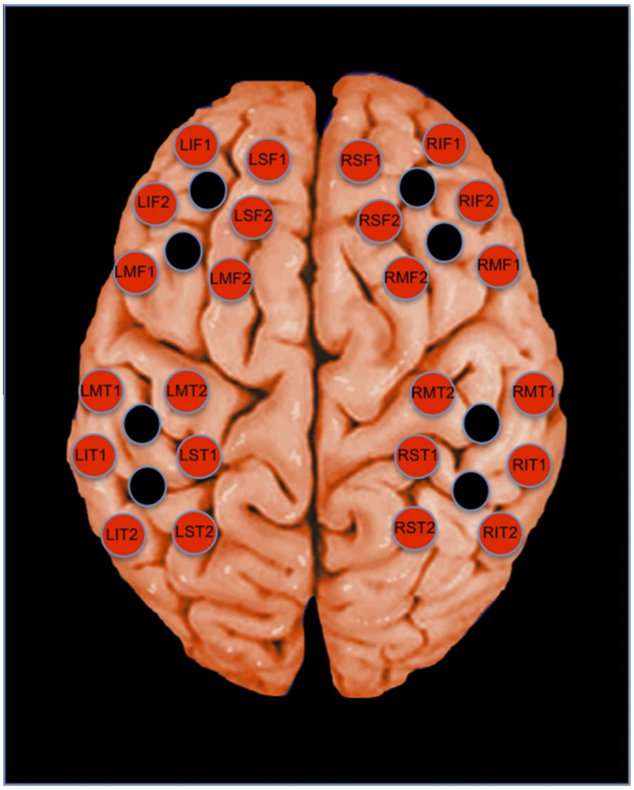


Fig. 2. Illustration of probe positioning on the head, bilaterally. *Note*: Detectors are displayed in black; sources are represented as red dots.

chological assessments. The second session was devoted to the simultaneous acquisition of fNIRS and behavioral data. A pre-experimental training task was used to make sure that participants understood the procedure. The two fNIRS experimental runs were separated by a 15-min pause, during which the participant could relax. The fNIRS probes (emitter/detector set) were left in place between the runs in order to guarantee the same positioning for data recording in the two languages.

The fNIRS probes were placed bilaterally, anterior and posterior to the precentral sulcus, to allow for simultaneous recording of signals from the frontal and temporal regions, within both cerebral hemispheres, including Broca's and Wernicke's areas. Probes LIT2, LIT1, LST2, LST1, LMT1 and LMT2, where L stands for left, were localized in more posterior regions, while LMF2 to LIF1 were located in more anterior regions (see Fig. 2); the same distribution was adopted in the RH, where the probes were named RST2, RST1, etc., with R standing for right hemisphere. In order to allow inter-subject comparisons, the plates were placed based on the 10 × 20 system positioning (Jasper, 1958) usually used for fNIRS acquisition.

The plaques were positioned following the procedure adopted by Friederici, Hahne, and von Cramon (1998), so as to cover Broca's and Wernickés areas, and their homologous areas at the right hemisphere. Thus, Brocás region was defined in the crossing point between T3-Fz and F7-Cz in the left hemisphere and T4-Fz and F8-Cz in the right hemisphere, in the fronto-temporal region approximately between electrodes LIF2 (left inferior frontal 2) and LIF1 (left inferior frontal 1) and RIF2 (right inferior frontal 2) and RIF1 (right inferior frontal 2), upwards. Wernickés area was marked at the crossing point between T3-P3 and C3-T5 in the left hemisphere and T4–P4 and C4–T6 in the right homologous area, in the posterior-temporal region corresponding approximately to the regions between electrodes LIT1 (left inferior temporal 1) and LST1 (left superior temporal 1) and RST1 (right superior temporal 1) and RIT1 (right inferior temporal 1).

The measurements obtained by CW5 detectors were applied to calculate the HbO and HbR concentration changes. It is important to mention that these concentration changes are normalized values over the course of the experiment. The HbO and HbR concentration changes are calculated by the modified Beer–Lambert law first, and further analysis of data is completed within HomER (a Matlab based toolbox to analyze the measurements in fNIRS format), by measuring the signal average for each source-detector pair, over the window of our experimental bloc design. The time window ranged from a few seconds before the bloc until 10 s after the end of the bloc, so as to ensure the coverage of changes in the level of HbO and HbR concentration. In order to contrast activation and control blocs, the functional data were subtracted from baseline (signal of rest bloc). This subtraction is completed in order to detect any differences in the pattern of HbO and HbR concentration resulting from the underlying task-induced neural activity. To do so, the average data of all functional blocks was subtracted from the one related to the baseline.

2.4. Data analyses

Means of fNIRS data were compared within subjects, using a repeated measures analysis of variance (ANOVA), with three factors (ROI, hemisphere and language). In order to better explore each factor's possible differences, a one-sample t Test was run. The test allowed for comparisons regarding activation in each probe per hemisphere and language condition, verifying if there was an activation superior to zero. A paired sample t Test was also performed to compare activation within each language between hemispheres (lateralization analysis) per probe, and activation across languages per hemisphere and ROI.

3. Results

The neuropsychological assessment ruled out any cognitive deficit that could have an impact on syntactic processing. All participants scored above the norms (see Table 1).

3.1. Behavioral results

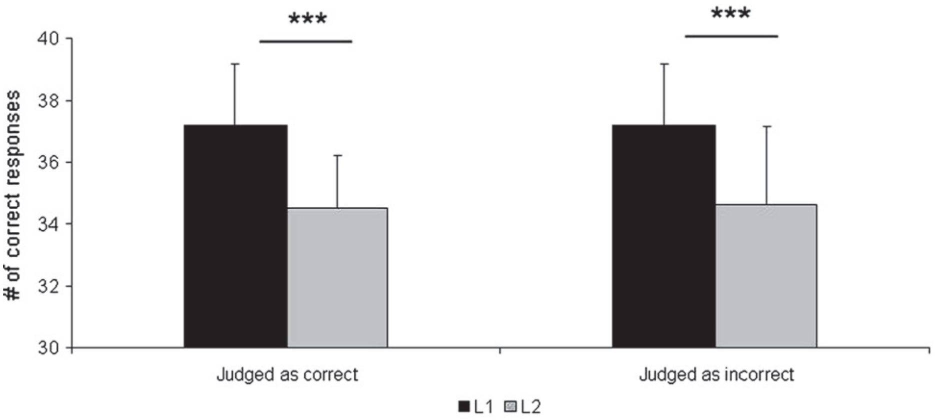
Participants' high proficiency in both languages was attested. Mean scores on the DELF B2 and the grammar judgment test were 93.44 ($SD = 2.29$) and 96.95 ($SD = 6.84$), respectively. However, behavioral data collected during fNIRS acquisitions showed significant differences in terms of accuracy and response time, as shown in Fig. 3. More specifically, syntactic judgments were less accurate in L2 considering correct sentences (Portuguese = 37.20 out of 40, 93%; French = 34.60 out of 40, 86.5%) and also for incorrect sentences (Portuguese = 37.2 out of 40, 93%; French = 34.6 out of 40, 86.5%), all $ps < .01$. Therefore, error rates were 7% in L1and 13.5% in L2. Also, there was a significant difference in RT between L1 and L2 ($p < .000001$), with larger RT being observed in L2 (see Fig. 4).

3.2. fNIRS results

Mean values for HbO and HbR by probe (source-detector pair) corresponding to the two languages are displayed in Table 2. For a graphic representation of the probe display, see Fig. 2.

A repeated measures ANOVA showed no significant main effect, and no significant interaction between the three factors (ROI, hemisphere and language) ($p > 0.05$). To better explore the impact of each factor, results of one-sample t Test for activations in each

(a) Behavioral results for accuracy in both languages



(b) Behavioral results for response time (RT) in both languages

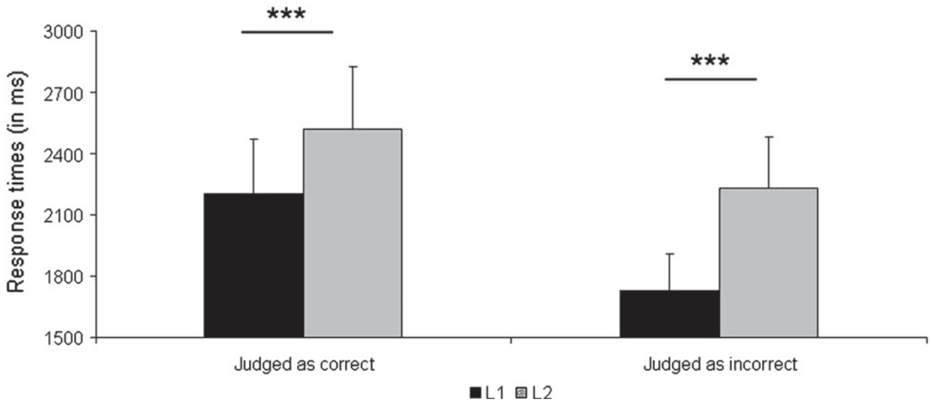


Fig. 3. Behavioral results for correct responses and response time (RT) in both languages. (a) Behavioral results for accuracy in both languages. (b) Behavioral results for response time (RT) in both languages. *Note*: Paired sample statistics; accuracy in correct sentences ($p = .001$), Portuguese mean = 37.20, *SD* = 1.32; French mean = 34.50, *SD* = 1.72; accuracy in incorrect sentences ($p = .009$), Portuguese mean = 37.20, *SD* = 1.23; French mean = 34.60, *SD* = 2.55); response time for correct sentences ($p = .004$), Portuguese mean = 2.201.05, *SD* = 272.08; French mean = 2.521.10, *SD* = 302.75; response time for incorrect sentences ($p = .0001$), Portuguese mean = 1.729.54, *SD* = 178.89; French mean = 2.228.57, *SD* = 254.46.

probe within cerebral hemispheres, and of paired-samples *t*-Tests for activations between LH and RH's probes, that is, across cerebral hemispheres, and between L1 and L2 are presented to be discussed.

3.2.1. Results per probe within cerebral hemispheres

Table 2 presents data on HbO and HbR means per probe with reference to syntactic processing per language and per hemisphere. All significant activations are shown, in light of the hypothesis that HbO means were different from null.

The results show significant activation in three different locations: LMF2, LSF2 and LSF1. All of these locations are in LH frontal areas and are activated with both L1 and L2. Activation in LIF2 was observed during L1 syntactic processing only. In the RH, activations included posterior areas, covered by RST2 and RST1, for both languages. Also, RIT2 showed activation for L2 processing only.

3.2.2. Comparisons across cerebral hemispheres

Each probe was compared to its contralateral equivalent. The only significant result concerned RMF1 and LMF1, which cover the right and left mid-frontal area; thus, the pair sample *t* test showed a significantly higher HbO concentration in LMF1 with L2 syntactic processing ($p = .001$), also registered in L1 ($p = .05$).

Further analysis included grouping two probes per region; this showed a significant difference in HbO concentration between RST2/RST1 and the contralateral LST2/LST1. These pairs covered the superior temporal area in the RH and LH respectively; a significant activation ($p = .05$), was observed in the RH pair during the processing of L2.

3.2.3. Results of across-language comparisons

Comparing activation of each probe in L1 to its activation in L2, no significant differences between language conditions were found in RH sites. Conversely, the comparison L1–L2 showed a significant difference in LMF2, located in the left posterior superior frontal region ($p < 0.05$).

Similar statistical analyses performed on mean HbR concentrations failed to reach significance in any comparison.

4. Discussion

The purpose of this fNIRS study was to analyze the neural correlates of syntactic processing in high-proficient bilinguals. In particular, the aim was to bench-test fNIRS‘s potential in the study of syntax processing in bilinguals. A group of 10 high-proficient bilingual adults were examined on a syntactic judgment task, performed in L1 (Portuguese) and L2 (French).

The global pattern of results was in line with previous neuroimaging evidence, thus suggesting that fNIRS is a suitable neuroimaging technique to study syntactic processing in bilingual adults. Specifically, the behavioral pattern is in line with Rüschemeyer

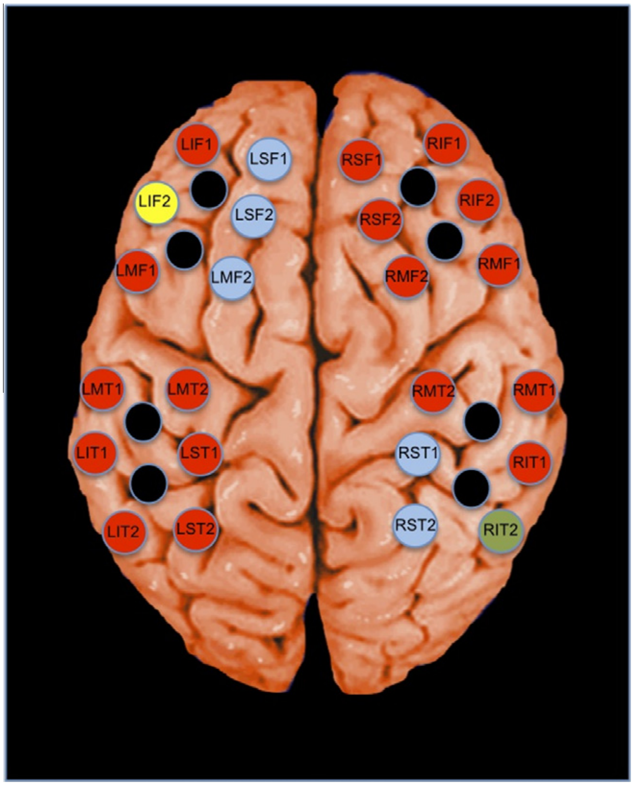


Fig. 4. *Results per probe*: HbO changes during the syntactic judgment task. In blue, optodes that were significantly different from zero during both Portuguese and French runs. In yellow, optodes with HbO different from zero only in Portuguese (left hemisphere, LIF2). In green, optodes with HbO different from zero only in French (right hemisphere, RIT2).

Table 2
Mean HbO and HbR values per language and probe.

Left hemisphere				Right hemisphere			
Channel	Group	Means (*SD*)		Channel	Group	Means (*SD*)	
HbO							
L1	F	0.430	(1.021)	R1	F	0.954	(0.813)
	P	0.080	(0.391)		P	0.392	(0.388)
L2	F	0.481	(1.276)	R2	F	0.677	(0.816)
	P	0.068	(0.355)		P	0.410	(0.380)
L3	F	1.064	(1.437)	R3	F	0.671	(0.766)
	P	0.259	(0.400)		P	0.264	(0.575)
L4	F	0.982	(1.439)	R4	F	0.316	(0.679)
	P	0.421	(0.597)		P	–0.014	(0.342)
L5	F	1.621	(2.498)	R5	F	0.331	(1.507)
	P	0.098	(0.494)		P	0.148	(0.691)
L6	F	1.116	(1.407)	R6	F	0.028	(1.809)
	P	0.061	(0.437)		P	0.499	(0.752)
L7	F	0.723	(0.818)	R7	F	0.639	(1.170)
	P	0.427	(0.479)		P	0.610	(1.302)
L8	F	–0.048	(1.095)	R8	F	0.457	(0.673)
	P	0.178	(0.423)		P	0.577	(0.907)
L9	F	0.829	(0.904)	R9	F	0.196	(2.224)
	P	0.629	(0.535)		P	0.380	(0.882)
L10	F	0.877	(1.050)	R10	F	0.651	(1.258)
	P	0.748	(0.746)		P	0.426	(0.702)
L11	F	0.352	(1.351)	R11	F	0.189	(1.519)
	P	0.877	(0.825)		P	0.369	(0.617)
L12	F	–0.071	(1.716)	R12	F	0.231	(1.930)
	P	0.492	(0.670)		P	0.333	(0.718)
HbR							
L1	F	–0.019	(0.140)	R1	F	–0.199	(0.331)
	P	–0.106	(0.199)		P	–0.002	(0.271)
L2	F	–0.093	(0.223)	R2	F	–0.306	(0.566)
	P	–0.068	(0.200)		P	0.044	(0.232)
L3	F	0.031	(0.240)	R3	F	–0.104	(0.294)
	P	–0.181	(0.303)		P	0.128	(0.148)
L4	F	–0.099	(0.156)	R4	F	–0.362	(0.620)
	P	–0.089	(0.274)		P	0.048	(0.191)
L5	F	–0.453	(0.689)	R5	F	0.031	(0.545)
	P	0.020	(0.320)		P	–0.150	(0.371)
L6	F	–0.167	(0.363)	R6	F	0.003	(0.352)
	P	0.137	(0.279)		P	0.030	(0.208)
L7	F	–0.253	(0.499)	R7	F	0.073	(0.668)
	P	–0.012	(0.397)		P	–0.202	(0.578)
L8	F	–0.312	(0.596)	R8	F	–0.558	(1.009)
	P	–0.222	(0.623)		P	–0.120	(0.486)
L9	F	–0.227	(0.764)	R9	F	–0.282	(0.763)
	P	–0.194	(0.561)		P	–0.163	(0.487)
L10	F	–0.286	(0.749)	R10	F	–0.592	(0.541)
	P	–0.097	(0.658)		P	–0.203	(0.540)
L11	F	–0.149	(0.961)	R11	F	–0.367	(0.887)
	P	–0.322	(0.654)		P	–0.131	(0.376)
L12	F	–0.160	(0.648)	R12	F	–0.312	(0.884)
	P	–0.258	(0.701)		P	0.019	(0.402)

et al. (2006), and the neurofunctional pattern is in line with Rüschemeyer et al. (2006), Suh et al. (2007) and Friederici (1995).

In particular, from a behavioral point of view, although participants respected all criteria to be considered highly-proficient bilinguals, slower response times and higher error rates were observed when judging L2 as compared to L1 sentences. This difference across languages may have resulted from the fact that these were late highly proficient bilinguals. Thus, late L2 acquisition has been shown to be correlated to less automatic levels of syntax processing, even in highly proficient bilinguals (Wartenburger et al., 2003).

From a neurofunctional perspective, and in line with previous neuroimaging studies (Rüschemeyer et al., 2006; Suh et al., 2007), the present study shows a considerable overlap between L1 and L2 activation maps of syntactic processing. Specifically, overlapping L1–L2 significant activations in the LH concerned LMF1, LMF2, LSF2 and LSF1, which cover the left middle inferior, middle superior, and anterior superior frontal areas respectively. Significant L1–L2 overlapping activations in left frontal regions during syntactic processing have been claimed to represent a common pattern of brain activity in highly proficient bilinguals (Kotz, 2009). Our results are in line with this evidence (Kotz, 2009), and show that fNIRS can capture frontal activations associated with syntax processing.

Overlapping L1 and L2 activations in the RH concerned the RST2 and RST1 pairs, which correspond to the right superior posterior temporal region; significant right temporal activations have been previously reported in functional neuroimaging studies of syntactic processing in monolinguals. Specifically, bilateral superior temporal activations have been reported to be modulated by syntactic complexity (Fiebach et al., 2005); also, RH temporal activations have been claimed to reflect an attempt to repair syntactic errors (Meyer et al., 2000). In the present study, syntactic complexity was not manipulated as it was the case in Fiebach and colleagues' study. Conversely, and in line with Meyer et al. (2000), the RH activation may represent and attempt to judge syntactically anomalous versus correct sentences,

In summary, the overlapping L1–L2 activations observed in the present study are in line with previous evidence from functional neuroimaging studies on syntax processing in highly proficient bilinguals (Kotz, 2009) and syntax incongruity (Meyer, Friederici, & von Cramon, 2000) in monolinguals.

Despite the most of the activations for L1–L2 were overlapping, and concerned critical syntax processing areas, some other significant activations were specifically observed in the L2 condition; these included the right inferior posterior temporal area (RIT2), and the superior temporal region bilaterally (RST2 and RST1, and LST2 and LST1; $p = .047$). In line with Rüschemeyer et al.'s (2006), distinct activations across languages in highly proficient bilinguals may result from the greater involvement of specific areas of an overall comparable first and second language networks. As already stated, temporal areas seem to contribute for the resolution of syntactic incongruity or complexity. In our study, a higher temporal activation, mainly in the RH, during L2 processing as compared to L1 processing may reflect a lower automaticity in L2 as compared to L1, possibly resulting from L2 late acquisition.

Another possible explanation regarding the activated areas specific to L2 comes from functional connectivity studies on syntactic processing in bilinguals. For instance, Dodel et al. (2005) suggest that specific areas may be differently functionally linked to L2 sentence processing as compared to L1, as a result of the bigger inter-subject variability in L2 as compared to L1 processing (Dehaene et al., 1997). Thus, even in homogeneous groups of highly proficient bilinguals, L2 processing results in larger inter-subject variability than L1 processing, as a result of consolidation factors (Veroude, Norris, Shumskaya, Gullberg, & Indefrey, 2010), which have a particular impact on syntactic processing (Kotz, 2009). The higher L2 inter-subject variability may have led to specific L2 activations in areas that deal with incongruity linked to morphosyntactic aspects, known for intrinsically relate syntactic and semantic features of words presented in sentences.

Finally, HbO concentrations were sometimes significantly higher with the L2 condition as compared to the L1 condition, in line with previous evidence (Herschensohn, 2004). This result suggests that, even at high proficiency levels, syntactic processing remains particularly demanding, given the multiple cognitive operations involved (Herschensohn, 2004; Kotz, 2009). Thus, even at high proficiency levels, L2 syntax processing is less automatic than semantic processing, and thus requires stronger activation of processing areas as compared to mother tongue processing. This perspective is supported by the behavioral pattern of results. Specifically, although all participants showed a high L2 proficiency level on a standardized French proficiency test and in a syntactic judgment task, and reported high L2 proficiency and high exposure to L2, their performance on the L2 syntactic task was less efficient, in terms of accuracy and response time, than their performance in their mother tongue.

The hypothesis that activations would be more widespread for L2 as compared to L1 was partially confirmed. Two regions (LH posterior frontal and RH superior temporal) showed higher HbO concentration levels in the L2 condition. However, participants recruited more temporal areas but fewer frontal areas for L2 than for L1, which suggests that L2 was more demanding and less automatic. In particular, the temporal activation may reflect the intrinsic relation between the morphosyntactic and semantic aspects of this syntactic task, which involved verbal agreement judgment. Thus, as stated by Raettig et al. (2010), ‘‘lexical, syntactic and semantic features of verbal stimuli interact in a complex fashion during language comprehension’’ (p. 613).

Our results are as well in line with Rüschemeyer et al.’s (2006), who report overlapping activation patterns, with some distinct activations with L2, and also replicate those of previous studies showing bilateral syntactic processing, particularly in Broca’s area and its RH homolog (e.g., Friederici et al., 2000; Grodzinsky & Friederici, 2006). Also, as proposed by Wartenburger and colleagues (2003), the differences in activation patterns observed across languages may have resulted from an age of acquisition effect. Thus, the impact of L2 age of acquisition on the neural substrate of L2 processing has been intensively debated (Abutalebi, 2008; Birdsong, 2005; Perani et al., 2003; Saur et al., 2009, among others); research on this topic has brought mismatching results, specially due to poor control of variables such as the number of years of formal L2 education, and the amount of daily exposure to and effective use of the L2. In the present study, all of these variables were controlled for by means of the standardized test and questionnaires, which provide external validity to our results in this regard. Thus, differences in the neural substrate of L1 and L2 syntactic processing might result from the reliance on different memory systems in each language; thus, declarative memory systems store less automatic processing, whereas procedural memory are responsible for storage and processing of L2 automatic processing (Ullman, 2005). Given the behavioral pattern of results, it is possible that the neurofunctional differences observed across languages may have been resulted from a late acquisition L2 which lead to lower automaticity in L2.

To conclude, the evidence reported in this study is convergent with previous research on the role of the fronto-temporal structures in L2 syntactic processing, and with the assumption that activations in highly proficient bilinguals tend to be overlapping. Also, the present work replicates previous findings on the role of specific areas in L2 syntax processing in particular (Rüschemeyer et al., 2006). These areas may be more active in L2 due to lower automaticity in syntax processing possibly generated by late L2 acquisition, which would make L2 syntactic processing more depending on declarative memory systems than on implicit ones (Ullman, 2005).

Furthermore, the findings on significant left frontal areas and right temporal activations are in line with neuroimaging studies on syntactic processing in monolinguals (e.g., Friederici, 1995), suggesting that both these areas are involved in syntactic judgments, bringing together morphological and semantic features related to verbal agreement processing in tasks presented within the context of a sentence.

Altogether, the results of the present study suggest that fNIRS is a promising tool for studying the neural basis of syntactic processing in bilinguals. Thus, previous neuroimaging evidence was replicated, despite the rather small sample studied, and the potential high inter-subject variability that characterizes late bilinguals. Further fNIRS studies could examine the influence of syntactically correct and anomalous sentences in an event-related design, so as to discriminate between the neural substrates of anomalous vs. correct sentence processing, in particular regarding the specific roles of the left and right cerebral hemispheres. An analysis of the patterns of correct and incorrect sentence processing was developed in a study conducted by Friederici et al. (2003), which showed that, in comparison to the processing of correct sentences, processing both semantically and syntactically anomalous sentences resulted in the recruitment of larger portions of the superior temporal gyri, and yielded more left-lateralized patterns for syntactic anomalies, whereas bilateral patterns were found with semantic anomalies.

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